# A Heuristic for Technology Strategies in post-Kyoto Bottom-up Climate Policy

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## Abstract

The series of recent UNFCCC conferences starting with Bali in 2007 until Lima in 2014 have paved the way for the integration of nationally determined initiatives into the global climate governance architecture. National 'green growth' strategies have become a new paradigm for policymakers and executives. Designed with the aim of decoupling economic development from adverse environmental impacts, these bottom-up policies hold the promise of overcoming the gridlock in international climate negotiations. Building on the literature on innovation research, this paper contributes to the understanding of technology strategies in the context of nationally appropriate mitigation actions (NAMAs) under the UNFCCC. It is evident that NAMAs aiming to create domestic industries by leveraging technological innovation must consider the characteristics of the targeted technology. Working from this notion, this paper proposes a heuristic to differentiate between four distinct types of technologies. Each type features specific forms of technological learning, value chain constellations and modes of technology transfer. We illustrate the four types using the cases of small hydro, wind turbines, electric vehicles and solar cells and discuss methodologies to classify further technologies ex-ante. We argue that the heuristic captures essential technological characteristics that NAMAs and international support mechanisms need to consider. The different forms of technological learning and value chain constellations are relevant for a country's choice of technological priorities, while the modes of technology transfer can inform strategies for implementation and international cooperation. We discuss technology-specific strategies for developing countries at different stages of development and international institutions such as the Green Climate Fund and the new Technology Mechanisms under the UNFCCC.



**Keywords:** Climate policy; Industrial policy; Technological characteristics; Technological learning; Technology transfer

# 1. Introduction

On the road to Paris in 2015, the parties to the UN Framework Convention on Climate Change (UNFCCC) are negotiating a redesign of the global climate policy architecture. In keeping with the energy sector transformation envisioned by the Convention's 2° C target, the future climate policy regime will need to scale up and accelerate the development, transfer and diffusion of low-carbon energy technologies (IPCC, 2014). Developing countries [1] are expected to assume greater responsibility in this process than under the Kyoto protocol (Kanie et al., 2010; Raupach et al., 2014; Victor et al., 2014). However, rather than prescribing each country's responsibilities the UNFCCC now calls for them to make nationally determined contributions to global emission reduction efforts (UNFCCC, 2013, 2008). These Nationally Determined Mitigation Actions (NAMAs)[2] represent a paradigm shift in global climate policy. The concept of NAMAs leaves countries with considerable leeway to prioritize mitigation strategies according to their national political objectives (Höhne, 2011). Tailored to the host country's technological capabilities and development needs, NAMAs could align targets for climate mitigation and economic development. Therefore, the shift away from one-size-fits-all market mechanisms in the post-Kyoto climate policy regime has attracted much interest from development researchers who emphasize the need for development strategies that match and augment domestic technological capabilities (De Coninck and Sagar, 2015; Lema and Lema, 2013; Phillips et al., 2013; Rai et al., 2014; Suzuki, 2014).

Well-designed NAMAs could overcome an important trade-off in global climate policy negotiations from the bottom up. But while the appeal of NAMAs lies in their flexibility and adaptability to domestic contexts (Röser and Tilburg, 2014), their downsides are governance complexity and substantial information needs for national decision makers and international support mechanisms. Developing countries, many of which are currently elaborating specific NAMAs to submit to the UNFCCC before the conference in Paris in 2015 (Höhne et al., 2014), need to determine how exactly policies should be designed to deliver on both mitigation and

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[1] We use the term *developing country* synonymously with *non-Annex B country* as defined by the UNFCCC (UN, 1992).
[2] We use the term NAMAs as representative of all *nationally determined* mitigation actions and therefore do not distinguish between different NAMAs as submitted to the UNFCCC NAMA registry and other nationally determined mitigation actions, such as those expected in countries' Intended Nationally Determined Contributions (INDCs) defined at the UNFCCC Conference of the Parties (COP) 19 in Warsaw (UNFCCC, 2013).

development objectives. This requires what we call *technology strategies*: In view of the wide range of possible low-carbon technology pathways, national decision makers will have to prioritize mitigation actions in order to scale up mitigation actions effectively. And to maximize development impact, they have to decide which parts of a technology's value chain should be supported domestically and which should be imported, and how the international governance architecture should be called upon for support. Should a developing country NAMA that includes subsidies for solar PV aim for local solar cell production? Or should solar cells be sourced internationally and just installed and maintained locally? For international decision makers engaged in the design of the international institutional framework, important questions include specifying the mechanisms to channel finance, technology and capacity building, and how NAMAs can be matched with different types of support.

As NAMAs merge the agendas of climate and development policy, the debate on NAMA design is being informed by the climate change mitigation and the development communities. High-level policy recommendations derived from broader development experience have been formulated by many international development institutions, such as the Rio+20 Conference, the OECD (2012), the United Nations Environment Program (2012) and the World Bank (2012), all of which have embraced notions of *green growth, green economies* or *green innovation and technology*. Examples include calls for market-based approaches, private sector involvement and the elimination of fossil fuel subsidies. Policy recommendations from the climate change mitigation community emphasize the practical lessons to be drawn from the existing UNFCCC institutions – especially the Clean Development Mechanism (CDM) – such as baseline setting methodologies, additionality criteria, transaction cost and non-financial barriers (Schmidt, 2011; Schmidt et al., 2012; Upadhyaya, 2012; Würtenberger, 2012). Curiously, however, even though the need for technology strategies is very prominent in the NAMA and green growth debates, findings from the literature on technology-specific learning and innovation processes have received relatively little attention in the NAMA debate.

This article aims to address this gap. Innovation research suggests that public policies aiming to induce technological innovation must consider characteristics of each targeted technology (e.g., Gallagher et al., 2012; Nelson and Winter, 1977), a finding which resonates well with empirical evidence from the climate policy domain (e.g., UNFCCC 2003, 2012a). In particular, innovation research points toward the influence of technological complexity on the processes of innovation and catching up (Kiamehr et al., 2013; Miller et al., 1995). We build on this evidence and address the question *how developing country NAMAs and enabling international institutions should reflect different forms of technological complexity*. To that end, we introduce a heuristic that differentiates between four types of technologies, each exhibiting specific forms of technological learning, value chain constellations and modes of technology transfer. The low-carbon technology examples of micro-hydro, solar photovoltaics, wind power and electric cars are presented to illustrate the four types. For each technology type, we discuss implications for domestic strategies as well as how international institutions – especially the new Technology Mechanisms under the UNFCCC and the Green Climate Fund.

The remainder of the paper begins with a short review of recent climate policy trends and illustrates why NAMAs pose new challenges for developing-country policy makers (Section 2). Section 3 introduces a technology-centered perspective on learning and innovation as well as a heuristic to categorize technologies. We explore the implications of the heuristic for the design of NAMAs in developing countries in Section 4 before proceeding to discuss how the technology differences could be reflected in the international institutions in the climate policy architecture, such as the Technology Mechanism and Green Climate Fund (section 5). The main conclusions are summarized in section 6.

## 2. The Role of NAMAs in the Climate Policy Architecture

### 2.1. The Concept of NAMAs

The concept of NAMAs was first introduced in the 2007 Bali Action Plan (BAP). The BAP called for "nationally appropriate mitigation actions by developing country Parties in the context of sustainable development, supported and enabled by technology, financing and capacity-building, in a measurable, reportable and verifiable manner" (UNFCCC, 2008, p. 3). The Copenhagen Accord added that developing country NAMAs need to be "aimed at achieving a deviation in emissions relative to business as usual emissions in 2020" (UNFCCC, 2009, p. 10). In this way NAMAs are meant to support developing countries' efforts to deliver on their Intended Nationally Determined Contributions (INDCs), which each country is to prepare according to the Warsaw Outcome at COP 19 (Röser and Tilburg, 2014; UNFCCC, 2013). In Durban 2011, the Parties initiated a review process calling for all Parties to submit their NAMAs and process reports every two years starting from 2014. The following are the key characteristics of developing country NAMAs:

- They are designed to link mitigation and sustainable development.
- They are domestic actions identified through country-driven approaches, with the Conference of the Parties working "to *understand* the diversity of mitigation actions submitted, underlying assumptions and any support needed for the implementation of these actions, noting different national circumstances and the respective capabilities of developing country Parties" (UNFCCC, 2012, p. 10, italics added), rather than *to guide* it.
- Part of the incremental cost, i.e., the cost difference compared to the business-as-usual case, will be provided domestically, with additional international support potentially available (e.g., through the Green Climate Fund). The share of the international contribution may depend on income level, ambition and the impact on sustainable development (Würtenberger, 2012).
- They represent the mechanism currently most likely to be used to integrate developing countries' initiatives into the new, legally binding climate governance regime to be established by 2015 and to be implemented starting in 2020 (UNFCCC, 2012c).

The spectrum of governments' interpretation of the NAMA concept can be seen from the almost 90 submissions by developing countries in response to the Copenhagen Accord and to a UNFCCC-operated NAMA registry[3]. Some contain only statements of intention, while others describe programs in great detail – some down to the project level (Ethiopia provides a list of 36 planned renewable energy projects). These span economy-wide policies, sectoral programs, to specific technology initiatives and contain technological activities ranging from resource studies over demonstration projects to large-scale implementation (UNFCCC, 2011). However, only a handful of submissions make explicit how the countries aim to benefit from the described mitigation actions in terms of sustainable development – e.g., whether they plan to use indigenous or foreign technology or which type of tech-transfer they envision– and which kind of mechanism they intend to call upon for support, two aspects explored in depth in this paper.

[3]Available online at http://www4.unfccc.int/sites/nama/SitePages/Home.aspx

### 2.2. Characteristics of a NAMA-centered Governance Regime

The characteristics of NAMAs outlined above imply that the role of developing countries is changing under a future, NAMA-centered governance architecture. On the one hand, they will play a much more central role when it comes to designing policies and incentives for implementation than they have played until now. On the other hand, unlike under the Kyoto protocol, developing countries are now incentivized to focus mitigation actions on technologies and programs that are best aligned with domestic policy objectives, ideally those initiatives that have sustainable development impact. Both aspects are described in detail below.

#### 2.2.1. The Role of Developing Country Governments

Under the Kyoto Protocol, the most important mechanism affecting developing countries is the CDM, which allows countries with emission reduction obligations (developed countries, so called-Annex-1 countries) to offset some of their emission reductions through emission abatement projects in countries without obligations (non-Annex-1 countries). The mechanism is designed as a *flexible mechanism* (UNFCCC, 1997), an approach that can be described as *crowdsourcing* of mitigation initiatives (i.e., of projects and supportive methodologies). Figure 1 illustrates the structure of incentives as well as the proposal and review process. The institutional framework of the CDM is administered by subsidiaries of the UNFCCC, which decide on general project requirements (e.g., additionality, eligibility) and methodologies. Incentives for participation by Annex-1 country actors (and partly international actors) are created by climate policies in the offsetting countries, e.g., by the EU's Emission Trading System. Actual implementation – identification of mitigation potentials, project design, administration, operation as well as MRV (measurement, reporting and verification) – is carried out by market participants, mostly from the private sector, in the offsetting and hosting countries (Schneideret al., 2010). National governments of developing countries – via their Designated National Authorities – are only responsible for maintaining a domestic process for reviewing project eligibility and thus play a relatively minor role in the *top-down* governance architecture of the CDM (Aldy et al., 2003).

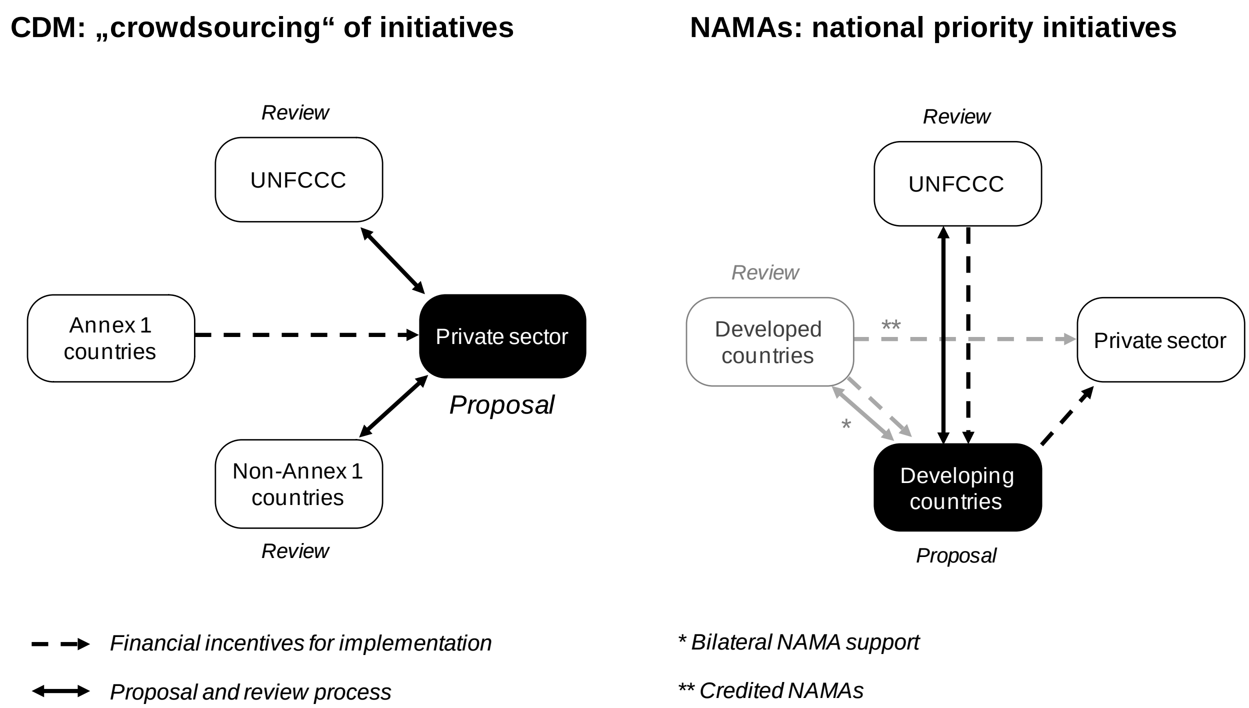


**Figure 1: The role of developing country governments in the CDM and under a NAMA-based regime: crowdsourcing of initiatives vs. national priority initiatives (Annex 1 and non-Annex 1 countries as defined in the Kyoto Protocol, UNFCCC, 1997).**

As opposed to the Kyoto architecture, the NAMA-centered regime envisioned for the post-Kyoto governance architecture is bottom-up and developing country-led, leaving most policy decisions affecting actual implementation to national governments (IRENA, 2012a). Decision makers have to identify ex-ante the mitigation potentials, development impact, suitable private sector incentives, as well as sources and mechanisms for support. The role of the UNFCCC would be confined to reviewing NAMA proposals and implementation progress over time (see Figure 1, right). Developed country governments would only be directly involved where support is bilateral or the NAMAs receive credits, an option that – like the CDM – would require markets for credits to be created by offsetting countries.

| | CDM | NAMAs |
|---|---|---|
| Scale | Project [programs of projects] | Project, sectoral, regional, economy-wide |
| Technological activity | Restricted to implementation | No restriction (e.g., research, demonstration, implementation, institutional activities) |
| Investment incentives | UNFCCC (framework) and developed countries (offsetting incentives) | National government |
| Technology choice | Private sector | National governments |
| Technology transfer | Involving private sector | Possibly involving governments, private sector, NGOs, official development agencies, academic and research communities |
| Review and approval | UNFCCC CDM Executive Board and Designated National Authorities | UNFCCC |
| International support | Financial [capacity building] | Technology, finance, capacity building |
| Development impact | Official objective, but de facto a side effect [only partially incentivized] | Central objective |

**Table 1: Key characteristics of the CDM and NAMAs compared. Square brackets indicate recent developments in the CDM.**

The country-led regime would address some of the shortcomings of the CDM. The small-scale, project-based mechanism suffered from high transaction costs, and the *one-size-fits-all* approach often failed to address technology-specific, often non-financial barriers (Bakker et al., 2011; Paulsson, 2009; Schmidt et al., 2012; Schneider et al., 2010b). Most importantly, NAMAs hold the promise of inducing long-term transformations of sectoral structures, a function the CDM was not suitable for (Höhne, 2011). To avoid burgeoning transaction costs, government-designed NAMAs can scale up mitigation actions through sectoral or economy-wide policies. This, however, requires careful selection of technically feasible and financeable priority actions. NAMAs can further be tailored to a country's unique situation, and targeted programs can address technology-specific financial and non-financial barriers. Yet, both prioritizing and tailoring policies will require expertise and resources that may not be available to in developing countries. Capturing a large share of the developing world's mitigation opportunities through NAMAs will therefore be challenging.

### 2.2.2. Mitigation Actions and Sustainable Development

The Kyoto Protocol and the Marrakesh Accord define sustainable development as one of the two core targets of the CDM (the other one being emission abatements), thereby – *de jure* – excluding from the CDM projects that do not contribute to sustainable development (UNFCCC, 1997). *De facto*, evidence suggests that the sustainable-development impact of many CDM projects is limited and rather regarded as a side-effect (Paulsson, 2009; van Asselt and Gupta, 2009). Since the definition of sustainable development is left up to the host countries, and developed countries are free to decide where to invest, there is a built-in incentive for national authorities to set the threshold for project clearance rather low, even for a race to the bottom. Sutter and Parreño (2007) show that the largest numbers of CERs are being generated by projects with the lowest sustainable development. In certain cases, the CDM methodologies even favor projects with lower contributions to sustainable development over projects with potentially higher ones (Rogger et al., 2011). As van Asselt and Gupta conclude, "the reality is that most CDM funding flows to projects with high greenhouse gas emission reduction potential, but no or questionable non-climate sustainable development benefits" (2009, p. 349).

NAMAs could alleviate this problem as they are required to be in compliance with national development plans (UNFCCC, 2008). Furthermore, since for all developing countries except least developed countries a part of the incremental cost is to be provided domestically, any mitigation action comes at a cost for these countries. This provides an incentive for mitigation actions with sustainable development impact and thus avoids a race to the bottom. However, NAMAs that deliver on development require national governments to assess highly context-specific impacts ex ante and to implement the actions effectively. Governments will need expertise and access to finance as well as to technological know-how and experience to ensure successful implementation (De Coninck and Sagar, 2015). Moreover, industries for environmentally sound technologies often have supply chains that span across countries and regions (Gallagher, 2014; Nahm and Steinfeld, 2014). In most cases, developing countries must import technology, high-tech components, or expertise for installation and operation (Huenteler et al., 2014a). This means that developing country governments must not only prioritize technologies, but also the targeted domestic share of the supply chain.

### 2.3. Technological Support Mechanisms for NAMAs in the Climate Policy Architecture

The two preceding sections showed that in contrast to the CDM, in a NAMA-centered regime national governments are at the core of a bottom-up decision making process. Therefore, for many developing countries, NAMA design and implementation are challenges that require international assistance, in the form of finance, technology and capacity building. Several elements of the climate policy architecture could be called upon for support.

The Technology Mechanism (TM), established under the Cancun Agreement and operational since the end of 2013, will likely be the most relevant in the future. The following are its three main objectives (UNFCCC, 2011, p. 18-19):

(i) To "support action on mitigation and adaptation in order to achieve the full implementation of the Convention"

(ii) To determine "technology needs […] based on national circumstances and priorities"

(iii) To "accelerate action consistent with international obligations, at different stages of the technology cycle, including research and development, demonstration, deployment, diffusion and transfer of technology in support of action on mitigation and adaptation."

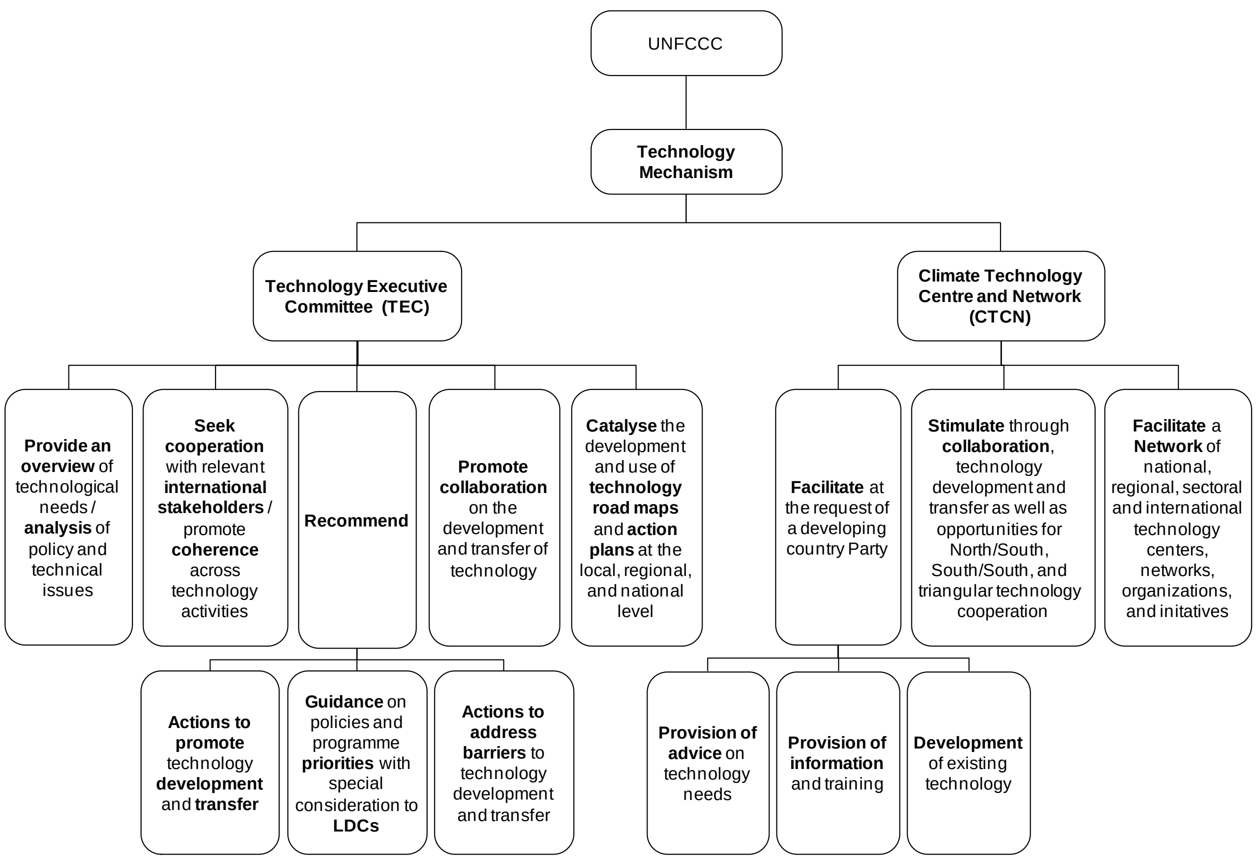


**Figure 2: Structure of the Technology Mechanism and its functions (adopted from ICTSD, 2011; UNFCCC, 2011).**

The TM consists of two entities, the Technology Executive Committee (TEC) and the Climate Technology Centre and Network (CTCN). The functions assigned to the TEC and the CTCN are shown in Figure 2. While the exact institutional arrangement is still in flux, the functional structure of the TM agreed upon in Cancun indicates that the TEC takes a rather coordinative and strategic role (the *political arm*), while the CTCN facilitates technology development and transfer ‘on the ground’ (the *operational arm*). In the context of the design and implementation of NAMAs, possible functions of the TEC include (TEC, 2012):

- Synthesizing global technology information
- Coordinating NAMA financing (e.g., with the Green Climate Fund)
- Developing regional and global technology roadmaps (possibly in cooperation with other UN organizations)
- Linking the TM to other global initiatives for specific issues (such as the UN’s Sustainable Energy for All)
- Coordinating NAMA priorities across countries
- Coordinating NAMAs with other international governance institutions (such as the World Bank, the World Trade Organization and the World Intellectual Property Organization).

Functions of the CTCN in the context of NAMAs may include:

- Supporting and implementing technology needs assessment studies in countries
- Conducting baseline and feasibility studies
- Providing assistance for designing national policies
- Coordinating regional technology programs
- Linking NAMA host-country firms with providers of technology transfer.

Emphasizing international coordination, technology development, innovation and knowledge networks, the TM’s functions go beyond the rather narrow focus on technology transfer through hardware import, the dominant mechanism under the CDM (Climate Strategies, 2012; ICTSD, 2011; Lema and Lema, 2013). This shift is in line with NAMAs’ objective of combining sustainable development and mitigation and the need for broader assistance to developing countries that goes along with it (see Section 2.2).

With NAMAs the focus of the TM's two arms moves from mere implementation (as under the CDM) to technology development, local value creation and sustainable development. Therefore, technology-specific considerations must go beyond the assessment of resources, mitigation potentials and costs, which have been the focus of so-called Technology Needs Assessments (UNDP, 2009). Many technology-specific factors affect the importance of the different functions of the TM. The TEC noted that (emphasis added) "each technology should be *considered separately* when trying to identify particular challenges and the opportunities it might face, as it often faces unique circumstances when trying to enter a new market." It notes further that "a particular industry may have different modalities for diffusion, as well as different financial needs and incentive structures, infrastructure constraints and end-user behaviors that must be addressed" (TEC, 2012, p. 6). In the next section, we explore how the literature on technological learning, technology characteristics and innovation can inform these *separate considerations* on single technologies of developing countries and the TM and introduce a supportive technology framework.

# 3. Technological Complexity, Learning and Technology Strategies in NAMAs

## 3.1. The Importance of Local Technological Learning for Technology Transfer

Perspectives on technology strategies in developing countries range across two paradigms (Lall and Teubal, 1998; Lema and Lema, 2013). One paradigm conceives of technology as capital goods and codified information (patents, manuals, etc.), both of which can be acquired by firms in developing economies – if made accessible – with relative ease. Innovations, i.e., advances of the international technology frontier, usually start in advanced economies before diffusing slowly to firms outside the developed world. From this perspective, the implications for climate policy are relatively straightforward and not technology-specific: subsidize innovation in developed countries, remove trade barriers and provide developing countries with resources for technology imports and know-how for operation and maintenance (Lall and Teubal, 1998). The second paradigm draws on research on innovation and technological learning in developing countries. Here, technology is assumed to go beyond either codified information or physical capital (Bell and Pavitt, 1996). Rather, the notion of technology adopted includes the knowledge embodied in individual skills and firm capabilities, much of which is difficult and costly to codify (or *tacit*). Both are costly to transfer (Cohen and Levinthal, 1989) and can only be acquired through complementary investments in technological learning (in addition to the capital goods themselves), often involving trial-and-error and tinkering with new technology´(Bell and Figueiredo, 2012). Technological knowledge is therefore inseparable from particular technologies, firms and country context (Bell and Pavitt, 1996). This perspective on technology has three important implications for the purpose of this paper, which all point toward the importance of localized technological learning for measures aimed at climate mitigation and economic development. *First*, innovation is no external productivity shock but an endogenous process involving numerous feedback loops and incremental modifications over an extended period of time. It is therefore elusive to distinguish between innovation and diffusion, especially in the case of complex technologies (McNerney et al., 2011; Nelson and Winter, 1982; Rosenberg, 1982). *Second*, innovation occurs not only at the global frontier but whenever firms adopt technologies in new organizations and contexts (Lall, 1993). *Third*, the competitiveness of firms in developing countries is dependent on more than just access to intellectual property and technology imports. The firms also need to be able to adapt technology to local circumstances and to integrate experience with the technology (Bell and Figueiredo, 2012). Technology strategies in developing countries therefore need to match and, ideally, augment technological capabilities and learning processes in the host countries. As De Coninck and Sagar (2015, p. 8) put it, "[t]he million-dollar question, of course, is how to get these policies right". In this paper, we will explore how these general implications can be translated into recommendations for action for different technologies.

### 3.2. A Heuristic to Account for Differences between Technologies in the Context of NAMAs

A particularly prominent research subject in the field of innovation studies has been how innovation and learning processes differ across sectors and technologies (starting with Pavitt, 1984). Yet even though empirical studies of the CDM have shown that barriers to implementation depend on the particular technology (Schmid, 2012; Schneider et al., 2008; van der Gaast et al., 2009), thus far little attention has been paid to technology-specific processes of innovation and technological learning as explanatory factors.

Innovation studies link the relative importance of tacit knowledge, technological learning and incremental innovation to different degrees of *technological complexity* (e.g., McNerney et al., 2011; Rosenberg, 1976).[4] In traditional innovation studies, where innovating firms are the subject of analysis, differentiating technologies according to the degree of complexity is usually sufficient for the analytical purpose. The organizational and technology policy implications of complexity apply equally to makers of aircraft and textile machines, as long as both feature a similar degree of complexity (Hobday, 1998). The common distinction in the literature is therefore that between *complex product systems* and *mass-produced products* (e.g., Magnusson et al., 2005).

From the perspective of climate policymakers, the type of complexity is relevant, too. Technological complexity may be the result of a *complex, scale-intensive production processes* or a *complex product or project design* (Hobday, 1998; Huenteler et al., 2014b; McNerney et al., 2011).[5] Building on differences in innovation processes to inform NAMAs therefore has to consider two dimensions of complexity (shown in Figure 3): For a given technology, how well do a countries capabilities match the complexity of the project design and the scale of the production process?

Local demand created through NAMAs can result in many different forms of local value creation in both design and production: e.g., local R&D, local product development, local component suppliers, local manufacturers or local operation and maintenance. The industries producing clean technologies are increasingly globalized (Gallagher, 2014; Lewis, 2012; Nahm and Steinfeld, 2014). Therefore, in a typical investment project, local firms in developing countries provide only part of the products and services. Only the learning in this share of the industry value chain is local in nature and driven by local market developments and policies (Huenteler et al., 2014a; Morrison et al., 2008; Mytelka, 2000). When policymakers choose technologies for priority actions, they will thus be interested in an integrated assessment of the technology that guides not only the choice of technologies, but also the choice of value chain steps that can be sourced and produced domestically. Such an assessment needs to go beyond the assessment of different technologies and

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[4] *Complexity* means here that scientific laws and models cannot fully predict the performance of products and processes, requiring extensive feedback loops in product design (Hobday, 2000) and processes of monitoring and incremental improvement that may stretch over decades (Rosenberg, 1982). The degree of complexity is affected in part by the existence or absence of a dominant design, uncertainty of the knowledge base involved, the number of components and their linkages and the predictability of the use environment (Nightingale, 2000).

[5] Product and project design is understood here as comprising conceptualization, fine-tuning of components and materials and adaptation of the design to specific applications, while production is understood as including all steps necessary to manufacture the product, from raw material extraction to installation.

assess entire value chains, identifying characteristics of the learning and technology transfer processes in both *production processes* and *product design*.

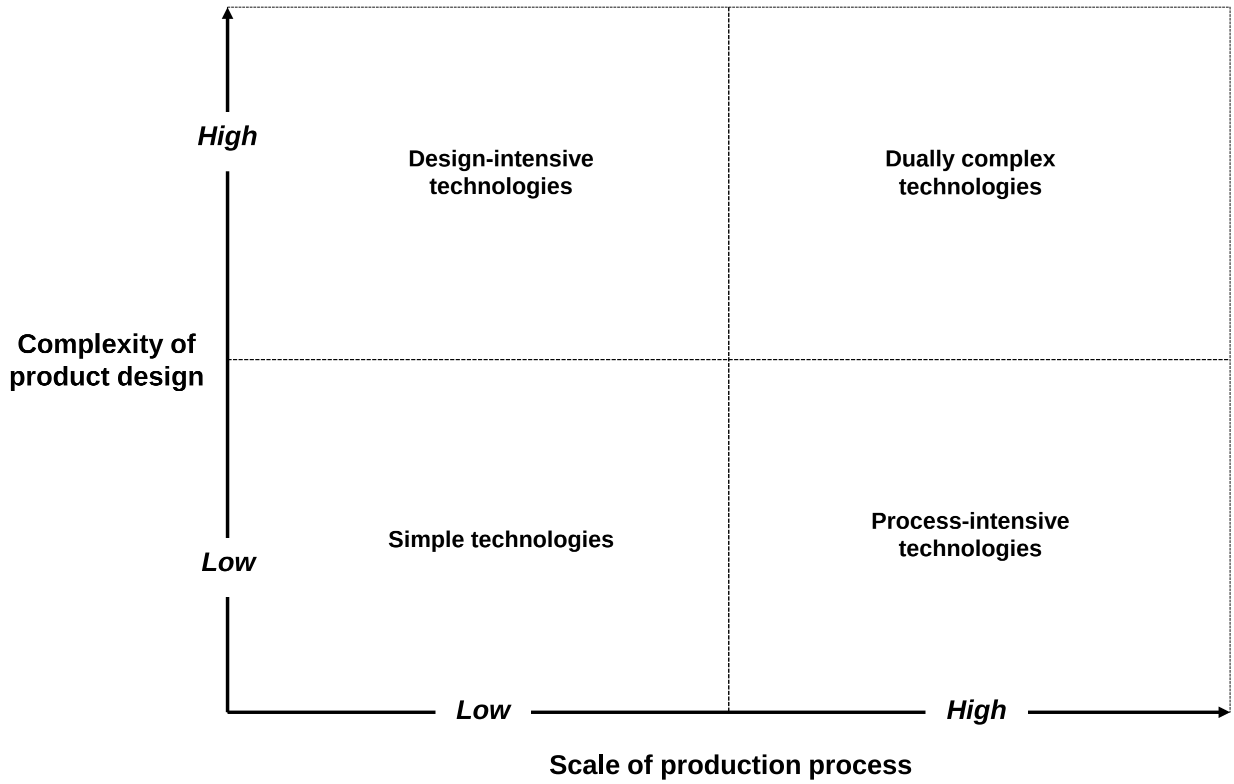


**Figure 3: A typology of four stylized types of technologies, distinguished by the complexity of the product design and the scale of the production process.**

As the two dimensions of complexity of product design and scale of the production process are largely independent, they span a typology of four technologies (see Figure 3)[6]. The two extremes are *simple technologies* and *dually complex technologies*, which score low and high on both dimensions, respectively. *Design-intensive technologies* exhibit high complexity of the product design but low scale of the production process, *process-intensive technologies* exhibit the reverse. Of course, both axes are continuous and differences regarding both dimensions can exist within

[6] In exploring the differences between technologies, the level of analysis is important. The terms *energy technology*, *wind turbine technology* and *rotor blade technology* illustrate how the term *technology* can be used on different levels of aggregation. For the purposes of this paper, technology refers to a set of artifacts and elements of knowledge that (i) build on a shared industrial knowledge base and (ii) facilitate, in functional conjunction, a specific mitigation action. For solar photovoltaic technology, for example, the underlying knowledge base is that of the semiconductor industry and the application is low-carbon electricity production. Put in practical terms, we use the term *technology* on a level of aggregation that differentiates between solar and wind energy technology but subsumes thin-film and crystalline silicon solar cells under one *photovoltaic technology*.

each group of technologies. Nevertheless, we consider the matrix a good heuristic when prioritizing technologies and designing NAMAs. To illustrate the typology, in the next section we will use low-carbon energy technologies as cases to describe one example for each type in detail.

### 3.3. Energy Technologies Positioned in the Typology

We chose four technologies – three from the electricity sector and one from the transportation sector – to illustrate the typology. Both sectors are among the biggest and fastest growing contributors to anthropogenic greenhouse gas emissions (IPCC, 2014). Therefore, transforming both sectors in developing countries – or leapfrogging the high emissions development path these sectors have taken in developed countries – lies at the heart of the climate change challenge (Bazilian et al., 2008).[7] At the same time, both sectors cover diverse sets of technologies, making it possible to distinguish very different supplying industries with characteristic innovation processes. The four energy technologies we use to illustrate the cases are small hydro, onshore wind, solar PV and electric cars. Like any characterization of a large number of technologies, the case description is inevitably brief and stylized but should help illustrating the heuristic. Additional technologies are located, in a stylized way, in Figure 4.

[7] A meta-analysis by the UNFCCC of technology needs assessments showed that across all world regions, renewable energy technologies were the most often identified priority mitigation actions, with the transportation sector coming second after energy in Europe and Latin America. The analyses can be accessed at http://unfccc.int/ttclear/jsp/Regionalanalysis.jsp.

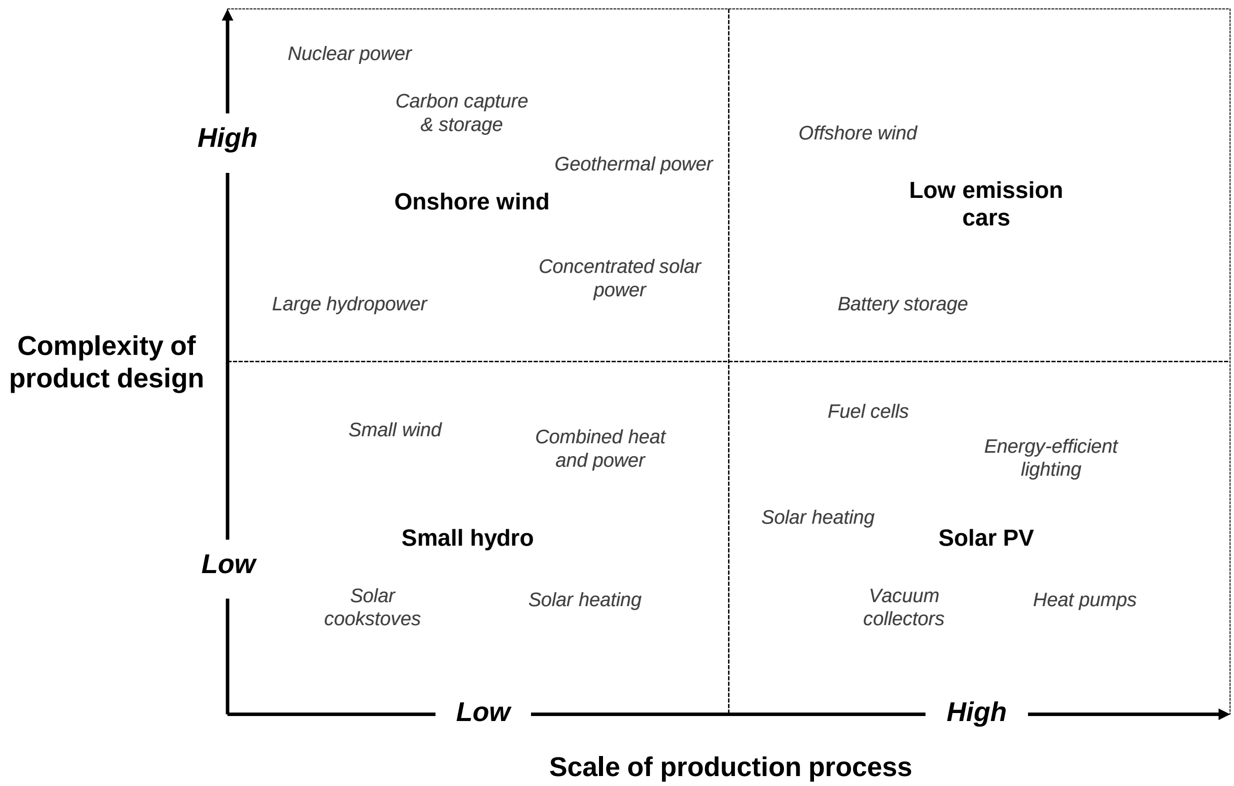


**Figure 4: Stylized location of different energy technologies in the typology matrix.**

### 3.3.1. Small Hydro Turbines

A relatively *simple technology*, small hydro exemplifies the lower left corner of the matrix. Hydroelectric turbines convert the energy of water passing small height differences into electricity and represent the oldest of all power generation technologies (IRENA, 2012b). Depending on the definition, *small hydro* covers generators from 100 kilowatt (kW) to 10 megawatt (MW). The size is usually determined by the locally available generation potential. Besides size, site-specific requirements are limited, making serial production possible. Most small hydro turbines are manufactured by suppliers that offer standardized turbine generator packages. These *water-to-wire* packages simplify the planning and development of the site. At the same time, economies of scale in production are limited and turbines can be manufactured with standardized machinery. As a result, despite low transport costs, turbine manufacturers are relatively small and scattered around the globe, including manufacturers from low-income countries like Nepal (Cromwell, 1992). A *simple product design* (little of which is patent-protected); readily available, standardized electrical and mechanical components; and the absence of economies of scale (indicating a rather *simple production process*) often create entry opportunities for local firms in new markets. Other low-carbon energy or transportation technologies that fall in the *simple technologies* category are for example small wind, small biogas systems, solar heating (with flat plate collectors), solar cook stoves and bicycles (compare Figure 4).

### 3.3.2. Onshore Wind Turbines

Wind turbines are *complex products*, consisting of several thousand customized electrical and mechanical components (Hau, 2013). These sourced and integrated into turbine systems by only a few dozen large manufacturers worldwide, while new entrants had difficulties acquiring the required system-integration capabilities. Wind turbines have to be adapted to climate, wind speed, wind profile, and local regulations concerning grid-connection, foundations and noise. Over the years, incremental innovations have continuously improved the manufacturers' turbines. Electric capacity has increased from 5 kW to around 2-5 MW, and turbine size from 10 m tower height to more than 120 m in the last 35 years. The *production process*, on the other hand, involves well understood and readily available manufacturing technology such as welding, drilling, metal casting and fiberglass casting and is not particularly complex. Consequently, while efficiency in production and cost are important, the principal competitive pressure for turbine manufactures is to achieve high product performance and reliability. Onshore wind technology can therefore be positioned in the upper left corner of the matrix in Figure 4. The entry barriers for new companies in the turbine business are rather high, with banks usually requiring several years of turbine performance data for projects to be bankable. Therefore, when new national industries were established, as in Spain, India and China in recent years, a common pattern was that local firms licensed designs from established manufacturers before moving on to indigenous R&D (Lewis and Wiser, 2007). A transfer of manufacturing equipment or related intellectual property was usually not involved. In smaller markets that cannot sustain domestic manufacturers, local firms often supply components such as towers or cast iron frames. Other technologies falling into this category are large hydropower, carbon capture and storage (CCS), geothermal power and concentrated solar power (CSP).

### 3.3.3. Solar Photovoltaic Power

Solar photovoltaic (PV) modules generate electrical power 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 has around 200 W electric capacity and covers an area of one square meter or less – and the auxiliary components, including the inverter, cables, controls, etc. There is a wide range of PV cell technologies that use different types of materials and production methods, but cells made of crystalline silicon still capture most of the market. The principal challenge facing all of the various technologies is bringing down production costs. The entry barriers for silicon and cell manufacturers are relatively high, mostly because of the size of the required initial investment. Since the physics behind some of the production steps is not fully understood, or not fully predictable, manufacturers have to control the scaled-up production process and balance the trade-off between material costs and performance. That is, while the product itself has many features of a commodity – even being traded on spot markets – the production process is highly complex. PV is therefore positioned in the lower right corner in the matrix (Figure 4). Technology transfer between countries proceeds either through imports of cells and modules for installation (with local firms focusing on installation), 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).

### 3.3.4. Electric Cars

The features of the fourth field of the matrix, for which both product complexity and scale of production process are high, represent a challenging combination and are therefore rare among widely-used technologies. But it can be well exemplified by electric cars. Equipping cars with partially or fully electric drivetrains (*electric cars*) is a challenge for both product design and production process. Consisting of thousands of customized components, automotive innovations require extensive simulation, testing, fine-tuning and continuous improvements. Often new car models are modified in response to high component failure rates for years after their initial introduction. At the same time, 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. Hence the characterization of electric cars as *dually complex technologies*, located in the upper right corner of the matrix. The cumulativeness of experience in car design and manufacturing creates advantages proportional to cumulative production, supporting a situation with few very large manufacturers and high entry barriers – related to cost *and* performance – for firms in new markets. 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 and the transfer of production equipment. Unlike in 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 been around for decades, the prohibitive cost of production creates a chicken-and-egg-problem of lacking competitiveness, limited production and limited learning. 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). Other technologies which fall in the category of dually complex technologies are offshore wind and grid-scale battery electricity storage.

## 4. Implications for Post-Kyoto Bottom-Up Climate Policy

As illustrated by the exemplary technologies in the previous section, the heuristic can be used to distinguish between four types of technologies with different patterns of innovation. The most important characteristics are the importance of experience in product design, operation and maintenance (upper half of the matrix) and the need for experience in scaling up manufacturing, integrating production process technology and operation and maintenance of manufacturing plants (right half of the matrix). Other features derive from these two, including the value chain constellation and the prevalent technology transfer modes. In the following we discuss these characteristics in detail.

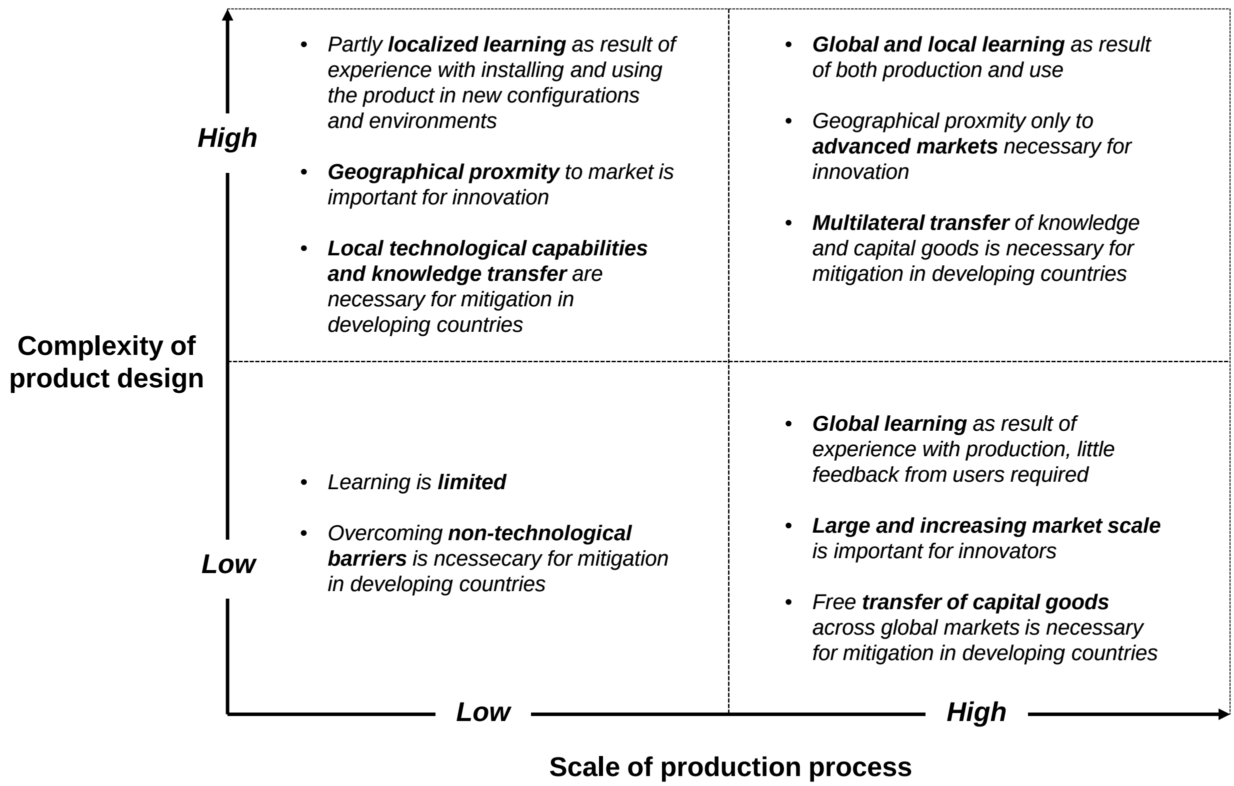


**Figure 5: Stylized differences in innovation processes and technology transfer mechanisms between the four technology types.**

## 4.1. Technology-specific Innovation Patterns

Technological complexity in capital goods leads to the pattern of incremental improvements in technologies over a long period of time, as firms refine, optimize and scale up designs and production processes. The two axes of the categorization indicate where most of the experimental learning takes place, which has implications for the type of economic activity that predominantly stimulates innovation. The further to the right or top the technology is located in the matrix, the more actual deployment of technologies is needed to improve performance.

The key characteristics of the four technology types and the patterns of innovation and technology transfer are presented in a stylized manner in Figure 5. The learning potential of *simple technologies* is rather limited. Thus, it is mostly non-technological barriers that block the diffusion of these technologies. In the case of *design-intensive technologies* it is essential to gain experience with installing and operating the technology. Geographical proximity of firms to installations is usually required to capture learning effects because of the required interaction and the project size. Close interaction between users and manufacturers and their suppliers is needed to feed back the experience gained from using into the design process. And since the products that fall in this category are often large, the more bulky components are usually sourced from local firms. The transfer of capabilities for local manufacturing to developing countries proceeds through the transfer of know-how rather than embodied capital equipment, making a strong national innovation system necessary for both technology transfer and for reaping the benefits of local learning. For *process-intensive technologies* the technological learning from actual manufacturing is the essential ingredient for innovation. Large local markets are therefore not as important as the manufacturers' access to large markets in order to grow to the scale required for state-of-the-art manufacturing. Since the 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 through production equipment rather than know-how. For *dually complex technologies*, both sources of experience are essential. Learning is global rather than national (as in design-intensive products), but learning also requires feedback from extensive testing and operation. This makes proximity to key markets, usually with demanding use environments or user requirements, necessary for innovation. Requiring transfer of know-how and capital goods, these technologies are the most difficult for developing countries to master.

## 4.2. Technology-Specific Implications for Technology Strategies in NAMAs

The international institutional architecture currently assists developing countries in their technology strategies in two ways. *First*, funding and expertise is provided for Technology Needs Assessments (TNA), which primarily focus their analysis on emission sources, mitigation potentials and barriers to implementation (most importantly costs). *Second*, funding is available for designing and formulating policies (to be submitted as NAMAs) based on these TNAs. From an innovation studies perspective, these two steps should be complemented by an intermediate step in which the technology priorities are assessed against their *potential to induce domestic innovation*, *competitiveness* and *economic development*. Such analyses should evaluate 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. The outcome of this analysis could then serve as a guidepost for the selection of technologies and corresponding low-carbon technology strategies, which target establishing the entire value chain or specific value chain steps domestically. Based on such a strategy, policy instruments can be designed that translate these technology strategies into NAMAs.

The technology strategy pursued under an effective NAMA should enable domestic suppliers to engage in innovative activity, gain experience and translate this experience into competitive products or components. The prerequisites for these activities depend on country-specific factors. In the following, we single out the level of economic development (low-, middle-, or high-income country) as the potentially most important determinant (as it is the most aggregated factor representative of technology-specific country differences) of the success of a value chain step in being localized. Differentiating further factors, such as location, regional integration, existing industry structures and other resources, would be possible but goes beyond the scope of this paper. Suitable strategies for each of the four technologies and all three country types are listed in Table 2.

For *simple technologies*, both the amount of experience and the scale of production required to become competitive is limited, such that countries of all income levels can reasonably assume that – given the right implementation of instruments – the whole value chain can be successfully localized.

The more complex the *design* of a technology, i.e., the further upwards in the matrix a technology is located, the longer domestic firms need to engage in 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. Only large middle-income countries (such as China or India) can afford such technology strategies. In case of design-intensive technologies (upper left field), system integration is the most important source of complexity. This provides low-income and middle-income countries opportunities in the supply of components, such as mirrors for concentrating solar power plants (North Africa), parts for geothermal power plants (Indonesia) or towers for wind turbines (South Africa), which are often costly to transport. If the domestic market is large enough, prolonged experience with the supply of components for local projects may give firms a competitive edge that may lead to exports into neighboring countries. Another field promising successful domestic engagement is operation and maintenance, which is often a significant share of value-add for design-intensive technologies. Middle-income countries may be successful in going beyond that and with persistent domestic support over a long time 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 larger and more complex the *production process*, i.e., the further rightwards in the matrix a technology is located, the more firms' competitiveness is based on experience and incremental improvements in manufacturing as well as the ability to scale up and realize economies of scale. Both can make catching up difficult for latecomer firms in low- and middle-income markets. However, if the product design is standardized or simple, as for *process-intensive technologies* (in the lower right field), 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). If they have access to large export markets, the catching up firms can then become globally competitive, since they often face lower unit costs in terms of labor and energy. Becoming a manufacturing hub for technologies such as solar PV, solar heating (vacuum tubes), heat pumps, energy-saving building materials or energy-efficient lighting might thus be a promising strategy for middle-income countries with access to large domestic or global markets. In the field of solar PV, Malaysia, the Philippines, Taiwan and particularly China are recent examples. Low-income countries, on the other hand, have in this case neither components to focus on (since the products are rather simple and often small in size), nor the need/opportunity to engage significantly in operation and maintenance (which is usually rather simple and takes a small share of value-add). They should therefore focus on installing the technology (especially if it exhibits low or even negative abatement costs).

| | Low-income country | Middle-income country | High-income country |
|---|---|---|---|
| **Simple technologies** | Whole value chain | Whole value chain | Whole value chain |
| **Design-intensive technologies** | Peripheral components, operation and maintenance | Components, installation, operation and maintenance | System integration, core components |
| **Process-intensive technologies** | Installation | Simple production steps, installation and/or Production and export | Manufacturing equipment |
| **Dually complex technologies** | Operation and maintenance | Simple components, installation, operation and maintenance | System integration, core components, manufacturing equipment |

**Table 2: Focus areas for efforts to create local value chains for different types of technologies and countries.**

*Dually complex technologies* (in the upper right field) combine the two largest hurdles for firms to innovate. They require prolonged experience in product design and 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 so challenging – often requiring large-scale production in competition with globally active component suppliers – that firms outside the developed world have few opportunities to enter the market and gain experience. In other words, they require scale and experience in manufacturing as do process-intensive technologies, but the products are not standardized and simple enough for latecomers to acquire know-how by purchasing production equipment, usually because manufacturers have to integrate production technology from various suppliers into an ever- changing production process as product design is continuously improved. This makes it difficult for firms outside large middle-income countries to gain experience in anything but installation and operation and maintenance. A recent example of the complexity of developing and introducing dually complex technologies is China's attempt to leapfrog to fully-electric cars, which despite political commitment has not been very successful thus far (e.g., Wang et al., 2011).[8]

How these stylized technology prioritizations and strategies translate into public policies can be illustrated using the example of a middle income country. For *simple technologies*, the most important policy function is to remove non-technical barriers (since little technological learning is

[8] For dually complex technologies (unilaterally financed), NAMAs implemented by groups of developed countries are a way to leverage the mitigation potential.

to be expected, anyway). Depending on the type of barrier, possible policies include investment incentives, capacity building and removing regulatory barriers. For *design-intensive technologies*, an adequate policy is to support local demand (possibly through financial incentives or public procurement) and local component manufacturing of those value chain steps prioritized in the technology strategy (e.g., through local content regulation). For *process-intensive technologies*, a strategy aimed at the prioritized (simple) production steps (such as assembly or installation) could be pursued with investment subsidies for local demand, while a strategy targeted at local manufacturing could include designated export-processing zones or subsidized loans for plants and imported machinery. For dually complex technologies, regulations attracting foreign direct investment could be pursued to attract foreign design know-how as well as production know-how and machinery.

### 4.3. Technology-Specific Considerations for International Support Mechanisms

The technological characteristics described in Section 3 and their implications on NAMA designs (Section 4.2) also have consequences for the international institutional architecture. To be effective in developing countries, the institutional functions of the UNFCCC's bodies have to be technology-specific. In the post-Kyoto regime, the Technology Executive Committee (TEC), the Climate Technology Centre and Network (CTCN) and the financing bodies (such as the Green Climate Fund) will most likely play an outstanding role. Hence, we will focus our discussion on these three institutions. The implications for each are presented in Figure 6.

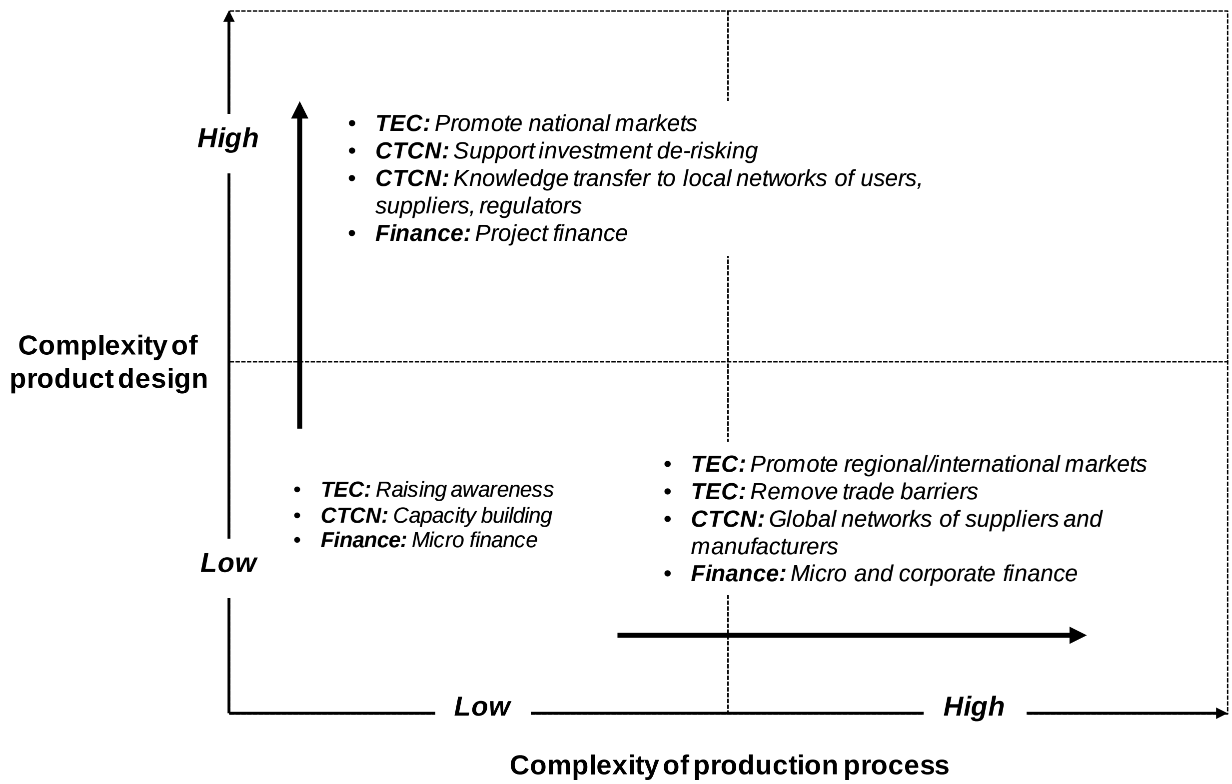


**Figure 6: Implications for the UNFCCC's Technology Mechanism and the Green Climate Fund for the different technology types.**

The TEC's functions are mostly concerned with promoting, coordinating and guiding NAMA development in and across developing countries. Since each of the four technology types relies to a different degree on domestic and international policy development, the balance between national policy development and regional coordination should differ across technologies. For *simple technologies*, the TEC should primarily guide and promote domestic, non-technological activities. For *design-intensive technologies*, the TEC should focus on promoting strong and persistent domestic policies; for *process-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. For *dually complex technologies*, both activities are important. Key markets should be supported strongly in their policy development, while regional and international coordination should receive equal attention.

The functions of the CTCN – and hence the technological characteristics its operations should reflect – are more operational. They include the type of learning networks to be created and the type of technology transfer to be facilitated. Whereas simple technologies mostly need capacity building in addition to the policies, 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. Process-intensive technologies require less local learning and thus fewer local networks and instead global networks of suppliers of production equipment, materials and manufacturers. And, as Figure 6 shows, dually complex technologies will likely require both in order to facilitate learning in global value chains and thus performance improvements and accelerated diffusion.

The implications for climate finance are primarily related to the type of financing needed for effective technological learning. Simple technologies, such as small hydro, small wind, solar heating and solar cooking, are usually rather small, so small-scale or micro-finance can be an important vehicle for production and diffusion. In order to reach scale and thereby additional investor types, bundling of small-scale activities in one financial vehicle is an option. Design-intensive technologies, in contrast, typically diffuse via large projects with a project-finance structure, making technology 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). Process-intensive technologies see innovations mostly in combination with large-scale manufacturing, making access to (low-cost) corporate finance a bottleneck (as seen in solar PV, for example). Dually complex 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).

### 4.4. Limitations

A heuristic such as the one presented in this paper has natural limitations. *First*, complexity is a relative characteristic. Only in comparison to each other can technologies be assigned to specific types with any certainty. This means that the patterns and implications derived from the heuristic need to be understood as tendencies – real world phenomena will always contain elements of all four, with some more pronounced than others. Assigning technologies to the four fields of the typology matrix is thus difficult and requires case-by-case analysis.

*Second*, there may be variation between technological characteristics within a technology. In solar PV, newer cell concepts often use advanced materials that are based on a somewhat different knowledge base. Thin-film solar cells, for example, can be produced in a more continuous production process than standard cells made of crystalline silicon. Manufacturers of such modules often have much more difficulty translating the high efficiencies and high yields of smaller, laboratory-constructed cells to production volumes. This means that thin-film cells would have be located at the far right of the typology matrix. However, differences between technologies appear to outweigh these intra-technology differences in most cases.

*Third*, technological characteristics may vary over time. Nascent technologies often lack standardized training curricula, design algorithms, standards, simulation procedures and so on. In the early years of the wind industry, for example, designers used algorithms known from the aerospace industry and the shipping industry, making more testing necessary and creating uncertainty on the side of potential buyers, thereby raising market entry barriers. Over the years a wind turbine-specific body of aerodynamic, meteorological and structural knowledge evolved and was shared through conferences, technical publications and informal channels. The technology thus moved downward in the matrix. But again, differences between technologies appear to outweigh these differences within technologies.

Despite these limitations, we believe that the heuristic provided in this paper holds the potential to significantly reduce information needs for developing-country policymakers during the design technology strategies and can thus help designing effective NAMAs.

## 5. Conclusions

We began this paper by illustrating the new challenges posed for national governments in developing countries by the emerging bottom-up, country-led climate policy architecture. We then highlighted the issue of technology strategies in NAMA design and proposed a heuristic to differentiate between four distinct types of technologies with specific innovation patterns: simple technologies (such as small hydro), design-intensive technologies (wind turbines), process-intensive technologies (solar PV) and dually complex technologies (electric cars). We highlighted how each type features specific forms of technological learning, value chain constellations and technology transfer.

By distinguishing different forms of technological learning and value chain constellations, the heuristic can inform technology strategies in developing countries and international technology institutions. Low-income countries, for example, should focus on manufacturing only in the case of simple technologies, on single value chain steps in the case of design- and process-intensive technologies and on operation and maintenance in the case of dually-complex technologies. The differences in technology transfer, on the other hand, can inform strategic priorities for the newly established Technology Mechanism (TM). The steering institution of the TM should work towards a systematic identification and consideration of differences between technologies. For technologies on the right half of our typology matrix, the Technology Executive Committee, the policy arm of the TM, could play a central role in scaling up collaboration for regional or international markets, while simultaneously working towards removing trade barriers in coordination with other international institutions. For technologies in the upper half of our matrix, the Climate Technology Centre and Network, the TM's operational arm, could play a central role in facilitating the transfer of know-how and experience. Progress in these technologies will need domestic demonstration projects and the creation of domestic and regional markets. For local suppliers to capture part of the value creation, establishing innovation networks including users, developers and manufacturers will be necessary. A global climate governance architecture that reflects these technological characteristics would be more effective on the ground, enable a linkage between climate mitigation and sustainable development, and could help overcoming the gridlock in global climate negotiations from the bottom up.

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