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Introduction to low-carbon innovation and development: insights and future challenges for research

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This special issue seeks to bring together the fields of low-carbon development (LCD) and innovation studies. It contributes to the debate by addressing how the learning, innovation, and competence-building lens adds to the discussion about the development outcomes of climate change mitigation. The aim of this introductory article is fourfold. First, it discusses key advances in the debate about the role of innovation and competence building in LCD in developing countries. Second, it seeks to add to the debate by paying particular attention to the heterogeneity of developing countries in terms of the context and innovative capacity for LCD. Third, it addresses the challenges to policy arising from such differentiated starting points. Finally, it sets forth the insights from the articles in this issue and the implications for future research.

Keywords: low-carbon development; innovation; capabilities; learning; innovation; and competence-building systems; pathways; leapfrogging

1. Introduction

During the last decade or so, the problem of climate change mitigation has emerged as an issue of intense public discourse. At the same time, it is increasingly accepted that mitigation in developing countries needs to be combined with economic and social development. Many developing countries have a wealth of renewable energy sources such as sun, wind, geothermal, and hydropower that present new horizons of opportunity for social and economic development while being used to foster energy. The 'innovation and development' research community has been influential in this debate about synergies between climate change and broader policy goals. It is becoming widely acknowledged that, while there is a great range of opportunities for the creation of 'co-benefits', that is, economic and social development benefits arising from climate change mitigation, these developments are not automatic and pose distinctive challenges to developing countries. They depend on innovative measures, including new policies and new models, for access to finance, public–private partnerships, and global collaboration. Furthermore, the challenges to low-carbon development (LCD) in developing countries are very different from those in developed countries, due to the distinctive political, economic, and social settings of these countries.

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This special issue aims to contribute to the debate by addressing how the learning, innovation, and competence-building lens adds to the discussion about development outcomes from climate change mitigation; special attention is paid to emerging new areas of research into LCD. Policy-makers in developing countries increasingly combine the climate change mitigation agenda with industrial development and innovation policy. This special issue will also seek insights from cases from different developing countries and different technological fields to set an agenda for research and policy deliberation.

This introductory article is structured as follows. Section 2 outlines briefly the debate about the role of innovation in LCD. Section 3 then shows the wide heterogeneity of developing countries in terms of vested capabilities. Section 4 highlights key policy issues and Section 5 outlines how the articles in this special issue contribute to these debates. Section 6 provides issues for new research.

2. LCD and innovation

Developing countries play an increasingly important role in debates about climate change. Any solution to climate change will involve a rapid and far-reaching 'diffusion' of low carbon technology in the course of the development process. The economics of innovation have suggested that the speed and trajectory of knowledge creation and the diffusion of innovations are highly heterogeneous and dependent on national and sectoral systems of innovation (Lundvall 1992; Nelson 1993; Malerba and Mani 2009). In order for more or less effective low carbon solutions to materialize, the development process will depend on and be shaped by the different social, cultural, and political situations of developing countries. Each country is endowed with very different 'initial conditions'. The combination of natural resources, human capital, technological capabilities, institutions, culture, and history is much more complex among developing countries than is often assumed. Focusing on the 'diffusion' of generic technological and institutional solutions is unlikely to provide effective and sustainable support for LCD.

Defined in a narrow way, LCD is the process of transforming the current fossil fuel-based economic system, particularly the energy system, towards the goal of CO_2 neutrality. This definition closely resembles notions of low carbon growth (DFID 2009; Ellis, Baker, and Lemma 2009). It is rooted in the goal of sustainable development (Mulugetta and Urban 2010) while not necessarily addressing the multiple planetary issues that exist in addition to climate change (e.g. loss of biodiversity and scarcity of water) and especially their inter-linkages.[1]

A broad view takes into consideration the linkages between the transformation of the fossil fuel-based system and multiple planetary boundaries, that is, between LCD and environmental sustainability (Altenburg and Pegels 2012). However, in this special issue, the notion of LCD works primarily to focus attention on what is probably one of the most serious global environmental threats: climate change.

More importantly, a broad view differs from a narrow one in other respects. First, in contrast to growth-focused concepts (low carbon growth and sustainable growth), the broad view explicitly brings together two objectives: climate change mitigation and the sustained development of low- and middle-income countries. It thus includes the social and political dimensions of sustainability; LCD in its broadest sense involves more than merely reduced levels of carbon growth, because it aims to promote international development, particularly inclusive development (Santiago 2014). The LCD concept is a projection not only of the co-existence of climate change mitigation and international development. It is also inherent in the notion that synergies between the two can be developed. For example, the push to create green energy systems – before brown energy systems take hold – in low-income countries may help to create energy access for the poor. In this special issue, LCD is defined as strategies that mitigate emissions in order to avoid dangerous climate change while at the same time achieving social and economic development.

Engaging in LCD means that innovation needs to take a new course that supports the shift to a 'green techno-economic paradigm' (Freeman 1996). It is more about the *direction of innovation* than the *rate of innovation* (Bell 2009). The green transformation will require major changes in production and consumption across a range of technological spheres. It will be a process of 'creative destruction' (Schumpeter 1942; Bergek et al. 2013) in the original sense of the term: existing economic systems have to be dismantled while new and more environmentally sound ones are created in their place.

This will also mean that future research will have to examine both new aspects of LCD and new actors. Developing countries have particular systemic problems including shortages of capacity, infrastructure, and institutional frameworks. Under such conditions, new actors – associations, local communities, NGOs – to name just a few – come to play an important role. Furthermore, it is increasingly becoming evident that 'developing countries' are now a diverse set of countries ranging from fragile state, low-income to emerging countries. In other words, we need to focus on new challenges and opportunities when we try to understand the process of LCD for 'developing countries'.

The research community working on learning, innovation, and competence building has had an important influence on the LCD debate over the last 10 years. There are three main areas in which the thinking about climate change mitigation has been transformed:

- *From 'technology' to learning and innovation*: The policy community, which has driven the climate change mitigation agenda, has long emphasized the role of technology in climate change mitigation, including access to low carbon technologies in developing countries (Stern 2007). However, there is mounting agreement that the policy community from the outset was guided by a rather narrow concept of technology and the technology development process. Moreover, it is often argued that the resulting focus on access to technological hardware has been predominantly ineffective (Ockwell and Mallett 2013). Conceptual advancement arose from Bell's (2009) distinction between designs, complete equipment, and installation services (hardware) and skills, knowledge, and expertise for short-term operation and maintenance and long-term change (software). It is the attainment of capabilities (learning) within the 'software' dimensions that may enable local low carbon innovation most effectively. It is thus increasingly recognized that innovation is a comprehensive and interactive process, which is not only, or even primarily, about breakthrough 'high-tech' equipment emerging from R&D labs. Here, the emerging research challenge is to understand how learning and the capability-building process takes place in the diverse settings of developing countries.
- *From international 'transfer' to interactive collaboration*: The debates about technology transfer and ways to achieve it have traditionally considered the problem, in the manner referred to above, as simply providing access to hardware technologies. Little regard was paid to the facilitation of knowledge exchange and development of local technological capabilities and system building.[2] This paradigm characterized trade and Intellectual Property Right (IPR)-related discussions for several decades of the twentieth century; the aim was to increase international commitments to technology transfer rather than to structure institutional arrangements that fit local circumstances in order to ensure the absorption, contextualization, and deployment of technology (Lema and Lema 2012; Sampath and Roffe 2012). Notwithstanding the limited economic and human development benefits achieved through technology transfer in conventional sectors, the initial structuring of discussions within the United Nations Framework Convention on Climate Change (UNFCCC) had a traditional, limited viewpoint of technology transfer. This led to efforts to stimulate climate-friendly technology transfer limited to hardware and financing assistance, a strategy widely

deemed unsuccessful (Ockwell and Mallett 2013). However, this approach has evolved: recognition of the centrality of greenhouse gas-reduction technology deployment in developing countries addresses not only the public good in terms of climate change challenge, but it also recognizes the limitations of the traditional position on technology transfer. There is a growing consensus that international action to harness technology for climate change mitigation and general development in the global South must go beyond a debate on technology transfer to focus instead on innovation cooperation, that is, joint action to accelerate the development, adaptation, and deployment of suitable technologies (Sagar, Bremner, and Grubb 2009). This innovation-*cum*-cooperation needs to extend beyond the technological aspect to encompass other facets of the innovation system that support the deployment of technology. The new challenge for research is to identify collaborative patterns for better knowledge creation and diffusion for LCD. While globalization has provided wider institutional avenues for technology transfers (i.e. IPR, licensing, increasing FDI, and exports), this may have created greater disparities in the flow of knowledge among those with absorptive capacity, infrastructure (ICT), and institutional framework, and those without.

- *From 'diffusion' to systems building*: The notion of technology diffusion in the climate change debate has commonly referred to the deployment – introduction or increase – of low carbon technologies, for example, renewable energy technologies or energy efficiency measures. While this is obviously necessary, there has been increasing attention paid to the complexity of the underlying process, which is not simply about rolling out technologies, but also about transforming the relevant socio-technical setting. Effective LCD needs to include organizational and institutional change as well as changes in the realms, instruments, and techniques of policy-making. This calls for a systems approach in analysing LCD. More specifically, we refer to learning, innovation, and competence-building systems rather than solely to innovation systems, which has emerged as a concept from studies in developed countries. When it comes to LCD, the challenge is not confined to a process of diffusion and adaptation initiated from the North. It is primarily a process of strengthening systemic development so that systems for energy production and use can gradually become greener and more capable of meeting local needs. In other words, developing countries are forging ahead through the uncharted waters of finding their own solutions.

Cutting across the three points mentioned above are the need for more context-specific and interactive approaches towards the transition to LCD. Globalization had provided knowledge infrastructure such as the IPR system and information and communication technology (ICT) to increase access to frontier technology if the country is equipped with absorptive capacity. Even though knowledge and technology may not originate in developing countries, populous and dynamically growing emerging economies provide an interesting seedbed for innovations that work towards LCD. To make this happen, the active collaboration in unconventional modes is essential for learning and system building. The transfer of knowledge and technology alone is not sufficient for effective implementation. The country should be equipped with a complementary system to enable such acquired knowledge to be diffused and adapted locally. International collaboration should go beyond the technology focus to a capability and system-building focus if the change is to be well grounded and effective in each country.

3. Levels of low carbon innovation capability in developing countries

Countries of the South have considerably different levels of technological competences for dealing with the low carbon challenge. One problem with distinguishing among countries at

these levels of capability is that the world is changing rapidly and becoming increasingly complex.[3] We have multiple growth poles of emerging countries: BRICS (Brazil, Russia, India, China, and South Africa) as well as large emerging countries that follow BRICS (such as Indonesia, Turkey, and Mexico); fast-growing African countries (such as Ethiopia, Botswana, Nigeria, and Kenya) as well as Southeast Asian countries (Myanmar, Laos, Vietnam, and Cambodia). On the other hand, there are countries with fragile states (Central African nations) as well as those who are trapped in the 'middle' (Malaysia, Thailand, etc.). Diverse and variable growth patterns and conditions among developing countries influence greatly the trajectories for low carbon innovation.

These conditions shape the pathways along distinct 'innovation paths' (Lema et al. 2014a). Innovation paths for low carbon transformation are likely to differ markedly among countries because of the diversity in policies, endowments, and technological capabilities; this has implications for the effectiveness of mitigating climate change and tackling related domestic energy challenges as well as on the degree to which low carbon technologies and solutions can become a source of national competitiveness.

The ability to shape such paths depends crucially on extant capabilities. Walz and Marscheider-Weidemann (2011) have shown that some newly industrializing countries are building up considerable capabilities and show considerable potential to become technology providers. On the other hand, some of the newly industrializing countries are still far from such a position. An update of the data from Walz and Marscheider-Weidemann (2011), which focuses specifically on low carbon technologies, confirms that there is a wide variation in capabilities (see Table 1 and Figure 1).[4] Additionally, Walz and Eichhammer (2012) point towards an even stronger need to build up capabilities in various middle-income countries, and especially in lower-income countries.

Taken together, the preceding data suggest that the countries of the South are extremely heterogeneous. Below, the countries are grouped by three criteria: innovation capability (degree of technology creation and adaptation capability), level of system provision (degree of innovation system availability), and specification of type of technologies (degree of technological specificity). The following taxonomy helps to illustrate the differences:

Table 1. World shares for innovation indicators for low carbon economy relevant technologies in 2010/2011 (%).

	Literature	Patent	Exports
Argentina	0.5	0.03	0.1
Brazil	1.3	0.36	0.5
Chile	0.2	0.07	0.0
China	15.9	5.49	18.8
India	3.7	0.78	0.8
Indonesia	0.0	0.01	0.5
Korea	3.1	5.39	3.3
Malaysia	1.2	0.21	1.5
Mexico	0.9	0.15	2.8
Philippines	0.0	0.06	0.4
Singapore	0.9	0.27	2.2
South Africa	0.6	0.19	0.2
Thailand	1.5	0.58	1.3
Turkey	2.9	1.04	0.6
Venezuela	0.1	0.03	0.0

Source: Fraunhofer ISI sustainability lead market database.

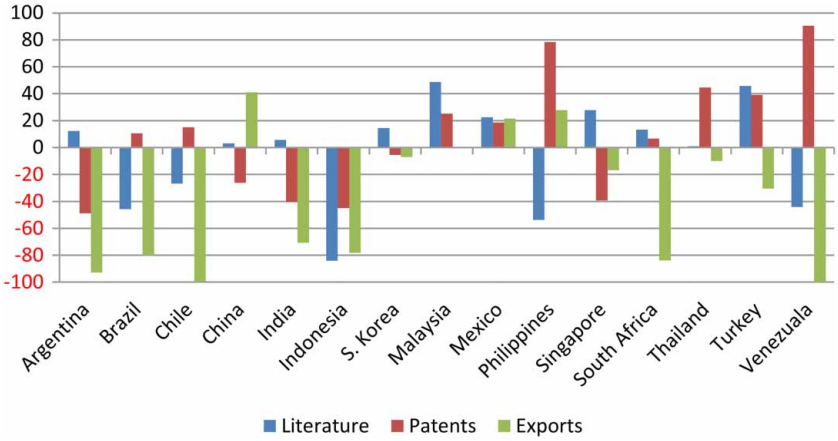

Figure 1. Specialization profile of newly industrializing countries for low carbon economy relevant technologies in 2010/2011.
Source: Fraunhofer ISI sustainability lead market database.

- The 'generalists' are characterized by a higher level of general innovation capability, but without specialization of sustainability technologies. Korea, Singapore, and China are examples of this group.
- The 'specialists' are characterized by specialization of low carbon technologies. Malaysia and Mexico, and to some extent Brazil and South Africa, fall into this category.
- The 'early followers' are characterized by a medium overall level of general absorptive capability, but without specialization of sustainability technologies, for example, Argentina, India, or Chile.
- The 'followers' need to increase capabilities substantially in order to improve conditions for the application of technologies. Venezuela, Thailand, the Philippines, and Indonesia, for example, show characteristics typical of this category.
- The 'late followers' are characterized by lower absorption capacity and very limited system availability. Some middle-income and most low-income countries fall into this category.[5]

By and large, it can be hypothesized that 'generalist' and 'specialist' countries – as emerging 'lead markets' – are already engaged in a process that will enable them to define their own path towards low carbon economy. It can be assumed that these countries will increasingly grow into the role of technology cooperation partners for the countries positioned in the other categories. This will have important effects on the political economy of technology cooperation and on the economic rationales for low carbon strategies. Followers and late followers may be more dependent on pre-existing trajectories, which, however, will be more extensively developed in countries of the South.

In addition to the heterogeneity of developing countries in terms of innovation capability, factors that influence the process of learning in these countries are diverse. These factors range from political economy (governance structure), history (path dependence), power structure (i.e. the presence of strong incumbent technology and energy actors), the presence of 'unconventional' actors in innovation systems (e.g. donor organizations, grass roots movements, and multinational firms pursuing base of the pyramid strategies) that can provide or alter the trajectory of knowledge transfer. This means that policy interventions in these countries are going to be complex and

require a careful look from systemic perspectives at local conditions, bottlenecks, and diverse actors.

It is clear, nevertheless, that all three conditions – innovation, low carbon technology focus, and system availability – need to come together for transition to occur. The next section provides an overview of key policy arising from this analysis, distinguishing among the different types of countries identified here. The subsequent section then provides an overview of the articles in this special issue. All of these articles draw on approaches that emphasize the role of learning, innovation, and competence-building systems to address the low carbon challenge. They bring together experiences from different countries at various levels of development, ranging from the category of generalist to late follower.

4. Policy issues

The low carbon imperative has become an integral element of the development agenda. A large number of governments and development organizations have now included LCD in their policies and portfolios of programmes and projects. The substantial attention from policy-makers and practitioners has arisen due to the prospect of using the LCD agenda to promote associated co-benefits such as industry and job creation, reduction of localized pollution, and enhancement of energy access (Ürge-Vorsatz and Tirado Herrero 2012). The key success factors that turn opportunities into realities are the central concern of policy-makers.

In this introductory article, we emphasize the need for a differentiated approach to policy for low carbon innovation. In particular, it is useful to distinguish between countries with different levels of technological capabilities as discussed in the previous section. Such distinctions provide better foundations for advancing policy than the older notations of developed and developing countries that underlie much policy deliberation, for example, as evidenced in the categories of Annex 1 countries and Non-Annex 1 countries in the UNFCCC. More finely grained categorizations help us to think through policy strategies in different settings where priorities and pre-existing capabilities differ in important ways (Lema et al. 2014b).

In 'generalist' and 'specialist' countries (as discussed in Section 3) where an institutional infrastructure is already in place, the challenge is about strengthening national low carbon systems in order to achieve a self-directed and wide-scale adaptation, dissemination, and use of new low carbon technologies. For 'specialist' countries the challenge is to use current comparative advantages while at the same time seeking to develop dynamic capabilities that avoid the danger of developing into 'core rigidities' as the technological environment changes. Generalist countries may seek to strengthen systemic interaction. Experience shows that, while it has been possible to build learning, innovation, and competence-building systems (LICS) components (e.g. universities, research institutes, R&D regulations, etc.) in many such countries, it has been much more difficult to stimulate the interactions among components, mainly because the demand for knowledge is lacking. New connections can centre on the direct creation of sustainable energy provisions and on the indirect creation of industrial and economic development.

In many follower countries – including some 'early follower' countries such as India – securing energy access is the overriding objective and involves the creation of new energy systems in rural areas and the transformation of existing urban ones. Table 2 shows that more than one billion people are without access to electricity in Sub-Saharan Africa and developing Asia, particularly in rural areas. Building new rural energy systems requires new energy routines, new institutions, and competence building for the application of new energy sources. Policies should focus on making new energy technology available and on supporting market formation via microcredit financing, thus creating socially inclusive learning spaces to facilitate the shift in energy technology.

Table 2. Electricity access in developing countries.

Region	Population without electricity (millions)	Electrification rate (%)	Urban electrification rate (%)	Rural electrification rate (%)
Developing countries	1265	76.1	92.1	63.7
Africa	590	43	72	24
North Africa	1	99	100	99
Sub-Saharan Africa	589	32	64	13
Developing Asia	628	83	96	74
China & East Asia	157	92	98	88
South Asia	471	70	92	61
Latin America	29	94	98	76
Middle East	18	91	99	75
Transition economies & OECD	2	99.8	100	99.5
World	1267	81.5	94.7	68

Source: OECD/IEA (2012).

Governments and donor organizations may seek to support experimentation with new business models for decentralized energy provision, bringing together system actors such as energy service providers, financial institutions, equipment manufacturers, and suppliers of operation and maintenance services (Chaurey et al. 2012). This support may combine policies for renewable energy with funding for infrastructure, such as mini-grids. It will also involve consultations that bring together local community government and service providers to combine service-level standards and social standards for democratizing technology choices and enhancing job generation. Engaging with and supporting system operators with the capacity for oversight in particular technology fields are crucial to providing advice and connecting stakeholders. System operator organization can facilitate project replication and upscaling. A key task is to engage with local administrations to build the 'meta-capabilities' necessary for bringing together and orchestrating the various actors (Chaudhary, Sagar, and Mathur 2012). Bringing experiences and capabilities to the system level should be a key priority.

For 'late followers', many of the points mentioned immediately above, that is, those concerning 'early followers', can be considered strategic deliberations. However, there are also other strategic issues that need extra attention in these cases. Obviously, absorptive capacity is low and there is a marked need to establish learning systems to build such capability. The nurturing of low carbon innovation pathways requires a higher level of governance capacity in public organizations than actually exists. To enhance governance capacity may thus be a core prerequisite for LCD in these countries. Furthermore, the policy priorities in these countries are often concerned with more urgent developmental issues. Hence, successful LCD should involve a diverse agenda of inclusiveness, poverty, and socio-political aspects in order to make such a transition more viable for developing countries. Another consideration is that, in these countries, innovation can often take place informally on a small scale, driven to fulfil 'needs' that have never been satisfied through formal means (Fressoli et al. 2014). These innovations can be comprised of, for example, community mobility systems, climate change mitigating housing with the simple alteration of rooftops, farming practices, agricultural processing mechanisms, electricity generation from off-grid renewable sources, etc. Supporting such 'under the radar' or informal practices for sustainability can be a step in the right direction, making sustainable transition more inclusive. These changes would eventually complement current 'technology transfer'-led policy and help to move the transition process more definitively towards sustainability.

5. The articles in the special issue

The concepts of LICS comprise a further development of the innovation system concept for development (Johnson and Andersen 2012; Lema et al. 2014b). LICS puts the mutually reinforcing processes of learning, innovation, and competence building at the heart of the development process. Fundamental to the notion of LICS is that local context matters: highly abstract systems analysis or policy that ignores the specificities of particular environments can be of only limited use in understanding and promoting innovation and development. The articles in this special issue use systems perspectives to examine the transformational challenges; the articles also make a number of contributions to the debate and emphasize particularities of 'systems thinking' regarding low carbon technologies and settings in developing countries.

The first article in this special issue is 'The adoption of energy-efficiency measures by companies in the cassava processing and maize milling industries in Nigeria and Kenya', by Jacinta Ndichu, Julian Blohmke, René Kemp, John Adeoti, and Elijah Obeyelu. Some of the barriers to adoption identified in the study are similar to those in developed countries: high upfront investment costs, lack of information, and concerns about discontinuities in production. But the barriers seem to be greater in Nigeria and Kenya. The article shows that, in late-follower countries, only a few firms have introduced measures of energy saving due to issues arising from systemic problems, such as the limited availability of upfront investment finance and a relatively weak knowledge base for technology selection. Informal mechanisms of learning are important, whereas the importance of formal system actors such as universities and public research institutes is marginal. The authors show that there is a greater reliance on external advice than in developed countries. But even in this late-follower setting, with relatively weak domestic systems for innovation and learning about energy efficiency, innovation occurs due to a combination of local and global knowledge and technology. Even though strong energy efficiency exists outside, the strengthening of the local system – particularly by providers of both technical and relevant managerial training – is a prerequisite for further development and deployment of energy efficiency technology in these two countries. The substantial reliance on foreign technology and consultancy services observed by Ndichu et al. can be interpreted as one way of compensating for relatively weak domestic technology creation and absorption capacity in the late-follower setting.

The article 'The role of civil society organizations in low carbon innovation in Kenya' by Muok and Kingiri identifies formal and informal NGOs as particularly important actors in low carbon innovation in Kenya; the authors also argue that these organizations take on roles that tend to be ascribed to formal government and private sector actors in the literature on developed country innovation systems. Drawing on a study of grass roots innovation in East Africa, the authors argue that the current literature tends to overestimate the capacity of governments as agents who fail to recognize the role of non-governmental actors, such as grass roots civil societies that tend to substitute for inadequate government action. The article shows that NGOs – under conditions of a weak innovation system – can also deliver key 'functions' regarding advice, sponsorship, and funding. This underscores the importance of looking at intermediary actors – which have very often been neglected in the past – in many late-follower settings.

The article by Georgeta Vidican, 'The emergence of a solar energy innovation system in Morocco: a governance perspective', further highlights insights that can be derived from the analysis of low carbon innovation in follower settings by exploring the challenges to system-building initiatives for the development of the solar energy sector in Morocco. Apart from low capabilities specific to solar energy technology, a key challenge to the development of a solar innovation system in Morocco is the lack of a strategic approach to sectoral development that engages the key stakeholders and their diverse objectives. The article emphasizes the importance of governance of politics, particularly the power of the ruling elite in influencing the pace of

development. Vidican shows that coalitions among the most powerful actors have been effective in attracting large investments, but a tendency towards concentration of activities is likely to hinder system formation processes that can emerge more organically and bring more widespread co-benefits to the local population. Hence there is a need to pay particular attention to power and politics – exemplified by the political 'capture' of the solar energy trajectory in this case – when examining low carbon systems in follower settings.

The next article is also about solar photovoltaics (PV), but shifts the focus to a 'generalist' lead market setting for solar energy. The article 'Diverse and uneven pathways towards transition to LCD: the case of solar PV technology in China' by Michiko Iizuka examines the remarkable increase in energy-generating capacity by solar PV in that country. She shows that the changes in the external landscape outside China have affected the export-oriented Chinese solar PV industry significantly, leading to policy changes having their bearing on the ability of both firms and the government to target diffusion in the domestic market. This will contribute to achieving a sustainable transition within China, because the incentives for such a path are transferred to China and adapted specifically to the Chinese landscape. However, Iizuka points out that this development has only been possible because of a changing global environment. International markets were not only offering an opportunity for Chinese exports, but were also providing for large learning and scale effects, which reduced the costs of PV. This results in both lower costs for the diffusion of PV within China, and the development of local technological capabilities and system building.

The article adds to the systems framework by drawing on the multilevel perspective of the sustainability transition literature (Geels 2002). However, the article also shows that solar PV as a sustainability niche was not initially the product of environmental policy in China. Instead, it was a product of the export-oriented industrial policy in China combined with a renewable energy policy in the developed world. Hence the case underscores the interconnectedness of low carbon systems, that is, developed countries can have an important influence on the sustainable transition process in developing countries. This is particularly interesting in the Chinese solar PV case because the initial export-oriented building of capability was later helpful in the deployment of solar PV within China itself (Schmitz and Lema 2015).

Andre Furtado and Radhika Perrot, in the article 'Innovation dynamics of the wind energy industry: Technological and institutional lock-ins', examine the development of the wind energy industry in South Africa and Brazil. The comparison of renewable energy industry development in BRICS countries with strong existing energy systems (hydroelectric energy in Brazil and coal in South Africa) is interesting, as each country needs to break away from 'path dependencies'. Although the settings of the two countries are very different, similar patterns emerge in the ways in which policy interventions were made, entrepreneurial activities are stimulated, and its capacities are developed. These patterns emerge from observing the evolutionary process of both countries by paying attention to 'directionality of search', 'knowledge creation', and 'entrepreneurial experimentation'. The cases demonstrate the importance of these factors for national policy, which is, however, shaped by political economy factors, vested interests, and incumbent firms. Furthermore, global influences are an important factor. In the case of the financial crisis of 2008, for example, global knowledge flowed through patenting and licensing, which also interacted with national efforts and made the process of renewable energy development a complex one. It is a constellation of circumstances that leads South Africa to be more path-dependent on existing technological trajectories. The authors show that, although the innovation systems share many similar features, the innovation outcomes are different due to differences in knowledge resources and economic endowments. Local content rules seem to work in Brazil whereas they have little effect on knowledge transfer in South Africa due to limited absorptive capacity.

While the majority of articles in this special issue use the systems lens to seek insights from national-sectoral cases, the final articles are more conceptual in nature. The article 'LCD, social inclusion, and systems of innovation' by Allan Andersen and Björn Johnson examines the intersection of 'low carbon' and 'inclusiveness' in development. They argue that inclusion is crucial to achieving LCD and thus seek to make connections between research on LCD (Mulugetta and Urban 2010; Ockwell and Mallett 2013; Urban and Nordensvärd 2013; Lema et al. 2014b) and socially inclusive innovation (Johnson and Andersen 2012; Heeks, Foster, and Nugroho 2014; Santiago 2014). They add to the literature by proposing six channels through which inclusion enables large-scale transition, such as LCD, and they illustrate with empirical examples how social inclusion affects such development across various spatial scales.

In the article 'Recasting truisms of low carbon technology cooperation through innovation systems', Alexandra Mallet shows how the innovation systems perspective could help making low carbon technology cooperation more effective. The article questions the widely held notion that developing countries do not have innovation systems and that producer–producer interaction is weak. Like the article by Mouk and Kingiri (in this issue), Mallet emphasizes the roles of alternative actors in developing innovation systems. Drawing on various anecdotal cases from developing countries, she argues that new framing is needed when thinking about low carbon technology cooperation.

6. Further research

Low carbon innovation and development is a new field of research that does not yet have a firmly established trajectory. In this special issue, we have sought to bring together cases and conceptual discussions about innovation and development problems as they apply to the low carbon field. A common theme binds together the articles in this special issue: the idea that learning, innovation, and competence-building system lens can help to understand the diverse settings in which 'developing countries' are situated and ultimately help to enhance synergies between climate change mitigation and socio-economic development. We have covered both energy production (solar and wind energy) and consumption (energy efficiency) and have highlighted various aspects, such as new actors in system development and international collaboration. While each of these issues requires further research in their own right, we emphasize here three topics that appear particularly ready for further research in this field.

First, there are various *megatrends* that call for a more integrated view of innovation trajectories towards low carbon societies. Many of the articles in this special issue refer to these megatrends as changing contextual factors, but none of them are addressed directly. However, these megatrends will need to be incorporated into new research on low carbon innovation and development, focusing on the various trends that are likely to influence these trajectories. For example, the low carbon strategies have been emphasizing the build-up of the energy infrastructure but we currently see a tendency that especially energy and water infrastructure are becoming intertwined. The so-called water–energy nexus is of utmost importance especially for developing countries, which face the double need to build up a water infrastructure and to adapt it to climate change. At the same time, developing countries face a tremendous urbanization trend. In 2008, the segment of the population living in urban areas reached 50%. The United Nations Population Fund (UNPF) estimates that by 2030, the number of people living in urban areas will swell to almost five billion, with urban growth concentrated in Africa and Asia. However, substantial drivers of residential and transport energy use are related to the future design of urban areas. Thus, research has to broaden its scope towards integrating LCD into regional and city planning. The same holds true with regard to the integration of material and industrial energy use. Low carbon strategies for lowering industrial energy demand will increasingly move from emphasizing

energy-efficient processes in industry towards material efficiency, in order to avoid the production of energy-intensive materials altogether. Future innovation research needs to address more systematically the many interconnections between the low carbon transition and ongoing megatrends.

Second, questions about the *political economy* of low carbon innovation and development have been emphasized by several authors in this special issue (e.g. Vidican), but the issue has received very limited attention overall. The need to take the political economy more into account has been expressed in various reflections by scholars working on sustainability transitions (Hess 2014; Valentine 2014; Walz and Köhler 2014). There is a need to understand the influence of interest groups on the direction of low carbon innovation in developing countries. Hence, the specific actor structure in low carbon innovation and development must be taken into account. Among the incumbent players of fossil-based energy systems, there are major energy players in the gas and oil sector or utilities and other power producers in electricity generation and distribution.[6] Other energy supply companies belong to the core of companies for which the term 'multinationals' was framed. Thus, the incumbents of a fossil fuel-based energy system are typically very powerful and sometimes have extremely powerful links to government. The actors for many low carbon innovations, especially renewable energy technologies, are newcomers. Some of them are small and medium-sized firms; others are spin-offs from established companies (e.g. some of the big wind turbine producers in China). Furthermore, there are also community-based groups and NGO-type actors, which are among the key proponents of LCD. This reflects the fact that energy is a basic need that cannot depend on individual market-based decisions alone. To sum up the argument, important actors in energy innovation systems are different from the typical actors in other innovation systems. Thus, it can be expected that low carbon innovation and development can be characterized as an arena with a very uneven power structure. On the one hand are large companies, which profit from existing fossil fuel lock in, sometimes directly linked to government; on the other, there are the drivers of low carbon innovation, which very often are not part of the established innovation system and possess neither capital reserves nor experience in fostering innovation. How such a political economy impacts the prospects for LCD, and how to overcome such uneven power structures are other major topics for future research.

Third, there may be new and changing *pathways* to LCD on the horizon in developing countries; pathways may be more varied than sometimes assumed. As emphasized, 'developing countries' consist of a diverse set of countries ranging from emerging economies, to low-income countries, to fragile states. An important discussion is whether only relatively strong countries (e.g. 'generalists' and 'specialists') will be able to shape their own low carbon pathways or whether there is a greater opportunity for countries (including followers and late followers) to make their own way. As the catch-up nomenclature implies, countries that are 'following' typically produce innovations by creating a new combination of 'borrowed' technology (created in 'leading' countries) or they apply it to new market conditions. On the other hand, a wave of indigenous innovations in developing countries – captured by concepts such as 'under the radar innovation' (Kaplinsky 2011) – means that such followers may in fact also be able to find their own way in the case of LCD. These countries may be able to 'leapfrog' into sustainable techno-economic paradigms (Lee and Mathews 2013). When it comes to low carbon innovation and development, these countries might be less path-dependent in terms of infrastructural and organizational solutions originating from high-carbon models of energy. A particularly interesting area in this regard is the process of addressing the rural electrification challenge (Table 2). In Sub-Saharan Africa and developing Asia, there are major drives to create access to electricity with alternative (renewable) power sources and entirely new (decentralized) models of infrastructure provision. The countries that are currently engaged in creating access to electricity for their populations may

thus be able to create entirely new pathways. While there will be international learning involved – not the least South–South learning – these models will be unique at the international level and may over time become exemplary examples for others to follow.

Collectively, the articles in this special issue suggest the need for new frameworks to understand LCD in developing countries. Rapid urbanization in 'developing countries' is accompanied by radical changes in the provision of large physical infrastructure. This can be a 'window of opportunity' to leapfrog towards carbon-efficient systems in many developing countries if the political economy is favourable and new actors are allowed to create spaces for innovation. One emerging feature of LCD in the 'South' is diversity of trajectories. Each country is now required to devise a unique energy portfolio, accompanied by varied provisions of the physical and institutional infrastructure, against the backdrop of diverse factors, resource endowments, and capability settings. This means that the 'catching-up' process of LCD will not evolve along a single path. Instead, developing countries will move along increasingly diverse 'path creation processes'. Our systemic and evolutionary framework would be increasingly relevant in this context. However, further research is needed to redefine the framework so that it can be flexible and open to new possibilities and cope with challenges that developing countries confront in the search for sustainable solutions.

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Notes

1. In an earlier special issue of this journal that was focused on China and India, Altenburg and Pegels (2012) explicitly addressed the broader concept of 'sustainability'.
2. The discussion on pathways towards LCD often overlooks this point and tends to seek solutions in 'technological transfer' that draws upon a traditional 'catch-up' logic: laggard countries follow in the footsteps of the leaders. However, recent research casts doubt on whether such a singular view of 'catching-up' is valid across different technological regimes (Lee and Lim 2001) or is sufficient to reach the sustainable goals (Byrne et al. 2012).
3. The problem of defining country classifications for a changing world is discussed at greater length in Harris, Moore, and Schmitz (2009).
4. For methodological and data background, see Walz and Marscheider-Weidemann (2011).
5. The numbers are so low that sound calculation and interpretation of a specialization is not feasible, see Walz and Eichhammer (2012).
6. Especially in electricity, low carbon pathways depend on integration with the electricity system. Indeed, low carbon innovation paths in electricity have to meet a triple regulatory challenge (Walz 2007), having to adapt the sectoral pattern of electric utility regulation. This adds a third dimension to environmental regulation and R&D specific regulations. So far innovation and learning systems-based research has been studied only reluctantly to see how electricity reform might influence the prospects of low

carbon paths. On the other hand, a vigorous debate about electric utility regulatory reform has opened recently in newly industrializing countries, but with only minor connections to low carbon innovation. Thus, future research on low carbon electricity paths will need to integrate both strings of research.

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