Considering technological characteristics in bottom-up climate governance - A framework to inform green growth strategies and technology transfer institutions

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Abstract

The recent UNFCCC conferences from Bali in 2007 to Durban in 2011 have paved the way for the integration of unilateral initiatives into the global climate governance architecture. National 'green growth' strategies have since become a new paradigm for policymakers and executives. Aiming to decouple economic development from adverse environmental impacts, such initiatives hold the promise of overcoming the gridlock in international negotiations from the bottom up. Building on the field of innovation studies, this paper contributes to the green growth debate by taking a technology-centered perspective. Evidence suggests that development strategies aiming to leverage technological innovation have to consider characteristics of the targeted technology. Based on this notion, this paper informs strategic policy decisions by proposing a heuristic to differentiate 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 with 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 classification captures the essential technological characteristics that green growth policies need to consider. The different forms of technological learning and value chain constellations can inform a country's choice of technological priorities, while the modes of technology transfer can inform strategies for implementation and international cooperation. Going beyond national strategies, we then discuss how international institutions – such as the Green Climate Fund and the new Technology Mechanisms under the UNFCCC – can facilitate the vertical integration of national strategies into the global climate governance architecture.

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1. Introduction

The parties to the UN Framework Convention on Climate Change (UNFCCC) are currently negotiating a re-design of the global climate policy architecture. In view of the 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 technologies. In this process, developing countries are expected to assume greater responsibility (Kanie et al., 2010). Rather than prescribing each country's responsibilities, however, the UNFCCC now calls for them to take Nationally Appropriate Mitigation Actions (NAMAs) to reduce emissions (UNFCCC, 2008). The concept of NAMAs represents a paradigm shift in global climate policy. It leaves developing countries with considerable leeway to define and pursue mitigation strategies according to their national priorities (Höhne, 2011). The idea is that if tailored to the host country's capabilities and development needs, NAMAs could align targets for climate mitigation and economic development, representing international and domestic responsibilities, respectively. Well-designed NAMAs could hence overcome an important trade-off in global climate policy negotiations from the bottom up.

While the appeal of NAMAs lies in their flexibility and adaptability to domestic contexts, the flipside are governance complexity and substantial information needs by national decision makers. For developing countries, many of which are currently elaborating specific NAMAs (Ecofys, 2012), the question is how exactly policies have to be designed to achieve substantial mitigation and development impact. In view of the wide range of technological pathways, national decision makers will have to prioritize actions in order to scale up technological change effectively. They will have to decide, amongst others, which low-carbon technologies in which sectors should be prioritized; which parts of a technology's value chain should contribute to domestic economic development and which are to be imported; and how the international governance architecture should be called upon for support. For international decision makers engaged in the design of the international institutional framework, important questions include through which mechanisms finance, technology, and capacity building should be channeled; how NAMAs can be matched with different types of support.

Merging the agendas of climate and development policy, the debate on NAMAs is being informed from both the climate change mitigation as well as development arena: High-level policy recommendations have been formulated by many international institutions, such as the Rio+20 Conference, the OECD (2012), the United Nations Environment Program (2012), and the World Bank (2012), who have all recently embraced notions of “green growth”, “green economies” or “green innovation and technology”. Examples include the calls for market-based approaches, private sector involvement, or the removal of fossil fuel subsidies. , Many experts and researchers from the climate change mitigation arena highlight the practical lessons to be drawn from the existing UNFCCC institutions – especially the CDM – such as baseline setting methodologies, additionality criteria, transaction cost, and non-financial barriers (Schmidt, 2011; Schmidt et al., 2012; Upadhyaya, 2012; Würtenberger, 2012). In the development arena, the broad research fields of development and technology transfer are obviously rich sources of lessons-learned and best practices. Curiously, however, even though the need for technology and innovation is very prominent in the NAMA and green growth debates, findings from the literature on technological learning and innovation have received relatively little attention in the debate on future climate governance architectures.

This article aims at filling this void. Innovation theory (Nelson and Winter, 1977; Gallagher and Grubler, 2012) suggests that policy strategies aiming to induce technological innovation must consider characteristics of each targeted technology (for details see section 3). This resonates well with empirical evidence from the climate policy domain (UNFCCC, 2003, 2012a). We build on this evidence to address the question *how developing country NAMAs and enabling international institutions should reflect different forms of technological complexity*. We introduce a heuristic that differentiates 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 – can facilitate the vertical integration of national strategies into the global climate governance architecture.

The remainder of the paper begins with a short review of recent climate policy trends and illustrate why NAMAs pose challenges for developing country policymakers (Section 2). Section 3 introduces a technology-centered perspective on learning and innovation, and the technology framework. We explore the implications of the heuristic for the design of NAMAs in developing countries in Section 4, before we 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 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). Most recently, 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. Key characteristics of developing country[1] NAMAs are the following:

- They refer to a broad range of mitigation actions that are voluntary.
- 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 *guiding* it.
- They are designed to link mitigation and sustainable development.
- A 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 possible. The share of the international contribution may depend on income level, ambition, and sustainable development impact (Würtenberger, 2012).

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[1] We use the term "developing country" equivalent with "non-Annex B country", as defined by the UNFCCC (UN, 1992).

- They represent the currently most likely stepping stone towards integrating developing country action into the new, legally binding climate governance regime to be established by 2015, and to be implemented from 2020 (UNFCCC, 2012c).

How differently governments interpret the NAMA concept can be seen from the roughly 50 submissions by developing countries in response to the Copenhagen Accord and to the central registry that has been open for submissions since October 2012[2]:. Some only contain statements of intention (India communicated that it plans to reduce the emissions intensity of its GDP by 20-25 % by 2020 compared to 2005), others describe programs in much detail – some down to the single project (Ethiopia provides a list of 36 planned renewable energy projects). They cover 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). What even the most detailed submissions do not make explicit is 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 want to call upon for support, two aspects to be dealt with in this paper.

2.2. Characteristics of a NAMA-centered Governance Regime

The characteristics of NAMAs outlined above mean that the role of developing countries is changing under a future NAMA-centered governance architecture. On the one hand, they take up a much more central role when it comes to designing policies and incentives for implementation than they did up to now. On the other hand, in contrast to the Kyoto protocol, developing countries are now incentivized to focus mitigation actions on those technologies and programs that are best aligned with domestic policy objectives, i.e. 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 Clean Development Mechanism (CDM) that allows countries with emission reduction obligations (developed countries, so called-Annex-1 countries) to offset some of their emission reductions

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[2] http://unfccc.int/cooperation_support/nama/items/6945.php.

through emission abatement projects in countries without obligations (non-Annex-1 countries). The mechanism is designed as ‘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 proposal and review process. The institutional framework of the CDM is administrated 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 induced by the governments of the offsetting countries. Actual implementation – identification of mitigation potentials, project design, administration, operation and MRV[3] – is carried out by market participants, mostly from the private sector, in the offsetting and hosting countries (Schneider et al., 2010). National governments of developing countries are – via their Designated National Authorities – 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).

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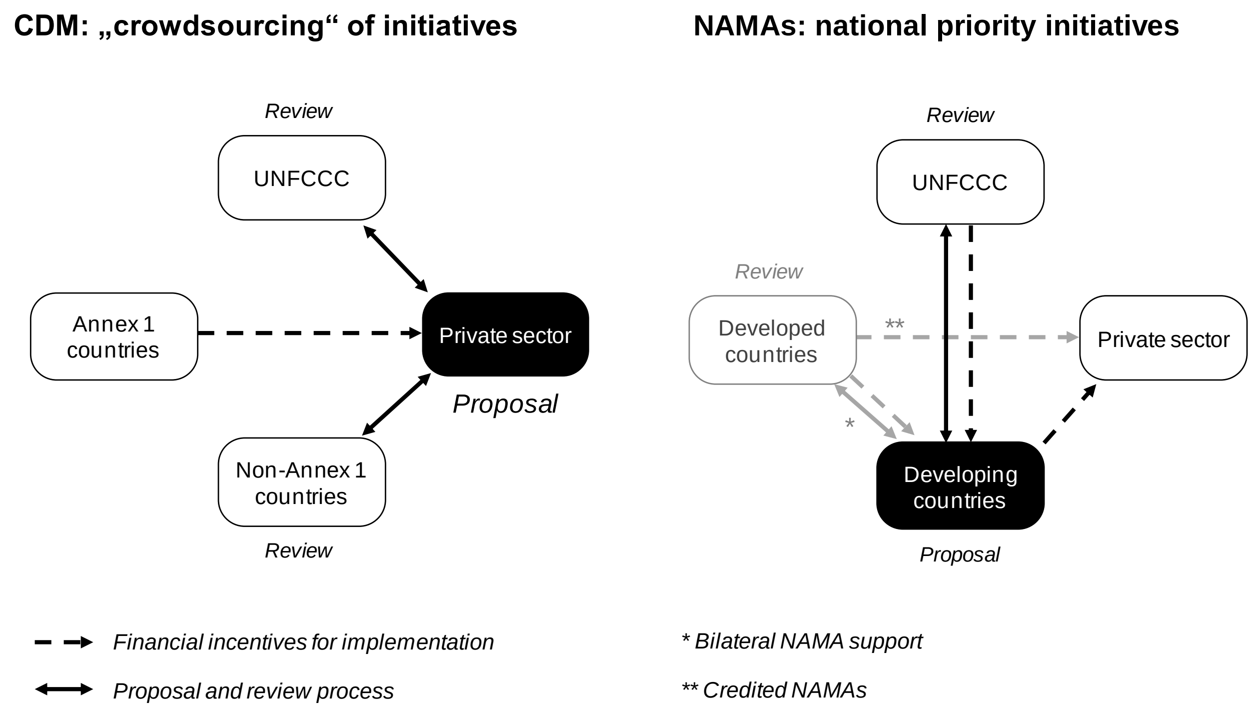
[3] Measuring, reporting and verification.



CDM: „crowdsourcing“ of initiatives

NAMAs: national priority initiatives

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)

Contrary 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, 2012). Decision makers have to, ex-ante, identify 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 if support is bilateral or the NAMAs receive credits, an option that – as 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 (Paulsson, 2009; Schneider, Schmidt, et al., 2010; Bakker et al., 2011; Schmidt et al., 2012). Most importantly, NAMAs fuel the hope of inducing long-term transformations of sectoral structures – a task the CDM was not capable of (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 (compare Table 1). 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 decision makers 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 projects that do not contribute to sustainable development from the CDM (UNFCCC, 1997). De facto, evidence suggests that the impact of many CDM projects is limited and rather regarded as side-aspect (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 greatest amounts of CERs are being generated by projects with the lowest sustainable development. In certain cases, the CDM methodologies even favor project with less over projects with potentially higher contributions to sustainable development (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 the problem as they require to be in compliance with national development plans (UNFCCC, 2008). Furthermore, since for all except least developed countries a part of the incremental cost is to be provided domestically by most developing countries, 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 state-of-the art technology, each of which carries the danger of pitfalls for implementation. Moreover, industries for environmentally sound technologies often have supply chains that span across countries and regions, especially if the recipient country is small and has no strong manufacturing base. In most cases, developing countries will have to import technology, high-tech components, or expertise for installation and operation. That means that developing country governments will not only have to prioritize technologies, but also the 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 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 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, will likely be the most relevant in the future. Its three main objectives are the following (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”.

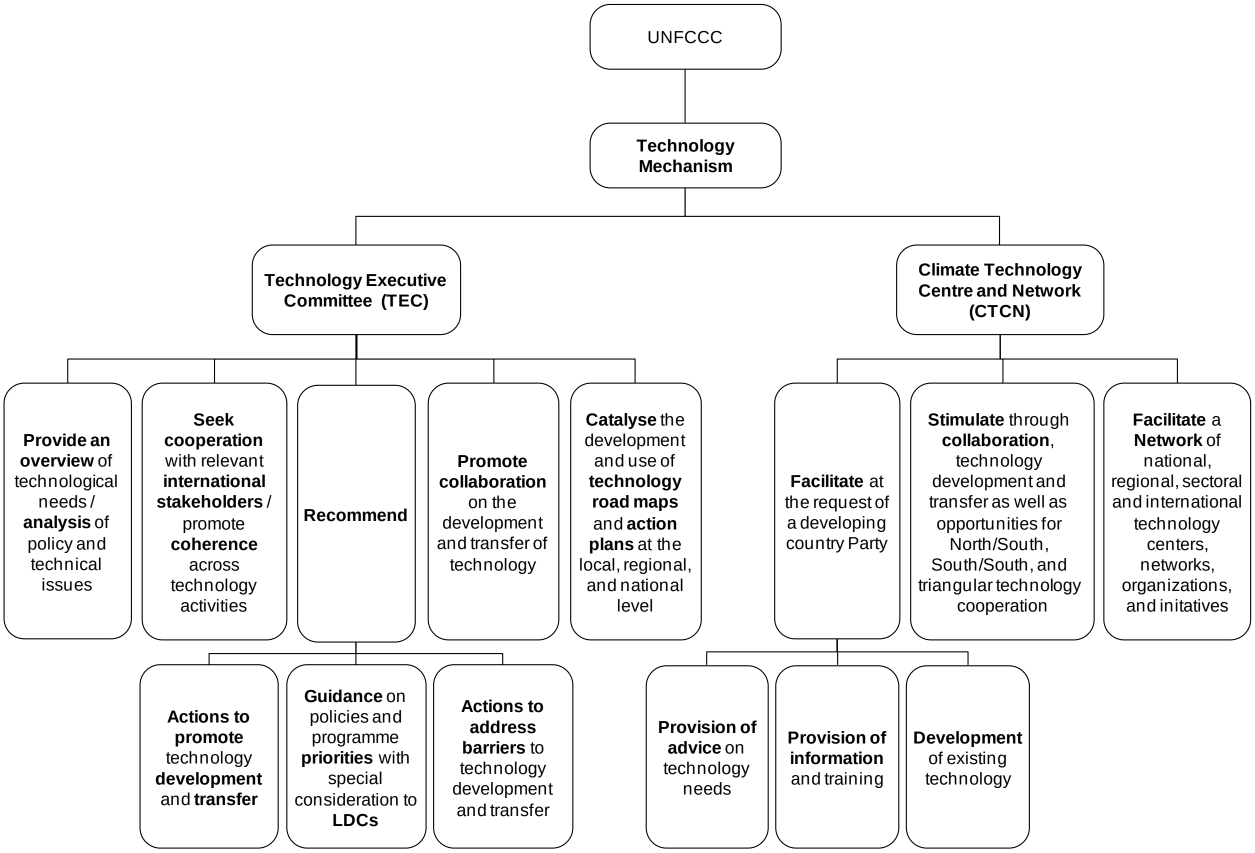


Figure 2: Structure of the Technology Mechanism and its functions (adopted from ICTSD, 2011; UNFCCC, 2011)

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 institutional arrangement is not yet fully determined, the functional structure of the TM agreed upon in Cancun indicates that the TEC takes up a rather coordinative and strategic role (‘the political arm’), while the CTCN is facilitating technology development and transfer ‘on the ground’ (‘the operational arm’). Regarding 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 Sustainable Energy for All of the UN)
- Coordinating NAMA priorities across countries
- Coordinating NAMAs with other international governance institutions (such as the World Bank, the World Trade Organization or the World Intellectual Property Organization).

Functions of the CTCN in the context of NAMAs could 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 (ICTSD, 2011; Climate Strategies, 2012; Lema and Lema, 2012). This shift is in line with the objective of combining sustainable development and mitigation of NAMAs, and the need for broader assistance to developing countries that goes along with it (see Section 2.2).

The roles and the relative importance of the TM’s two arms are yet to be determined in detail. They will likely differ between technologies. As with NAMAs the focus moves from mere implementation (as under the CDM) to technology development, local value creation, and sustainable development, the 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 in its most recent meeting that “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”, and that “a particular industry may have different modalities for diffusion, as well as different financial needs and incentive structures, infrastructure constraints and end-user behaviours 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 Priorities in NAMAs

3.1. Innovation Studies and Technology Transfer

Perspectives on technology and innovation range between two paradigms. One is the perception 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 (World Bank, 2010).

The perspective applied in this paper, drawing from the field of “innovation studies” (Fagerberg et al., 2012), is close to the other paradigm. Here, technology is assumed to be too complex to be fully encompassed by either codified information or physical capital (Bell and Pavitt, 1996). Rather, the adopted notion of technology includes tacit knowledge embodied in individual skills and firm capabilities. Both are costly to transfer (Cohen and Levinthal, 1989) and can only be acquired through technological learning, often involving trial-and-error and tinkering with new technology. Technological knowledge is therefore inseparable from particular technologies, firms, and country context. This notion of technological knowledge has three important implications for innovation in the context of climate policy and the purpose of this paper. 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 difficult (and elusive) to distinguish between innovation and diffusion, especially in case of complex technologies (Nelson and Winter, 1982; Rosenberg, 1982; McNerney and Farmer, 2011). Second, innovation is not only occurring at the global frontier, but whenever firms adopt technologies in new organizations and contexts (Lall, 1993). And third, the competitiveness of firms in developing countries is dependent on more that access to intellectual property and technology imports. The firms also need capabilities to adapt technology to local circumstances and to integrate experience with the technology (Bell and Figueiredo, 2012), and the countries need networks of producers, suppliers, users, and research institutions to enable knowledge flows for continuous learning and improvements (‘national innovation systems’; Lundvall et al., 2009). In this paper, we will explore how these general implications can be translated into recommendations for action for different technologies.

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

The emphasis on innovation networks and national innovation systems in the Cancun Agreements and the functions of the TM (UNFCCC, 2011) show a trend that is in line with the implications from innovation studies. The innovation perspective on technology transfer has also made inroads in the literature on climate policy (among many others, Brewer, 2008; Marechal and Lazaric, 2010; Lema and Lema, 2012). A particularly prominent research subject in the field of innovation studies has been how innovation processes differ between technologies (e.g., Pavitt, 1984). Yet even though empirical studies of the CDM have shown that barriers to implementation differ between technologies (Schneider et al., 2008; van der Gaast et al., 2009; Schmid, 2012), so far little attention has been paid to different innovation processes as explanatory factor.

Innovation studies link the significance of technological learning and incremental innovation to technological complexity (Rosenberg, 1976; McNerney and Farmer, 2011). In many technologies, 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). This complexity comes in different degrees and different forms. The degree of complexity is affected, among others, 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).

From the perspective of developing countries, transferring complex technology would require – apart from hardware – resources for state-of-the-art simulations, demonstration projects, and possibly extensive field tests, and organizations that have the necessary capabilities to absorb experience and translate it into designs adapted to local needs and circumstances. If developing country firms are subject to international competition, these hurdles mean that typically only smaller components are sourced from local suppliers, while firms from advanced economies provide the high-value-add components. When wind turbines are installed in low-income countries, for example, the local content is typically confined to the steel towers, while international suppliers have an edge over local firms in most other components. Less complex technologies could be implemented involving much more local content, or even be developed indigenously.

Technological complexity may be the result of complex production processes or complex product designs (Hobday, 1998; McNerney and Farmer, 2011). Product design comprises conceptualization, fine-tuning of components and materials, and adaptation of the design to specific applications, while the production process comprises all steps necessary to manufacture the product, from raw material extraction to installation. In innovation studies, where innovating firms are typically 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 resulting distinction is that between ‘complex product systems’ and ‘mass-produced products’ (Magnusson et al., 2005).

Yet from the perspective of climate policy makers the type of complexity is relevant, too. Local demand created through NAMAs could results in economic development through local suppliers, local manufacturers, or local operation and maintenance. When policymakers choose technologies for priority actions, they will thus be interested in an integrated assessment of the technology. Such an assessment will go beyond the innovation processes in specific types of firms (say, the suppliers of photovoltaic production equipment) but in entire value chains, encompassing both *innovation in production equipment* and *innovation in the design of the product*. Building on differences in innovation processes to inform NAMAs therefore has to consider both types of complexity.

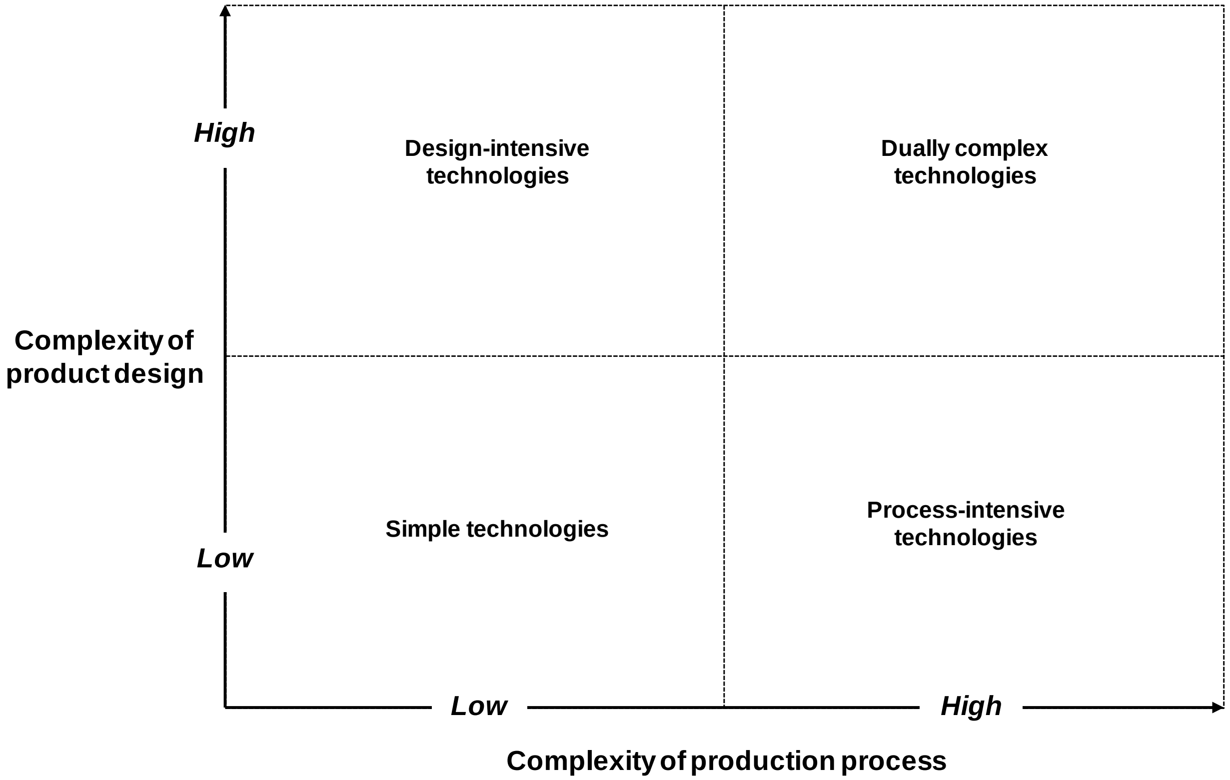


Figure 3: A technology framework of four stylized types, distinguished by degree and type of technological complexity

As the two dimensions of complexity of product design and complexity of production process are largely independent, they span a typology of four technologies (see Figure 3)[4]. The two extremes are ‘simple technologies’ and ‘dually complex technologies’, scoring low and high on both dimensions, respectively. ‘Design-intensive technologies’ exhibit high complexity of the product design but low complexity of the production process, ‘process-intensive technologies’ vice versa. 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.

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[4] When exploring the differences between technologies, the level of analysis is important. The terms “energy technology”, “wind turbine technology”, and “rotor blade technology” illustrate that 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’.

3.3. Four Energy Technologies Positioned in the Framework

We chose four technologies – three from the energy, and one from the transport sector – to illustrate the typology. Both sectors are amongst the biggest contributors to anthropogenic greenhouse gas emissions. 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).[5] At the same time, both sectors cover diverse sets of technologies, making it possible to distinguish very different supplying industries with characteristic innovation processes (Wiesenthal et al., 2011). The four energy technologies we use to illustrate the cases are small hydro, onshore wind, solar PV, and electric cars. As any characterization of larger number of technologies the case description is inevitably brief and stylized, but should help illustrating the framework. Additional examples, especially from the energy sector, are given in Figure 4.

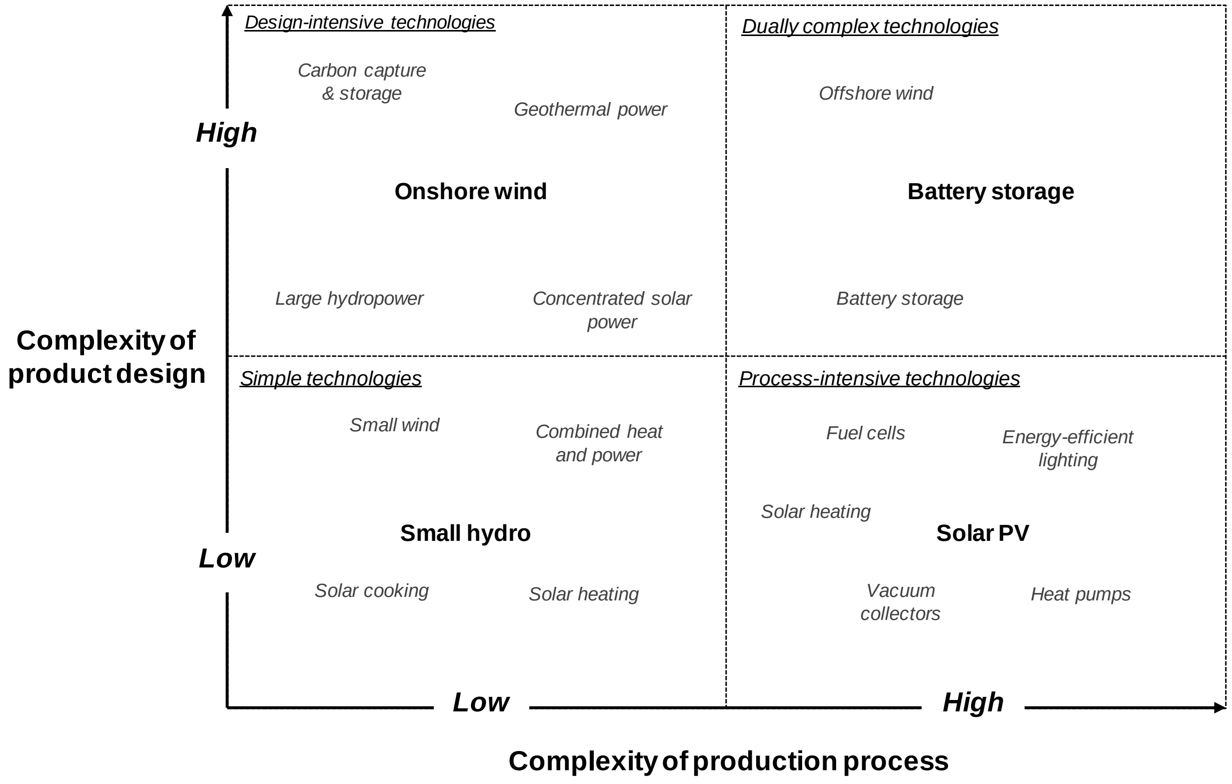

Figure 4: Stylized location of different energy technologies in the typology matrix

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[5] 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 transport sector coming second after energy in Europe and Latin America. The analyses can be accessed at http://unfccc.int/ttclear/jsp/Regionalanalysis.jsp.

3.3.1. Small Hydro Turbines

A relatively simple technology, small hydro exemplifies the lower left corner of matrix. Hydro turbines are used to transform the energy of rivers passing small height differences into electric energy and represent the oldest of all power generation technologies. Depending on the definition, ‘small hydro’ covers generators from 100 kilowatt (kW) to 10 megawatt (MW). The size is usually determined by the local 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, so that – despite low transport cost – turbine manufacturers are relatively small and scattered around the globe, including manufacturers from low-income countries, like Nepal. A *simple product design* (little of which is IP-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 (Cromwell, 1992). Other low-carbon energy or transport technologies, that fall in the ‘simple technologies’ category are e.g., small wind, combines heat and power, solar heating (with flat plate collectors), solar cooking or bicycles (compare Figure 4).

3.3.2. Onshore Wind Turbines

Wind turbines are *complex products*, consisting of several thousand customized electrical and mechanical components. These are integrated to systems by only a few dozen large manufacturers world-wide. Wind turbines have to be adapted, among others, to climate, wind speed, wind profile, and local regulations concerning grid-connection, foundations, and noise. Since the beginnings of the modern wind energy industry, 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, fiberglass casting, and so on, i.e. is *not extremely complex*. 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 to 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. A transfer of (intellectual property for) manufacturing equipment was usually not involved (Lewis and Wiser, 2007). Other technologies falling into this category are large hydropower, carbon-capture and storage (CCS), geothermal power or 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 are a wide range of PV cell technologies using different types of materials and production methods, but cells made of crystalline silicon still capture most of the market. What the different technologies have in common is that the main challenge is to bring down production costs. Entry barriers for silicon and cell manufacturers are relatively large, mostly because of the size of the required initial investment. Since the physics behind some of the production steps are 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 spot markets exist -, the production process is highly complex. PV is therefore positioned in the lower right corner in the matrix (Figure 4). Technology transfer between countries is proceeding 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 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 and production process complexity 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 for firms in new markets. Technology transfer to developing countries in most cases begins with 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. 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 create 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 or battery electricity storage.

4. Implications for the Global Climate Policy Architecture

As illustrated by the exemplary technologies in the previous section, the heuristic can be used to distinguish 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 will discuss these characteristics in detail.

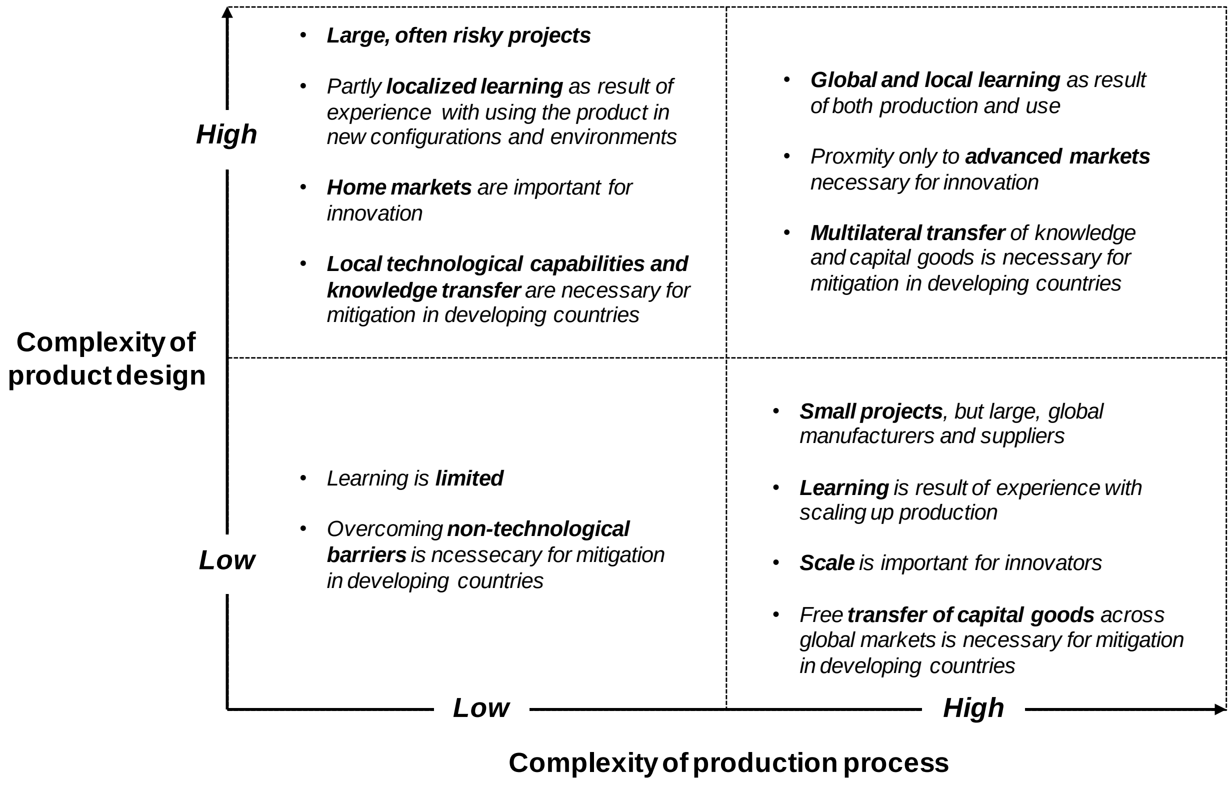

Figure 5: Stylized differences in innovation processes and technology transfer mechanisms between the four technology types

4.1. Technology-specific Innovation Patterns

Technological complexity in capital goods leads to the pattern that technologies are incrementally improved over a long period of time, as firms tinker with new designs and production processes. The two axes of the framework indicate where most of the experimental learning takes place, which has implications for the type of economic activity that predominantly stimulates innovation. The further right or up 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 given, 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 access for manufacturers to large markets in order to grow to 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 is also requiring 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. Implications for the Design of Technology-Specific NAMAs

The international institutional architecture currently assists developing countries in their technology priorities 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 as are assessed as *potential sources of domestic innovation, competitiveness, and economic development*. Such analyses could have two outcomes:

- Technology strategies, i.e., the selection of priority activities along the technology value chain (from materials over components, production equipment, system integration, installation, to operation and maintenance);
- Guidance for the selection of policy instruments that translate 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 potentially most important determinant (as it is the most aggregated factor representative of technology-specific country differences). Differentiating further factors would be possible but go 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, so that all countries can reasonably aim at covering the whole value chain. 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. That needs 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, so that low-income and middle-income countries have 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 often are 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 for domestic engagement is operation and maintenance, which is often a significant share of value-add for design-intensive technologies. Middle-income countries may go beyond that and, with persistent domestic support over a long time, 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 complex the production process, the more firms' competitiveness is based on experience and incremental improvements in manufacturing, often also economies of scale. Both potentially make catching-up difficult for late-comer firms in low- and middle-income markets. If the product design is standardized or simple, i.e., for *process-intensive technologies* (in the lower right field), however, 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 then can 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 suitable strategy for middle-income countries with access to large domestic or global markets. In the field of solar PV, Malaysia and China are two 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: Technology strategies for different types of countries in developing country NAMAs

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 late-comers 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 to globally active component suppliers, that firms outside the developed world have little opportunities to enter the market and gain experience. In other words, they require scale and experience in manufacturing as process-intensive technologies do, but the products are not standardized and simple enough for late-comers 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 has despite political commitment not been very successful so far (Wang et al., 2011).[6]

How these stylized technology strategies translate into policymaking 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 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 (through local content regulation). For *process-intensive technologies*, a strategy aimed at 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.

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

4.3. Toward an International Governance Architecture Leveraging Innovation for Climate Mitigation

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 equally have to be interpreted 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.)

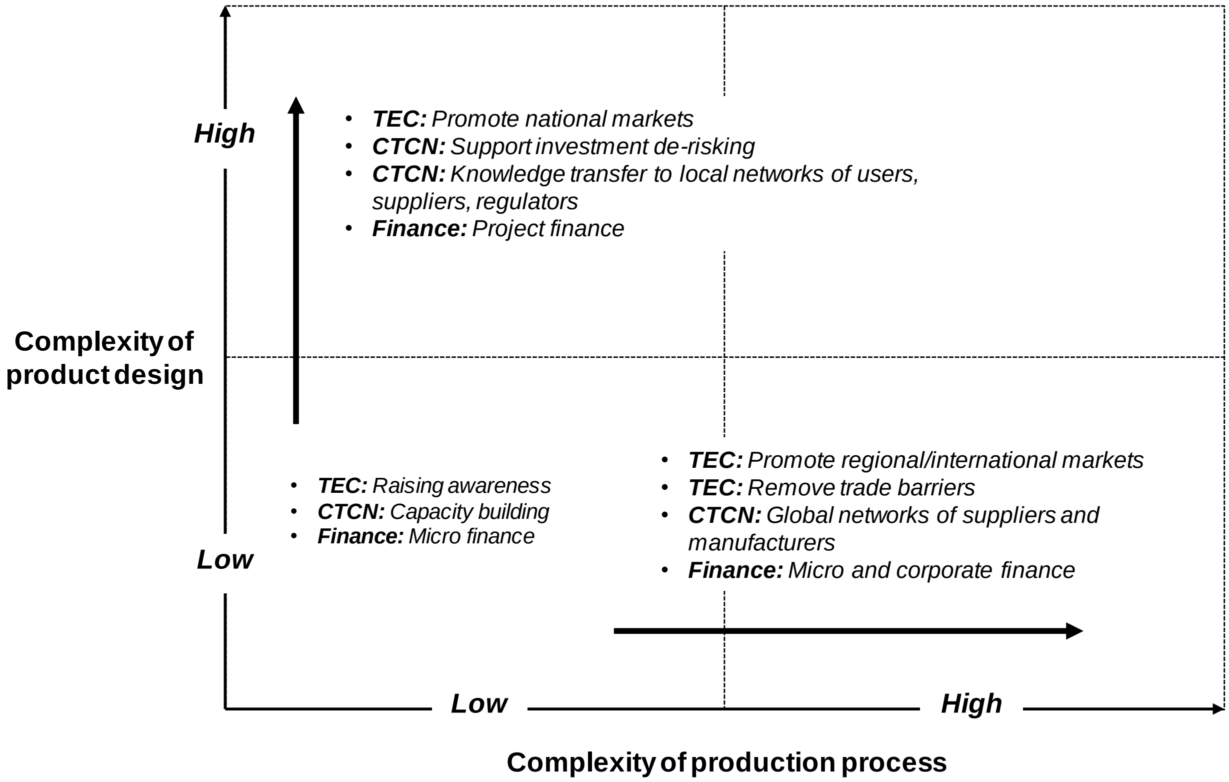

Figure 6: Implications for Technology Mechanism for different technology types

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 therefore 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, also the links to advanced technology suppliers in more mature markets will be crucial. Process-intensive technologies require less local learning and thus networks, but rather 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. Since simple technologies, such as small hydro, small wind, solar heating or solar cooking, are usually rather small, small-scale or micro-finance is an important vehicle for production and diffusion. Design-intensive technologies, in contrast, typically diffuse in via large projects with a project-finance structure making project finance a bottleneck, e.g., for wind farms, geothermal projects, efficient coal power plants, or concentrating solar power. Process-intensive technologies see innovations mostly in combination with large-scale manufacturing, making access to 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) – if the technology is not imported – and related infrastructure (project finance).

4.4. Limitations

A framework such as the one presented in this paper has natural limitations. First and most importantly, complexity is a relative characteristic. Only in comparison to others fields can technologies be assigned to specific fields 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 matrix is thus difficult and requires careful analysis.

There may also be some variation between learning processes within an industry. In solar PV, newer cell concepts often use advanced materials that are based on a partly different knowledge base. Thin-film cells, for example, can be produced in a more continuous production process than standard cells made of crystalline silicon. Manufacturers of such modules, however, often have much more problems to translate the high-efficiencies and high-yields of smaller, laboratory-constructed cells to production volumes. Partly this is due to the fact that, unlike for crystalline silicon, manufacturers cannot make use of equipment from the semiconductor industry. Each new production line is still a unique prototype designed for the respective process, raising the need for experience with production significantly.

Another reason of ambiguity is variation 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 aerodynamical, meteorological, and structural knowledge evolved and was shared through conferences, technical publications, and informal channels. Any technology can therefore change its positioning over time. Yet despite these qualifications, we are convinced to have provided a heuristic with potential for structuring and reducing the information needs by developing country policymakers.

5. Conclusions

We began this paper by illustrating the new challenges posed by the bottom-up, country-led climate policy architecture for national governments in developing countries. We then worked towards informing technology priorities in NAMAs and proposed a matrix heuristic to differentiate 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 that each type features specific forms of technological learning, value chain constellations, and technology transfer. The different forms of technological learning and value chain constellations can inform a country's choice of technological priorities. Low-income countries, for example, should focus on manufacturing only for simple technologies, on single value chain steps for design- and process-intensive technologies, and on operation and maintenance for 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 consideration of differences between technologies. For technologies on the right half of our matrix, the Technology Executive Committee, the 'policy arm' of the TM will have to 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', will have to play a central role. Progress in these technologies will need demonstration projects and the creation of national markets – and 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 overcome the grid-lock in global climate negotiations from the bottom up.

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