Anticipating Industry Localization Effects of Clean Technology Deployment Policies in Developing Countries

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Abstract

National 'green growth' strategies, which aim at decoupling economic development from adverse environmental impacts, have become a new paradigm for policymakers in developing countries. Many green growth strategies are based on policy instruments designed to incentivize the domestic deployment of relatively mature clean technologies and aim at fostering the formation of a local industry to develop and produce these technologies. While the empirical evidence on the localization effect of such policies in developing countries is mixed, there is a dearth of research systemically analyzing how differences between technologies affect patterns of localization, which could explain the observed variance. We address this gap and develop a typology which distinguishes four types of technologies requiring different types of capabilities. We do so by combining insights from the literature on technology transfer and catching-up of industries with insights from the literature on patterns of innovation across the technology life- cycle. We apply this typology to the case of low-emission development strategies and four exemplary low-carbon technologies, namely small and micro hydro power, wind turbines, electric cars, and solar cells, in order to analyze capability requirements, innovation patterns, and the effect of past deployment policies on industry localization. We synthesize these case studies and derive a heuristic to anticipate the localization effects of deployment policies for different types of technologies in countries with varying income levels. We argue that the heuristic can serve as starting point for policymakers aiming at clean technology industry localization. The paper concludes with a discussion of possible technology-specific green growth strategies for developing countries with different income levels and for international institutions supporting green growth.

Keywords: Green growth; Technology deployment; Green industrial policy; Technological characteristics; Technological capabilities; Technology transfer

1 Introduction

In recent years, the alignment of economic development with environmental protection has received much attention in policy circles. Many policymakers "would like environmental policy to bring much-needed jobs, new technologies and competitiveness to domestic industry, as well as to protect the environment" (Fankhauser et al., 2012, p. 902). While the concept of *green growth* and its various definitions are still being debated (Bowen and Fankhauser, 2011), the imperative of integrating environmental and development objectives is increasingly shaping international institutions and national policy frameworks. Developing countries in particular regard it as a strategy to "leapfrog" the "dirty" development path industrialized nations have historically taken and directly jump to the establishment of local green industries (Dasgupta et al., 2002). A better understanding of how to design policies that deliver on both objectives is therefore highly relevant for policymakers around the globe.

Many green growth policies implemented in developing countries target the wider deployment of relatively mature clean technologies such as hydro, wind and solar power, clean cooking solutions, water sanitation technologies, and efficient industry process technologies (OECD, 2012; World Bank, 2012). Often the host countries hope to benefit from the deployment of these technologies by attracting technology transfer from abroad and eventually becoming global manufacturing hubs (Mathews and Tan, 2014). In many cases, these policies are successful in terms of technology diffusion, as evidenced by the fact that investments in renewable energy projects (which are largely still dependent on deployment policies) in non-OECD countries have surpassed those in OECD countries (REN21, 2014). Empirical evidence of the success of these instruments in terms of industry localization is, however, mixed (Barua et al., 2012; Lund, 2009): In some cases, deployment policies have gone hand in hand with the formation of a local industry that creates value through activities beyond mere operation and maintenance (O&M). Prominent cases include Danish and German deployment policies for wind (Lewis and Wiser, 2007). For other clean technologies, such as photovoltaic (PV) cells, decisions on industry location seem to depend on other aspects such as economies of scale, the maturity of supply chains, and input factor costs (Goodrich et al., 2013). In these cases, deployment policies in developing countries mostly resulted in increased technology imports, with a local industry focusing mostly on installation and O&M.

Thus far there has been relatively little systematic empirical research on the effect of clean technology deployment policies on industry localization (Bell, 2012), especially research comparing different technologies. Currently, considerations of cost, cost reduction potential and environmental pollution mitigation potentials drive the design of green growth strategies. The localization potential and how it might differ across technologies is either ignored or only haphazardly considered. This oversight is partly due to the lack of research supporting decision makers in developing countries in understanding technology differences in localization. A framework differentiating clean technologies on the basis of their localization potentials could thus inform developing country policymakers in designing policies to effectively and efficiently unlock green growth and the formation of domestic green industries.

The literatures on international technology transfer and catching-up argue that the success of industry localization depends on the presence of domestic capabilities related to the development and production of a technology (Bell and Pavitt, 1992; Bell, 2012; Lee and Lim, 2001). Even for mature technologies, manufacturers need to master continued technology adaptation and incremental cost and performance improvements to compete in the (domestic or international) market, necessitating certain levels of technological capabilities. Yet the types of capabilities involved in the innovation of a technology differ from technology to technology, as demonstrated in the literature on innovation patterns across technology life-cycles (Davies and Hobday, 2005; Davies, 1997; Huenteler et al., 2015b). We argue that these differences between technologies with regard to the capabilities involved in innovation can help explain the above-described variation in the localization effects of clean technology deployment policies. In this paper, we develop a technology typology and a heuristic that informs the green growth debate by reflecting the need for different technological capabilities for successful industry localization. It serves as a starting point for technology selection and policy design for different types of technologies in different countries. We develop the heuristic using four technology cases in the context of low-emission development strategies (LEDS) in developing countries.

The remainder of the paper is structured as follows. Section 2 introduces the theoretical background and proposes a capability-based technology typology, distinguishing four types of technologies. Section 3 introduces the case of LEDS and analyzes the innovation and localization patterns and the role of deployment policies for four different low-carbon technologies, each representing one of the technology types described in Section 2. Based on a synthesis of the four cases, Section 4 derives the heuristic, while its implications for national policymakers and international institutions are discussed in Section 5. We conclude by highlighting the paper's key contributions in Section 6.

2 Deployment policies, technological capabilities, and industry localization

2.1 The role of technological capabilities for industry localization

Studies from the fields of international technology transfer and catching-up have found that successful industry localization in developing countries depends on the presence of local capabilities required for innovation (Bell and Pavitt, 1992; Bell, 2010; Cimoli et al., 2009; Lee and Lim, 2001). Technological capabilities can be defined as "the skills—technical, managerial or organizational—that firms need in order to utilize efficiently the hardware (equipment) and software (information) of technology, and to accomplish any process of technological change" (Morrison et al., 2008, p. 41). Capabilities can only be acquired through the time-consuming, purposeful process of learning, often involving significant experimentation and accumulation of use experience (Bell, 2007).

Even for mature technologies, industry localization and technology transfer is not just an external productivity shock but an endogenous process involving numerous feedback loops and incremental innovations over an extended period of time (Bell and Pavitt, 1992). Therefore, policies targeted at industry localization need to match—and eventually augment—domestic technological capabilities (Coninck and Sagar, 2015; Lema and Lema, 2013; Phillips et al., 2013; Rai et al., 2014; Suzuki, 2015). Two observations have been made regarding the type of capabilities that need to be matched.

First, while deployment of technologies always requires a certain level of O&M capabilities, the available capabilities need to go beyond O&M in order to foster a competitive industry that develops and manufactures technologies (Bell, 1990; Hansen and Ockwell, 2014; Ockwell et al., 2014). For industry localization, the capabilities to develop, improve, and produce the technologies are of a much greater importance (Bell, 2012, 1990; Lall, 1995).

Second, it has been recognized that different technologies require different capabilities (e.g., Walz and Marschneider-Weidemann, 2011). The catching-up and technology transfer literatures have mostly focused on the effect of a technology's maturity level on the need for particular types of capabilities in a national innovation system. It has been found that less mature technologies require higher levels of capabilities, which are more closely related to the research and development (R&D) stage, whereas more mature technologies require capabilities more closely related to the production of technologies (Bell, 1990; Hansen and Ockwell, 2014; Lall, 1992). While industry localization for less mature products requires higher levels of technological capabilities related to R&D, the literature stresses that capabilities are also needed for successful localization of more mature technologies, as local firms need to be able to adapt technology to local circumstances and to integrate experience with the technology (Bell and Figueiredo, 2012). However, although most technological learning and innovative activity that addresses the most pressing development needs is concentrated on technologies that are already being deployed and manufactured at scale – i.e., what we would call relatively mature technologies – the development literature focuses less on differences within the large space of relatively mature technologies in terms of the capabilities needed to localize industries.

2.2 Technology life-cycles, innovation, and industry localization in mature technologies

The role of different types of capabilities is analyzed in the technological life-cycle literature (Davies, 1997; Lee and Berente, 2013; Utterback and Abernathy, 1975). This literature stresses that, for mature technologies, factors determining competitiveness and, consequently, the focus of innovative activities of an industry can differ significantly across technologies (Abernathy and Utterback, 1988; Davies, 1997; Huenteler et al., 2015b). In particular, the literature provides evidence for two contrasting patterns of competition in mature technologies (Huenteler et al., 2015b).

In some industries, the growth and maturation of technology is accompanied by the emergence of dominant designs (Abernathy and Utterback, 1988; Anderson and Tushman, 1990). After a dominant design has emerged, competitiveness is mostly driven by the ability to produce efficiently and coordinate complex value chains (Utterback and Abernathy, 1975). This results in a focus of innovative activities on process innovations, economies of scale, and supply chain efficiency improvements (Abernathy and Utterback, 1988). User input is important in early stages of the life-cycle but loses relevance after a dominant design has emerged. This decoupling allows manufacturers to geographically disconnect production from product markets and to shift manufacturing facilities to the locations that offer the lowest input factor prices, often in low-wage countries (Vernon, 1966).

Other industries never reach the stage of dominant designs in which competition is based purely on process innovations (Davies and Hobday, 2005; Davies, 1997; Huenteler et al., 2015b; Miller et al., 1995). Technologies in these industries often develop dominant product architectures (Henderson and Clark, 1990). These technologies often take the form of one-off projects—such as nuclear power plants—in which no two projects are exactly the same (Hobday, 2000). In such cases, throughout the entire technology life-cycle, innovative activity remains focused on (incremental) product performance improvements and changes to project or product designs, e.g., by introducing new technology in specific components (Brusoni et al., 2001; Davies, 1997). As product or project design requirements and component technology continue to change over time, user-producer interaction remains important even in later stages of the life-cycle. Firms are much less likely to move manufacturing away from large product markets (Miller et al., 1995), and a strong presence in a home market is often a prerequisite for export success (Lewis and Wiser, 2007).

2.3 A proposed capability-based typology of technologies

The technology life-cycle literature suggests that clean technologies based on product innovation are much more dependent on local product or project *design capabilities*. Conversely, clean technologies whose competitiveness is based on efficient production are highly dependent on the presence of local *manufacturing capabilities*. In still other industries, both design and manufacturing are important in order to achieve or maintain competitiveness (Huenteler et al., 2015b). However, while the literature has highlighted these technology differences, the resulting insights have rarely been used to conceptualize patterns of catching-up and industry localization.

We argue that these differences between technologies with regard to the capabilities involved in innovation can help in explaining much of the variation in the localization of clean technologies in the last decades. We propose a two-by-two typology differentiating technologies along the two types of capabilities (adapted from a technology-lifecycle typology developed by Huenteler et al. (2015b)), as shown in Figure 1, and will proceed to test the explanatory power of this framework in the remainder of this paper.

We label technologies requiring a low level of both design and manufacturing capabilities as *simple technologies*, technologies requiring high levels of design capabilities but low levels of manufacturing capabilities as *design-intensive technologies*, technologies which require high levels of manufacturing capabilities and low levels of design-capabilities as *manufacturing-intensive technologies*, and technologies requiring high levels of both capabilities can be regarded as *design- and manufacturing-intensive technologies*.

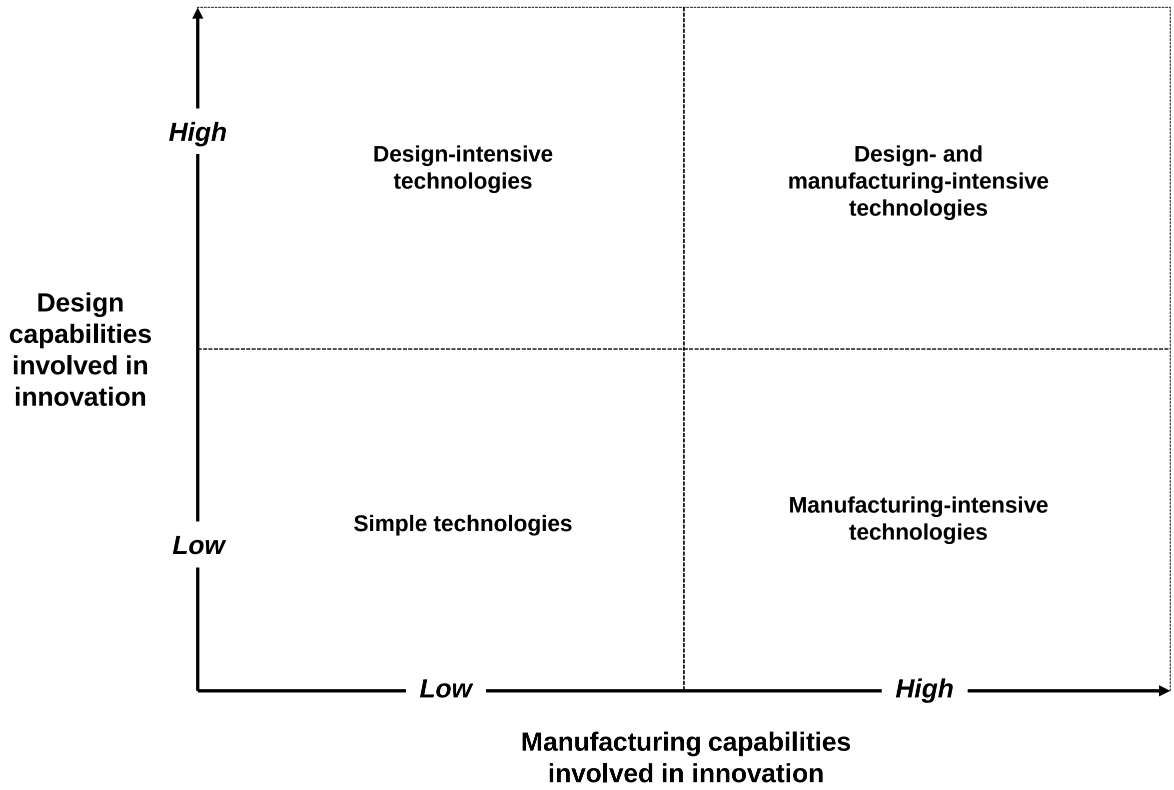

Figure 1 A typology of four stylized types of technologies, distinguished by the types and levels of capabilities necessary to master innovation and be competitive.

In order to ‘absorb’ specific technologies and become competitive in related product markets, countries and their national innovation systems need to achieve certain levels of the two capability types. The typology’s two axes imply that the two types of capabilities—design and manufacturing—are largely independent: the technical, organizational and managerial skills involved in (re-)designing a technology are typically distinct from the skills needed to re-arrange the manufacturing process, and different types of professions are involved in each (e.g., product and project designers versus manufacturing and process engineers) (Davies, 1997). Consequently, countries that master one type of capability may still lag in the other, resulting in uneven localization patterns across different types of technologies.

While we show below that the suggested typology is helpful for thinking about experiences of specific countries with different technologies, it has natural limitations. *First*, the required capabilities represent continua: only in relation to other technologies can a particular technology be assigned to a specific type with any certainty. The patterns and implications derived from the heuristic therefore need to be understood as tendencies—real world phenomena will always contain elements of all four, with some more pronounced than others. *Second*, there is variation in technological characteristics within a technology. For example, in solar PV, one of the cases discussed below, the production process of thin-film solar cells, even with smaller batch sizes, is more complex and integrated than that of standard cells made of crystalline silicon, and thus requires greater manufacturing capabilities. This means that thin-film cells would have to be located further right in the typology matrix. However, we believe that differences between technologies outweigh these intra-technology differences in most cases. *Third*, technological characteristics may vary over time. After a dominant design emerges, a technology gradually moves downward in the matrix. But again, we believe that differences between technologies outweigh these differences within technologies. In the following sections, we use the case of climate change mitigation technologies to examine our hypothesis that technology differences translate to differences in a country’s ability to foster a competitive industry around the respective technology and elaborate on its implications.

3 A review of the innovation patterns of four climate change mitigation technologies

Many developing countries design and enact policies that encourage the local deployment of clean technologies with the dual objectives of protecting the environment and fostering local industry. While these policies address environmental problems in a range of fields (e.g., water, air pollution, or agriculture), in recent years a particular focus has been placed on climate change mitigation (Sterner and Damon, 2011). Substantial climate change mitigation involves the deployment of many different, often relatively mature, low-carbon technologies (Barker et al., 2006, IPCC, 2014). While under the Kyoto Protocol technology selection was mostly driven by the private sector, international post-Kyoto Protocol climate policy is mostly based on national policy, i.e. technology selection takes place rather in the realm of the public sector (Kanie et al., 2010; Rayner, 2010; Raupach et al., 2014; Schmidt et al., 2012, Victor et al., 2014). This development is also reflected in the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC). At the same time, many developing countries are already deploying low-carbon technologies on a large scale, enabling us to compare effects between diverse technologies. Developing countries’ policy efforts to diffuse low-carbon technologies are well documented in their Nationally Appropriate Mitigation Actions (NAMAs) proposals to the UNFCCC (UNEP DTU Partnership, 2015). When analyzing the 93 NAMAs submitted to the NAMA registry by July 1st, 2015, the following observations can be made: of the 93 NAMAs submitted by 24 countries—4 of which are least developed countries—80 represent deployment policies for relatively mature low-carbon technologies; 57 of those 80 NAMAs are related to energy generation, transmission and use; and 10 target the transportation sector. Both the energy and transport sectors are among the biggest and fastest growing contributors to anthropogenic greenhouse gas emissions (IPCC, 2014). The energy-related NAMAs target a wide selection of technologies, e.g., wind, solar PV, geothermal, biomass and biogas, small and large hydro, solar water heaters, efficient lighting, and efficient appliances. The transportation-related NAMAs target technologies such as bicycles, highly efficient cars and trucks, railways, and electric vehicles. Translated into Grubb's climate innovation chain terminology (Grubb, 2004), our observations show that NAMAs are mostly demand-pull policies targeting heterogeneous technologies in the late stage of the innovation chain. However, only a handful of submissions make explicit how the countries aim to benefit from the described mitigation actions in terms of sustainable development, especially in terms of fostering a local low-carbon technology industry. Most NAMAs also do not state whether they plan to use indigenous or foreign technology or which type of tech-transfer they envision—or what kind of mechanism they intend to call upon for support.

In the remainder of this section we illustrate how technology differences play out in four different climate-mitigation technologies in which developing countries have invested substantial public funds small and micro hydro, wind turbines, solar PV and electric cars. We selected these technologies based on how quickly and easily different types of countries were able to localize certain supply chain steps of these technologies. All four technologies are targeted by current (demand-pull) NAMA proposals. After introducing each technology briefly, we analyze the types of capabilities involved in innovation in order to place each technology in one of the quadrants of the technology typology introduced in Section 2. We also review the knowledge acquisition involved in innovations, entry barriers for new firms, and how local markets led to the creation of domestic industries in the past. Finally, for each technology, we briefly discuss what this implies for deployment policies aiming at localization. Like any characterization of a large number of technologies, the case description is inevitably brief and stylized but should help illustrate the heuristic.

3.1 Small and micro hydro plants

Small and micro hydro plants (SMH) convert the energy of water passing small height differences into electricity (at capacities of up to 10MW) and represent the oldest of all power generation technologies (IRENA, 2012a). The design of each project depends on local circumstances; however, the key components (turbine, generator, switch gear) are mostly standardized and of simple *design* (Williams and Simpson, 2009). Adjusting SMH plants to local circumstances therefore mostly involves relatively elementary civil engineering tasks, and the knowledge involved is easily accessible, with some readily available on the internet. Simple and standardized turbine layouts limit the level of capabilities involved in alternating technical designs (Paish, 2002).

At the same time, economies of scale in production are limited. Turbines can be *manufactured* with standardized machinery and are mostly assembled by hand (Sovacool et al., 2011). The technological capabilities necessary to manufacture SMH are also very limited, such that the components and assembly of smaller systems "can easily be mastered by villagers in less developed countries" (Kenfack et al., 2009, p. 2259). The processes (welding, wiring, piping etc.) are standard electro-mechanical processes that are used in many other technologies, and the technical knowledge involved can be achieved through training. Because of the manual labor-intensive production process, local manufacturing in developing countries is typically lower-cost than imported equipment (Khennas and Barnett, 2000; Williams and Simpson, 2009) or even large hydro (Smith, 1996). As a result, despite low transport costs, turbine manufacturers are relatively small and scattered around the globe, and include manufacturers from low-income countries such as Nepal, Sri Lanka, and Indonesia (Cromwell, 1992; Paish, 2002). Given the low levels of design and manufacturing capabilities required for innovation, SMH plants can be described as *simple technology.*

Market entry barriers for local firms are consequently rather low. Countries that have introduced SMH deployment policy schemes have typically experienced the rise of a local manufacturing industry. This effect was most prominent in China in the 1970s but was also observed in, for example, Nepal and Sri Lanka (Khennas and Barnett, 2000). Today, technological innovation potentials in SMH technology are low. Efficient and reliable designs are readily available and the manufacturing processes and equipment are also highly mature (Paish, 2002). Therefore, the likelihood of fostering a local industry that exports the technology is rather low.

Deployment policies for SMH are thus likely to achieve relatively high success in industry localization. However, policymakers should be aware of the limited learning—and thus, performance improvement and cost reduction—potentials and export opportunities. In the past, successful policies have focused on the removal of investment barriers, providing finance to project developers, as well as activities to integrate the local communities operating the plants (Khennas and Barnett, 2000; Purohit, 2008).

3.2 Wind turbines

Wind turbines are complex products, consisting of several thousand customized electrical and mechanical components. Electric capacity has increased from 5 kW to around 5 MW, and rotor size from 10 m to more than 150 m in the last 35 years (Hau, 2013). Components are sourced and integrated into turbine systems by only a few dozen large manufacturers worldwide that hold the required *product design* and system integration capabilities, which they have built up gradually in time-consuming learning-by-doing and learning-by-using processes (Andersen, 2004; Garrad, 2012; Kamp, 2004). Designing a new generation of wind turbines takes many years, involves a high level of tacit knowledge, and requires highly skilled mechanical and electrical engineers with experience in the field (Garrad, 2012). Wind turbines must be adapted to climate, wind speed, wind profile, and local regulations concerning grid-connection, foundations and noise. Furthermore, because of the complex structural interactions between the rotor, hub, and drive-train, changing one component often requires changing others (Thresher et al., 2008). Also, the project design, installation, operation, and maintenance of wind-farms requires specialized skills (e.g., turbine siting), training (e.g., for industrial climbers), and equipment (e.g., installation cranes).

The *manufacturing*, on the other hand, involves well understood and readily available processes and technologies such as welding, drilling, metal casting, and fiberglass casting (Hau, 2013). The manufacturing is relatively manual labor intensive but the capabilities required by the manufacturing personnel are relatively limited and are often found in local labor markets or can be built up relatively quickly through training programs. Given the high level of design capabilities and the low level of manufacturing capabilities needed, wind turbines can be regarded as *design-intensive technology*.

The entry barriers for new companies in the turbine business are rather high, with banks usually requiring 100 or more turbine-years of performance data for projects to be bankable (Wood, 2012). Therefore, when new national industries were established, as in Spain, India and China in recent years, a common pattern was that local firms (typically from countries with a relatively wide and well-trained engineering base) licensed designs from established manufacturers before moving on to indigenous R&D (Lewis and Wiser, 2007). A transfer of manufacturing equipment, on the other hand, is not involved. The innovation potential in wind turbines remains high. Efficiency improvements due to new and larger designs are very much ongoing and are resulting in lower power generation costs per unit of electricity (IRENA, 2012b). Firms that mastered market entry in the past are often able to tap into regional (and partly even global) export markets.

All countries that have created a domestic wind turbine industry have enacted deployment policies (Lewis and Wiser, 2007). Industry build-up was most successful when these policies assured stable demand over a significant period and at a relevant scale (Bergek and Jacobsson, 2003; Lewis and Wiser, 2007). Many of the policies also contained local-content requirements, which incentivized an often rising share of locally manufactured components (Liu and Kokko, 2010). Starting with certain value chain steps, the industry could then vertically integrate. The availability of a significant market size (Pueyo et al., 2011) allowed domestic firms to build the capabilities and tacit knowledge involved in designing and integrating entire turbine systems and then to completely manufacture them locally (Lewis and Wiser, 2007). In smaller markets that cannot sustain domestic manufacturers, local firms often supply the bulky components, such as towers or cast iron frames (Huenteler et al., 2015a).

Developing countries that enact deployment policies for wind can therefore anticipate a certain level of industry localization, at least for bulky and rather easy-to-manufacture parts. Depending on the design capabilities present, even some forms of system integration activities might be localized. However, policy needs to be stringent and persistent. The more the localized activities involve system integration aspects, the higher the likelihood that they will generate exports at least within the region.

3.3 Solar photovoltaic systems

Solar photovoltaic (PV) power is generated by converting solar radiation into electricity using semiconductors that exhibit the photovoltaic effect. A PV system consists of semiconductor cells that are grouped together to form a PV module—which in most power sector-related applications has around 20-200W electric capacity and covers an area of one square meter or less—and the auxiliary components, including the inverter, cables, and controls. There is a wide range of PV cell technologies that use different types of materials and production methods, but cells made of crystalline silicon (c-SI) capture most of the market (Hoppmann et al., 2013).

PV cells and modules are mass-produced goods that can be integrated relatively easily into different PV power systems—from large-scale multi-MW open space plants to 20W solar home systems. C-Si cell designs produced commercially were developed predominantly in the 1980s and 90s (Saga, 2010), are relatively easily accessible to new entrants (e.g., by purchasing turn-key production lines) (De la Tour et al., 2011), and are simple enough for individuals to fully understand. Cell performance predicted in numerical and analytical models is very close to actual performance (Chenni et al., 2007). The capabilities involved in *designing* integrated PV power systems, too, are relatively easily accessible to new entrants, and installing PV-based power systems does not require as advanced equipment or skills as other power generation technologies (Seel et al., 2014).

While the product itself has many features of a commodity—even being traded on spot markets—the production process is highly complex, involving many disciplines (e.g., Saga, 2010). Production takes place in assembly lines and involves very costly and sensitive high-tech equipment, which embodies a high degree of engineering knowledge (Hoppmann et al., 2013). Even today, the physics behind some of the production steps is not fully understood, and changing one production step almost always requires adjusting other process steps and parameters, often in a trial-and-error process that requires significant experience. Setting up and operating a new assembly line or adjusting an existing line therefore involves high degrees of manufacturing experimentation ("learning-by-doing") and requires very advanced *manufacturing capabilities* and tacit knowledge built in long learning processes (Nahm and Steinfeld, 2014). China, for instance, was successful in quickly setting-up large scale manufacturing using returning engineers with production experience gained abroad (De la Tour et al., 2011). Given the relatively low level of design and the high level of manufacturing capabilities, PV can be termed a *manufacturing-intensive technology*.

The entry barriers for silicon and cell manufacturers are relatively high because of the high initial investment involved in setting up a manufacturing plant. A home market for PV power therefore does not automatically result in the scale-up of a local cell- or module-manufacturing industry (Algieri et al., 2011; Barua et al., 2012). Technology transfer between countries proceeds either through imports of cells and modules (sometimes even entire systems, including the inverter), or through the transfer of knowledge and production equipment to countries that focus on production, in recent years especially China, Taiwan, the Philippines and Malaysia (De la Tour et al., 2010). The flipside of the relatively complex manufacturing process is that the innovation potential in PV is still high, and firms that manage to produce cells at a significantly lower cost are quickly able to gain global market shares. Areas of possible advances include more efficient manufacturing processes, better materials, as well as better cell designs (many of which are already well known but difficult to produce with good quality and at low cost on a commercial scale).

All countries that introduced stringent deployment policies for solar PV in the past have seen the rise of a local industry around project design, installation, and O&M (Huenteler et al., 2015a). These steps of the PV value chain tend to be local and are quite relevant given the often high shares of installation costs in PV systems (Seel et al., 2014). In contrast, countries that were successful in creating a local silicon or cell manufacturing industry did not necessarily have a large local demand. The example of China's quick catch up in cell manufacturing shows that a large global market, access to low-cost capital for manufacturing plant finance, and local manufacturing capabilities are much more important to building up a local solar cell industry than the existence of a large home market (Grau et al., 2012; Iizuka, 2015).

Countries enacting policies to create local demand for solar PV power must therefore be aware that the likelihood of localization of up-stream value chain steps (silicon and cell manufacturing) is rather low. A local industry around downstream activities (e.g., installation) can be anticipated to be facilitated. Countries with very large home markets might also expect a certain degree of vertical integration locally, e.g., resulting in domestic assembly of solar cells into modules. In these cases, (mostly regional) export might be possible.

3.4 Electric cars

Equipping cars with electric drivetrains requires a high level of engineering capabilities for both product design and production process. With regard to *product design*, because they consist of thousands of customized components, automotive innovations require extensive simulation, testing, fine-tuning and continuous improvements (learning-by using). Thousands of engineers operating in teams that possess very task-specific skills are involved in the design of a new car model (Batchelor, 2006). Acquiring the knowledge to design cars involves expensive licenses (for the explicit knowledge involved) and experienced engineers (for the tacit knowledge involved) (Kim, 1998).

The *manufacturing* of (electric) cars, too, is scale-intensive and complex and requires a high level of engineering and management capabilities (Alford et al., 2000; Coriat, 2000). Manufacturing knowledge is embedded in both the manufacturing equipment and the experience of the manufacturing engineers and workers and therefore is hard to acquire (Kim, 1998; Simona and Axèle, 2012). Manufacturers plan and run large production facilities and have to coordinate global supply chains to bring down manufacturing costs, making subsequent production engineering necessary for any modification of the product. Car manufacturers therefore employ thousands of assembly planners, logistic coordinators, and process, robotics and tooling engineers. Given the high levels of design and manufacturing capabilities required, electric cars can be characterized as *design- and manufacturing-intensive technologies*.

The cumulativeness of experience in car design and manufacturing creates advantages for established firms, supporting a situation with few very large manufacturers and high entry barriers—related to both cost *and* performance—for new entrants (Baumol and Willig, 1981; Porter, 1979). Technology transfer to developing countries in most cases begins with the import of end-products. Manufacturing in developing countries is not uncommon but usually involves some form of foreign direct investment (FDI) and the transfer of production equipment and engineering teams. Unlike with technologies such as wind turbines, the scale of production creates economies of scale even in components, making it difficult for firms in developing countries to benefit from local production and assembly of cars. The cumulativeness also makes large investments in both R&D and production equipment necessary for innovation. Even though electric car concepts have existed for decades, the prohibitive cost of production creates a chicken-and-egg-problem of lacking competitiveness, limited production and limited learning (Steinhilber et al., 2013; Unruh, 2000). Despite huge investments, the ability of firms in emerging markets to outpace, or *leapfrog*, established manufacturers in electric cars has thus far been limited (Gallagher, 2006; Ou and Zhang, 2012). Given this situation, the future innovation potential for electric cars is still enormous (Aggeri et al., 2009). Firms that master the difficult task of designing and manufacturing electric cars are likely to be able to export their products to a global market.

The observable effects of policy-induced demand for electric cars on industry localization differ significantly across countries (or even states, e.g., within the US). Thus far, a domestic competitive electric car manufacturing industry has only been successfully created in a few geographies (e.g., California). Large developing countries such as China or India aim to create local electric car industries. However, despite supporting these industries through deployment policies, they have struggled to reach these goals (Altenburg et al., 2012; Howell et al., 2014): these local car industries still lack the capabilities to design electric vehicle technologies that are competitive. At the same time, FDI and imports are shielded by policy, preventing transfer of tacit knowledge.

Consequently, countries enacting deployment policies for electric cars can only expect the creation of a system-integrating industry if they already have very advanced capabilities related to automotive and battery-electric engineering. For countries lacking these capabilities (e.g., due to a lack of a competitive domestic internal combustion engine-car industry), it is rather unrealistic to expect deployment policies to foster the formation of a fully integrated domestic industry. Depending on the level of capabilities present, historical evidence suggests that a local industry would focus on the manufacture of the most simple components as well as repairs and maintenance.

4 Synthesis: Technological capabilities, deployment policies and localization

4.1 A Typology of technology-specific innovation patterns and localization

The four climate change abatement technology case studies show that the differences between even rather mature technologies can be very large with respect to the capabilities involved in innovation. Based on these differences, each of the four technologies can be placed in one of the quadrants of the technology typology introduced in Section 2. Figure 2 shows the locations of the four case study technologies and of other relevant low-carbon energy and transport technologies.

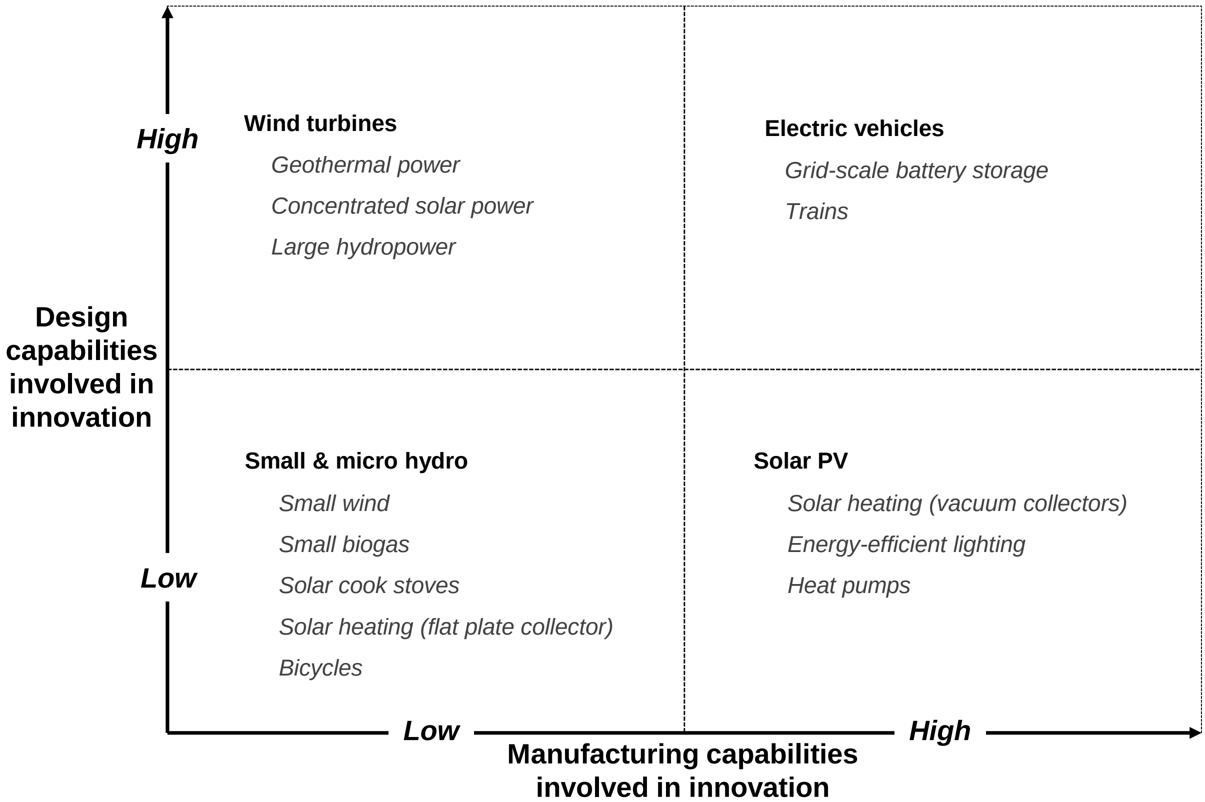

Figure 2 Stylized location of different energy technologies in the typology matrix.

Furthermore, the case studies show that the knowledge acquisition, technology transfer, and learning processes involved, as well as the role of home markets in the formation of a domestic industry differ strongly between the technologies. From these technology-specific observations we derive generalizable statements at the level of the four technology types. The key characteristics of the four technology types and the patterns of innovation and technology transfer are summarized in a stylized manner in Figure 3.

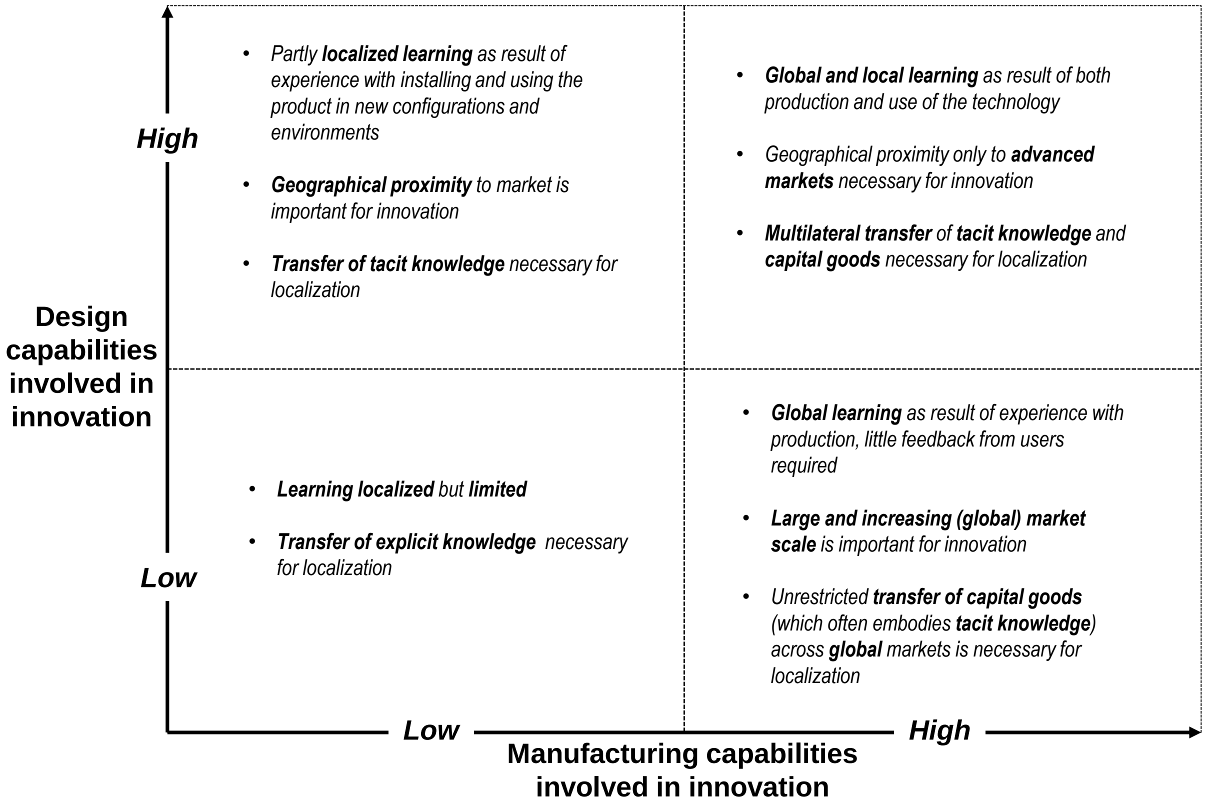

Figure 3 Stylized differences between the four technology types in terms of innovation process technology transfer mechanisms, and their role in industry localization.

Our case study suggests that the learning potential in *simple technologies* is rather limited. Transfer of mostly explicit knowledge is necessary to induce the formation of a local industry through local demand, as illustrated in the case of Nepal and SMH. In the case of *design-intensive technologies*, it seems essential for industry localization to gain experience with installing and operating the technology. Geographical proximity of firms to installations is usually required to capture learning-by-using effects because of the required interaction with users, regulators, banks, O&M service providers, and others. Close interaction between users and manufacturers and their suppliers is needed to feed back the experience gained from using into the design process (termed "local learning" in Figure 3). Additionally, since the products that fall in this category are often large, the more bulky components are usually sourced from local firms (such as the tower in the case of wind turbines). The transfer of capabilities for local manufacturing to developing countries proceeds through the transfer of know-how rather than embodied capital equipment, making a national innovation system with strong design capabilities necessary for absorbing transferred technology and for reaping the benefits of local investment. For *manufacturing-intensive technologies*, the technological learning from actual manufacturing proves to be the essential ingredient for innovation. Domestic markets are therefore less important for industry localization than the manufacturers' access to large (global) markets in order to grow to the scale required for state-of-the-art manufacturing (termed "global learning" in Figure 3) -- see the catching-up of the Chinese PV industry. Since most products are usually rather small, trade makes it possible to gain the necessary experience to become globally competitive from export. In contrast to design-intensive technologies, technology transfer to local manufacturers in developing countries can proceed embodied in production equipment rather than as direct IP transfer. For *design- and manufacturing-intensive technologies*, both local and global learning are essential for innovation and the formation of a competitive industry. Firms in a national innovation system learn from producing for the global market rather than national markets (as in manufacturing-intensive products), but learning also requires feedback from extensive testing and operation (as in design-intensive products). This makes proximity to key markets, usually with demanding use environments or user requirements, necessary for innovation. Requiring transfer of tacit know-how and capital goods, these technologies are the most difficult for developing country innovation systems to master.

4.2 A Heuristic to anticipate the localization effects of deployment policies

Many clean technologies are produced in industry value chains that span regions or the entire globe (Gallagher, 2014). Based on the case studies and the synthesized typology of innovation patterns, we develop a heuristic which helps to anticipate which activities along the technology value chain (materials, components, production equipment, system integration, installation, to operation and maintenance) would most likely become domestically successful and which would instead remain international. This heuristic can serve as a guidepost for the selection of technologies and corresponding green-growth strategies that target the establishment of the entire industry value chain or specific value chain steps domestically.

Our technology typology stresses the availability of local design and manufacturing capabilities. In the following, we single out the level of economic development (low-, middle-, or high-income country) as a proxy for the availability of these capabilities as it is the most aggregated factor representative of technology-specific country differences and correlates strongly with the presence of technological capabilities (Archibugi and Coco 2004). This categorization is meant as a means of illustration. Of course, countries can possess technology-specific capabilities at a level that exceeds their level of economic development (e.g., Kenya has built a relatively well functioning innovation system around small-scale PV systems; Byrne et al., 2014), or fall short of it. Assessing the capabilities of individual countries goes beyond the scope of this paper but could be done by country-specific technology assessments and strategies (see Section 5). The heuristic is summarized in Table 1.

Table 1 A heuristic to anticipate localization effects beyond operation and maintenance of deployment policies for different types of technologies and countries.

	Low-income country	**Middle-income country**	**High-income country**
Simple technologies	• Large shares of value chain	• Large shares of value chain	• Large shares of value chain
Design-intensive technologies	• Peripheral components	• Installation • Components	• Core components • System integration
Manufacturing-intensive technologies	• Installation	• Installation • Production	• Installation • Production • (Manufacturing equipment)
Design- and manufacturing-intensive technologies		• Installation • (Simple) components	• System integration • Core components • Manufacturing equipment

For *simple technologies*, the level of capabilities required to become competitive is low, such that countries of all income levels can reasonably assume that—given the right implementation of instruments—large shares of the value chain can be successfully localized through deployment policies.

The more *design* capabilities a technological innovation requires, i.e., the further upwards in the technology typology matrix a technology is located, the more experience a national innovation system needs with state-of-the-art technological activity to become competitive in the global market. This requires either early entry into the global market (often not possible for firms outside the developed world) or very persistent domestic policy support ensuring significant scales of diffusion over a longer period. Only high-income or large middle-income countries can afford such technology strategies and therefore reasonably assume to be able to create a competitive industry through deployment support. In the case of *design-intensive technologies* (upper left corner), low-income and lower middle-income countries should therefore expect deployment policies to result in the formation of a local industry offering installation and supplying components, such as mirrors for concentrating solar power plants (North Africa), parts for geothermal power plants (Indonesia), or bulky components (e.g., towers or blades) for wind turbines (South Africa), which are often costly to transport. With persistent domestic deployment support, large middle-income countries may expect to foster industries going beyond components that may even become competitive system integrators in global markets, as both China and India are demonstrating in wind energy and China in the field of large hydropower.

The more capabilities a *manufacturing* process requires, the more a national innovation system's competitiveness is based on experience and incremental improvements in manufacturing as well as the ability to realize economies of scale. Firms in *manufacturing-intensive technologies* do not profit greatly from a home market. Hence, countries cannot expect deployment policies to lead to the formation of a local industry active in value chain steps other than installation (and O&M, which typically is, however, limited due to the simple design), independent of the income level. Very large domestic markets might lead to the formation of simple production steps (e.g., the assembly of PV cells into modules), which could be induced through deployment policies in large middle- and high-income countries. In order to foster the localization of the production steps of the value chain of manufacturing-intensive technologies, factors other than domestic markets are more important, such as economies of scale, the maturity of existing supply chains, and input factor costs. Consequently, other policy strategies are needed for successful green industry localization (compare section 6). If this is done successfully, at least high income countries can expect the formation of an industry supplying the equipment necessary to manufacture these technologies.

Design- and manufacturing-intensive technologies (in the upper right field) combine the two largest hurdles for innovation systems to become competitive. They require a high level of capabilities and prolonged experience in product design as well as a large local market, making it difficult for latecomers to become system-integrators for the entire product (e.g., electric cars). But unlike design-intensive technologies, even component manufacturing is challenging, often requiring large-scale production in competition with globally active component suppliers. Low-income countries should therefore expect deployment policies to result in O&M-related industry localization only. Middle-income countries can anticipate that local industry will cover installation as well as the production of (simple) parts. Attempts by middle-income countries to build local industries that cover the system integration step for this type of technologies have thus far largely failed, as shown by the case of electric cars above. Only high-income countries with national innovation systems characterized by large endowments of advanced manufacturing and design capabilities (preferably in a related technology) can realistically expect that deployment polices might trigger the formation of an industry covering large parts of the value chain. Such deployment policies would need to provide a high level of diffusion over an extended period. Note that the manufacturing of (simple) components might be outsourced to other countries based on input factor costs, with the local industry focusing on the production of core components and manufacturing equipment (as e.g., seen in the automotive industry).

5 Implications for national green growth policy strategies and international support institutions

Our heuristic has several implications both for national policymakers who aim at incentivizing green growth as well as the international institutions supporting them. Technology selection in green growth strategies is often based on Technology Needs Assessments (TNAs), which are supported by international institutions with funding and expertise (e.g., UNDP, 2009). Many TNAs primarily focus their analysis on environmental benefits and barriers to implementation—most importantly economic barriers such as incremental costs (TEC, 2013). While TNAs face additional challenges, such as ensuring stakeholder integration (for a critique see e.g., Karakosta and Askounis, 2010), we suggest that TNAs that are meaningful to green growth strategies should be extended so as to include a step in which the technology priorities are assessed against their *potential to induce industry localization and domestic innovation.* A strong focus on clean technology industry localization could also help TNAs gain the support not only of the governmental bodies related to environmental questions, but also of those related to development and finance, and thereby gain significance. Our heuristic is a starting point for such augmented TNAs.

5.1 Implications for national green growth strategies in developing countries

National policymakers need to prioritize clean technologies and formulate policy strategies. Simply targeting entire sectors, which is often done in national green growth strategies, might be inadequate when technological characteristics are to be taken into account–particularly for sectors in which many different technologies are involved (such as in energy, transport, or industry). In the case of climate change, this view is supported by a proposal to the UNFCCC Technology Executive Committee (TEC), stating that "*each technology* should be *considered separately* when trying to identify particular challenges and the opportunities it might face" (emphasis added; TEC, 2012, p. 6).

The technology prioritization process should consider which shares of the industry value chain can realistically be localized and how much value and job creation is involved in these shares. While deployment policies can play an important role for industry localization, other (complementary) policy instruments should be considered. Such instruments can include incentives for local production, such as custom tariffs and local content requirements, whose success can also be related to local capability presence and thus informed by our heuristic. Finally, policymakers need to consider the effects of industry localization on capability enhancement (Bell, 2012). In case of (global or local) technological progress or increased levels of technological capabilities, green growth strategies might have to be adjusted to target new technologies or additional shares of the value chain.

For *simple clean technologies* which are selected in a TNA, green growth strategies should focus primarily on deployment policies. As the diffusion of these technologies is mostly blocked by non-technological barriers, deployment policies should focus on removing these barriers. Potential policies include deployment incentives, removing regulatory barriers, addressing investment risks, and providing (small-scale) project finance. Both low- and middle-income countries can realistically anticipate attracting local value creation along the entire value chain, but exports are unlikely. Incentives to localize production beyond deployment policies are typically not needed. Continuous monitoring of technological progress and the local capabilities is less important than in the other technologies.

Countries aiming at industry localization for a *design-intensive clean technology* should also make deployment instruments a cornerstone of their policy mix. The localization of an O&M industry can be expected, which is often a significant share of value-add for design-intensive technologies, but component manufacturing is also realistic. Deployment instruments include financial incentives and public procurement and could be complemented by local content requirements (or incentives). While low-income countries should limit such requirements to simple, rather peripheral components, middle-income countries can include more central components. In both country types, the demand requirements for locally produced components needs to be dynamically reflected against local technological progress and capability levels and—given that localization leads to local learning and capability enhancement—can be increased over time. If the domestic market is large enough, prolonged experience with the supply of components for local projects may give domestic firms a competitive edge that may lead to exports to neighboring countries. The process of capability building can potentially be accelerated by capability transfer requirements (e.g., through joint-ventures).

Incentivizing the localization of large shares of the industry value chain for *manufacturing-intensive clean technologies* requires much more than deployment policies. Low-income countries in particular could focus on installation, which often covers large shares of the technology costs and jobs involved. To localize installation industries, deployment policies are important, but localization incentives are often not needed because installation does not require high capability levels and competitiveness is mostly driven by labor cost. A middle-income country that aims at becoming a manufacturing hub for technologies such as solar PV, solar heating (vacuum tubes), heat pumps, energy-saving building materials or energy-efficient lighting needs to ensure access to large export markets and low input factor costs. Much of the required know-how can be acquired by purchasing production equipment from advanced economies (technology transfer in the semiconductor, textile and consumer durables industries took this path, for example). Export processing zones providing tax incentives and low-cost finance for investments in manufacturing equipment are a suitable policy option. However, policymakers need to be aware of the danger that other countries with lower input factor costs might catch up quickly, and that technological progress in the manufacturing equipment might need additional incentives in order to maintain competitiveness.

Localizing large shares of the value chain for *design- and manufacturing-intensive clean technologies* requires very long-term and stringent policy strategies. These need to provide incentives for large local deployment as well as for FDI or international joint ventures to attract foreign design and production know-how and machinery. Low-income countries are typically not able to provide such incentives, and even among middle-income countries, only large ones can realistically afford such strategies. Again, capability transfer requirements to enter home markets can accelerate gaining competitiveness. Dynamic monitoring and policy adjustment should be integral parts of these strategies. For smaller middle-income countries, a strategy to achieve large local markets is to form regional groups that provide deployment policies for a selected technology, thereby inducing regional industry formation that covers large shares of the value chain. Such a strategy would need to be informed by regional TNAs, which could be supported by international institutions.

5.2 Implications for international institutions supporting green-growth strategies

Besides supporting developing countries (and regions) in the technology-strategy development process, international institutions also provide access to knowledge and technology, as well as finance. Our localization heuristic also has implications for the international institutions around technology and finance. A first general implication is that in order to be effective in developing countries, the international institutional functions should also be technology-specific, as shown in Figure 4.

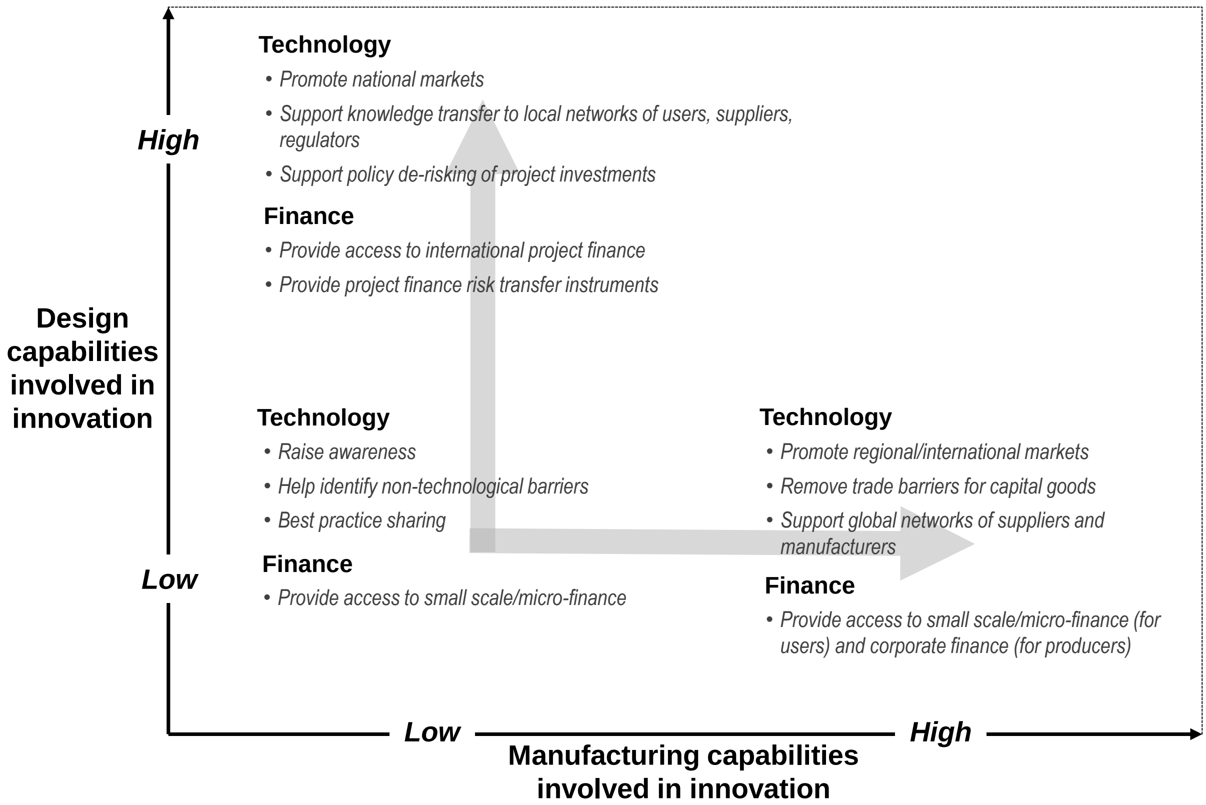

Figure 4 Implications for international technology- and finance-related institutions for the different technology types.

International support institutions, such as the World Bank, the United Nations Environmental Programme, the United Nations Development Programme and the UNFCCC's Technology Mechanism, are highly concerned with promoting, coordinating and guiding policy development in and across developing countries. They also often engage in knowledge exchange and network promotion (on a national, regional and global scale). Since each of the four technology types relies to a different degree on domestic and international policy development, the focus of these support activities should differ across technologies. For *simple technologies*, international institutions should primarily guide and promote domestic, non-technological activities related to the removal of (non-technological) market barriers. For *design-intensive technologies*, they should focus on promoting and supporting the formulation of strong and persistent domestic policies including local-demand requirements. Design-intensive technologies need local knowledge networks of suppliers, manufacturers and users to capture the learning benefits. Especially in early stages of domestic market development, the links to advanced technology suppliers in more mature markets will also be crucial. Building these networks could be significantly supported by international institutions. For *manufacturing-intensive technologies*, the focus should be more on coordinating regional and international market development. The former could involve supporting nations in adapting policies such as feed-in tariffs to their national requirements; the international coordination could include aspects such as technological standardization, the removal of trade barriers and the coordination of approval processes and investment conditions across regions. Manufacturing-intensive technologies require less local learning and thus fewer local networks, requiring instead more global networks of suppliers of production equipment, materials and manufacturers. Coordinating networks on a global level is therefore an important task for international institutions. For *design- and manufacturing-intensive technologies*, both activities are important. Key markets should be supported strongly in their policy development, while regional and international coordination should receive equal attention. As Figure 4 shows, design- and manufacturing-intensive technologies will likely require both in order to facilitate learning in global value chains and thus performance improvements and accelerated diffusion.

The implications for green growth finance are primarily related to the *type* of financing needed for effective technological learning. Simple technologies, such as SMH, small wind, solar heating and solar cooking, are usually rather small, making small-scale or micro-finance an important vehicle for production and diffusion. In order to reach scale and thereby tap additional investor types, pooling of small-scale activities in one financial vehicle is an option (Schmidt, 2015; UNEP, 2015). Design-intensive technologies, in contrast, typically diffuse via large projects with a project-finance structure, making project risk a bottleneck, e.g., for wind farms, geothermal projects, efficient coal power plants and concentrating solar power. Here, project-specific de-risking instruments seem highly relevant (Schmidt, 2014; Waissbein et al., 2013). Manufacturing-intensive technologies realize innovations mostly in combination with large-scale manufacturing, making access to (low-cost) corporate finance a bottleneck (as seen in solar PV, for example). Design- and manufacturing-intensive technologies, finally, require both. Electric car programs in the developing world, for example, would require significant investment in both manufacturing technology (corporate finance) and—if the technology is not imported—related infrastructure (e.g., through project finance).

6 Conclusions

While many developing countries enact deployment policies for relatively mature clean technologies aiming at green growth through industry localization, the empirical evidence of the localization effect of such policies is mixed. Currently there is a dearth of research systemically analyzing the role of technology differences in this effect. This paper addressed this gap by focusing on technology differences and offering several contributions.

First, we combined the technology transfer and catching-up literatures with the technology life-cycle literature and derived a technology typology that differentiates four types of mature clean technologies along their need for two types of technological capabilities: design and manufacturing capabilities.

Second, we offered a heuristic to anticipate the effect of deployment policies on the localization of different shares of the industry value chain. The heuristic differentiates the technology type and a country's endowment with technological capabilities. Despite certain limitations, which we discussed above, we believe that the heuristic provided in this paper holds the potential to significantly reduce information needs for developing-country policymakers during the design of green growth strategies and can thus help them to identify effective policies.

Third, we discussed the implications of our heuristic for national green growth strategies as well as for international institutions supporting developing countries with technological know-how and finance. Policymakers can use the heuristic not only to anticipate localization effects of deployment policies but—based on that anticipation—to design localization strategies that focus on certain value chain steps and/or combine deployment policies with other instruments. International institutions should support these strategies in a technology-specific way. Different forms of knowledge exchange and finance should be provided, depending on the targeted technology.

In order to improve policy decisions and refine our framework, more comparative research is necessary. Comparisons should not only consider countries (as is often done), but also technologies (seldom done). Often research and policy regard clean technologies as one technology category. Our paper stresses, however, that while all clean technologies might be able to mitigate environmental pollution, the innovation and industry formation dynamics differ largely across various clean technologies. Policies that aim at innovation and industry formation of clean technologies and the research supporting policy decisions should therefore also consider the differences in the innovation and industry formation patterns and the required technological capabilities.

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