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Technology transfer? The rise of China and India in green technology sectors

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International technology transfer is central to the debate about how to curb the carbon emissions from rapid economic growth in China and India. But given China and India's great progress in building innovation capabilities and green industries, how relevant is technology transfer for these countries? This paper seeks insights from three green technology sectors in both countries: wind power, solar energy and electric and hybrid vehicles. We find that conventional technology transfer mechanisms such as foreign direct investments and licensing were important for industry formation and take-off. However, as these sectors are catching up, new 'unconventional transfer mechanisms' such as R&D partnerships and acquisition of foreign firms have become increasingly important. We argue that there is limited practical and analytical mileage left in the conventional approach to technology transfer in these sectors in China and India. We argue that the emphasis should shift from transfer of mitigation technology to international collaboration and local innovation.

Keywords: technology transfer; climate change; innovation; technological capabilities; innovation systems; sustainability; China; India

1. Introduction

Rapid economic growth in both China and India has now been sustained for more than a decade and it is set to continue in the foreseeable future. These two countries now account for a substantial amount of the production of the world's goods and services. There is therefore increasing agreement that a global shift in economic power is under way: from the West to the East. However, the build-up of capabilities in China and India is not only occurring in the sphere of production, it is also in the sphere of innovation and technological development (Altenburg et al., 2008).

While commentators and the scholarly literature are still trying to catch up with the changing global distribution of innovation capabilities (Ely and Scoones, 2009; Leadbeater, 2007), climate change is emerging on the top of the economic and political agenda (Stern, 2007). Policymakers, scholars and the wider public increasingly agree that economic growth needs to change direction, not least in China and India. The change that is needed is one in which new technological paradigms decouple growth from environmental problems – particularly greenhouse gas emissions – through the development and use of new technologies (Altenburg and Pegels, 2012).

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Technology transfer is seen as a cornerstone in reaching a global solution to climate change. China and India are particularly important, not only due to the substantial climate change effects associated with the rapid industrial transformation in these large and populous countries but also because of their weight in the negotiations within the United Nations Framework Convention on Climate Change (UNFCCC). Q1

In this paper, we seek to connect the mounting shift from production to innovation capabilities in China and India with the debate over the global transfer of green technology. If China and India are making the transition from users to producers of technology, what does that mean for the green technology transfer debate?

In order to discuss this question we proceed in three main steps. First, we discuss the theoretical notion of technology transfer and provide a new conceptual framework devised to capture conventional and unconventional types of technology transfer as well as localised innovation (Section 2).

Second, we explore the extent of catch-up and the role of technology transfer in building technological capacity in three key green technology sectors in China and India (Section 3). It is necessary to step back and examine: (i) whether and to what extent the 'breakthrough' in the transition from production and innovation has occurred in low carbon technology and (ii) the extent and nature of technology transfer in this process. We review the insights from three key 'low carbon' sectors with high mitigation potential: the wind turbine sector, photovoltaic (PV) solar energy and electric and hybrid electric vehicles.[1]

Thirdly, we discuss the implications of the findings. We show that when it comes to key green technology sectors in China and India – two very important countries in the climate change equation – the conventional approach of technology transfer is increasingly surpassed by reality (section 4). Two main reasons lie behind this: (i) the technological gap is now small and decreasing in these key low carbon sectors and (ii) when technology transfer occurs, it is no longer conventional transfer that is most important. We discuss this by contrasting a broad and a narrow perspective on technology transfer.

We end the paper by discussing how much mileage is left in the concept of green technology transfer and implications of these findings for the technology policy debate in and around the UNFCCC. We also discuss the limits of this research and propose questions for further research in this area (section 5).

2. Conceptual framework

This section provides the key to analytical concepts which will aid our subsequent analysis of technology transfer in the chosen green technology sectors in China and India. It defines what technology transfer is and makes a simple distinction between (i) conventional transfer mechanisms, (ii) unconventional transfer mechanisms and (iii) localised innovation.

2.1. *Defining technology transfer*

A widely used definition describes technology transfer as a broad set of processes covering flows of equipment, know-how and experience between various types of actors (IPCC, 2000, p. 3). Our focus in this paper is mainly on the private sector because it 'is the main source for the worldwide diffusion of technology' (Schneider et al., 2008, p. 2930; see also Stern, 2007). We are not concerned with transfer within developing countries, but with the potential flows across the divide between OECD countries and emerging economies (China and India). We are concerned with the potential flows that may be involved in or lie behind effective mitigation of climate change (Ockwell et al., 2008; Stamm et al., 2009).

According to Bell (1990), technology is transferred through three types of flows of transferable technology between technology suppliers and technology importers (recipients):

- Flow 1: *Capital goods, equipment designs and other artefacts*. This flow consists of tangible assets such as equipment, as well as paper-embodied knowledge for processes and products such as blueprints.
- Flow 2: *Skills and know-how for operation and maintenance*. This flow consists of intangible assets that may also be thought of as 'disembodied technology'. The skills and competences to operate technical systems arrive as human and knowledge capital.
- Flow 3: *Knowledge and experience for technological change*. This flow also consists mainly of intangible human capital but in contrast to flow 2 it also includes organisational assets. It can be further specified as 'delivering' and creating people embodied technology.

The first two flows alone are useful to deliver new and increased *production capacity* to technology importing firms or countries. Alone they add little or nothing to their *innovation capacity* (Bell, 1990, 2009). The latter depends on all three flows, but it is the third flow that is most critical. The third flow is most relevant to breaking out of 'carbon lock-in' in emerging economies – following the premise that local technological capability and innovation is crucial for countries to leapfrog to low-carbon pathways. We proceed by outlining different organisational *mechanisms* that may facilitate these *flows* of transferable technology.

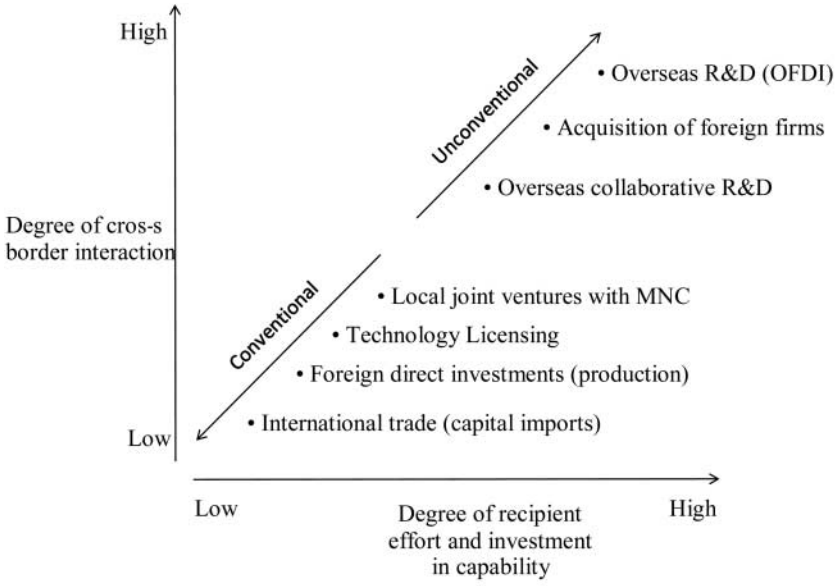
2.2. *Distinguishing transfer mechanisms*

Our analysis in later sections is based on the distinction between 'conventional' and 'unconventional' technology transfer mechanisms. Our starting point is the early economic literature in which there was a strong distinction between innovation and diffusion. It was assumed that once technology was developed in advanced countries, it would flow freely without significant interaction between technology producer and importer and without substantial investment in absorption and related capability building in importing organisations. It assumed that new technology, once created, can be used immediately by all actors. Economic and technological catch-up would therefore be rapid (as reflected in Grossman and Helpman, 1995; Romer, 1994).

However, a range of studies in the technology and innovation literature has now pointed out the limitations of this assumption (Shamsavari, 2007; Kulkarni, 2003; Reddy and Zhao, 1990). We draw on Reddy and Zhao's (1990) distinction between the 'transaction perspective' and the 'host perspective' of technology transfer. This line of thinking suggests that two key dimensions are central. First, transfer can occur with varying degrees of interaction across geographical and cultural distance between suppliers and importers of technology. Second, it can involve varying degrees of internal effort and investment in so-called 'recipient' firms and countries. These factors – (i) the degree of cross-border interaction and (ii) the degree of internal effort and investment – are key variables in our conceptual framework. We use them to distinguish between conventional and unconventional mechanisms in a two dimensional space as shown in Figure 1.[2]

2.3 *Conventional technology transfer mechanisms*

Conventional technology transfer mechanisms involve comparably low levels of cross-border interaction (one-way inward flow) and all else being equal they require less recipient effort and investment in capability. As observed by Stamm et al. (2009, p. 19): 'There are a number of technological artefacts for the transition towards more sustainable development patterns, and these are



Note: This figure is meant as a heuristic device and the notions of conventional and unconventional mechanisms are 'ideal types'. In reality there is not a proportional relationship between the two axes and the specific order of the different mechanisms along this continuum depends on the relative weight of the underlying factors.

Figure 1. Conventional and unconventional technology transfer mechanisms.

available "off the shelf"". The import of off-the-shelf equipment is the classical example of conventional transfer.

Recipient effort and investment is always required but may be limited to purchase and installation or minor tweaking of existing solutions. Typical joint ventures – with local production based on foreign technology – have higher interaction and investment requirements, but typically involve one-way technology flows from distant MNC headquarters to the joint enterprise (Lall, 1993). Our focus is on these firm-level modes of importing technology in 'local' firms. However, we also include the role of foreign direct investment since it is central to the policy and academic debate (Ueno, 2009). Most of the literature concerned with 'technology transfer' is focused on such conventional mechanisms (Popp, 2011; Schneider et al., 2008; Ueno, 2009; Less and McMillan, 2005)

As mentioned, these conventional mechanisms are unlikely – in and by themselves – to facilitate flows of knowledge, experience and expertise for generating and managing technological change (flow iii). Whether they do so depends on how they are used within 'recipient' organisations. Furthermore, as shall be discussed, these mechanisms may be dynamic and change over time.

2.4 *Unconventional technology transfer mechanisms*

Unconventional transfer mechanisms have higher interactive requirements and they depend on substantial investments. These mechanisms – overseas R&D, foreign acquisitions and collaborative R&D with foreign organisations – require substantial interaction and depend on substantial 'recipient' effort.

Unconventional mechanisms are typically difficult to manage. For example, it is not easy to internalise knowledge embodied in people and organisational routines in an acquired firm; it

requires absorptive capacity (Rui and Yip, 2008). In addition, they are likely to depend on significant expenditure outlays. While these mechanisms are difficult and costly, the literature on technological learning and catching up (e.g. Fu et al., 2011; Lall, 1993) suggests that they are critical to the creation of knowledge and experience for creating new technology. They have been particularly important in 'national champion firms' in emerging economies (Zeng and Williamson, 2007; Altenburg et al., 2008; Fu et al., 2011).[3]

Unconventional mechanisms are not new but have become increasingly relevant. As noted by Stamm and colleagues (2009, p. 2), large developing countries are 'less and less willing to accept traditional modes of transfer that imply continued dependence on international technology providers'. Our hypothesis is that unconventional mechanisms are also key in green technology sectors.

It is central to our hypothesis that, in general, these mechanisms are becoming increasingly central in the way globalisation unfolds. For instance, large MNCs from the developed world are increasingly locating R&D activities in China, India and Brazil due to the increasing technological capacity, access to human resources and proximity to growing markets (Lema et al., 2012). So the term 'unconventional' is used with particular reference to the way technology transfer is discussed in the climate technology debate; unconventional mechanisms tend to receive insufficient attention.

2.5 *The learning process and localised innovation*

In addition to discussing the role of conventional and unconventional technology transfer mechanisms we also discuss a closely related issue, namely how important technology transfer is in relation to – and in combination with – 'localised innovation'. Foreign technology transfer and local innovation are largely complementary and only partly substitutable (Fu et al., 2011; Lall, 1993).

At the micro-level (the firm), the accumulation of capabilities – technological learning – is likely to involve a sequence of activities that combines firm-internal generation of skills and capabilities with outside knowledge (Bell, 2009). It combines internal and external learning. Although some of the technology transfer literature describes the process as a simple matter of choosing off-the-shelf technology, the importing firms need to raise absorptive capacity and actively absorb and integrate the acquired technology (Ernst and Kim, 2002). It is beyond the scope of this study to examine this process in-depth. However, we can assess the role of firm-internal effort by examining the extent to which firms conduct local in-house R&D as a part of their technology development effort. They key issue is how firms combine internal and external learning.[4]

'External learning' is not necessarily international. On the contrary, there is a huge literature that stresses the importance of interactive learning in systems within the bounds of nation states (Lundvall, 1992). As argued by Altenburg and Pegels (2012), in the context of climate change, effective mitigation will involve the creation of 'sustainability-oriented innovation systems' (SoIS). To address this, we therefore examine local technology linkages such as collaborative R&D between firms and research institutes.

3. The rise of green technology sectors in China and India

How far have India and China come in catching up in green technology sectors and what mechanisms led to progress? Did these mechanisms differ in formative and catch-up phases? To examine this we review three sectors in both countries: (i) wind turbines, (ii) solar PV energy and (iii) electric and hybrid electric vehicles.

The purpose of this section is twofold. First, it seeks to examine the technological development of the industries and addresses the question of whether the green technology gap between emerging economies and OECD countries has diminished. Second, it seeks to identify the key technology transfer mechanisms. This is done primarily with the firm-level as a useful focusing devise, but the understanding of individual firms needs to be situated in the sectoral context.[5]

The micro-level analysis centres on 'national champions' defined as the firms with technological leadership and dominant market or export shares in their home economies. These firms are therefore key actors in climate change mitigation through diffusion of green technologies in China and India (Table 1).

Table 1. The key national green technology champions.

	Wind	Solar	Electric and Hybrid Vehicles
China	Goldwind Science and Technology (1998), a publicly traded company emerged as a subsidiary of the Xingjian Wind Energy Company established in 1986. Sinovel Wind (2006), a state-owned company based in Beijing; spin-off from giant Dalian Heavy Industry, established in the 1920s. Dongfang Electric (1984), a subsidiary of a state-owned power station contractor and manufacturer of power equipment, which dates back to the 1950s.	Suntech Power (2001), a private start-up by a Chinese entrepreneur who headed thin film research at the University of New South Wales, Australia. Yingli Solar (1998), a publicly traded vertically integrated photovoltaic manufacturer. Trina Solar (1997), a start-up by a group of scientists with an initial focus on systems installations and later a manufacturer of mono and multicrystalline modules.	BYD (2003), a private automobile company based in Shenzhen; spin-off from BYD Company (1995), an energy storage producer that started making rechargeable batteries for cell phones. Chery Auto (1997), a state owned enterprise (by local government of Wuhu) produces sedans and is China's largest auto exporter. Shanghai Automotive Industry Corporation, SAIC (1955), a major state-owned automobile company.
India	Suzlon Energy (1995) from Pune, Maharashtra, spin-off from a family-owned textile firm, which was ridden with power cuts and increasing electricity prices in early 1990s.	Moser Baer Photo Voltaic (2005), a subsidiary of Moser Baer, founded in 1983, a firm focused on optical storage media products such as DVDs and Blu-ray Discs. TATA BP Solar (1989), a joint venture between energy giant BP's solar spin-off and Tata Power; Tata Power is India's largest power utility company, a part of Tata Group, India's largest private conglomerate, which dates back to 1868. HHV Solar (2008), a subsidiary of Bangalore based Hind High Vacuum Company, a long time engineering company in vacuum and solar technologies.	Mahindra REVA (1994), originally an Indian majority share joint venture between the Maini Group and US company, AEV but is now majority owned by Indian Mahindra & Mahindra (1945), which also has hybrid-electric autos. TATA Motors (1945), a private held and Indian leading automobile company with numerous alliances and joint ventures; part of Tata Group. Bharat Heavy Electricals Limited (1952), a large state-owned power sector industrial company.

3.1 *Wind power sector*

Chinese wind power began in the mid-1980s with imports of turbines from Europe, but today it boasts more than 40 domestic manufacturers catering for what has become the world's largest wind power market with 44 gigawatt installed capacity (BTM, 2010). The national champion firms have become some of the world's largest in a very short period: in 2006, no Chinese companies were in the global top 10 but by 2009, Sinovel, Goldwind and Dongfang became global top 10 players (BTM, 2010).

In the formative phase, responding to the high-growth market and mandatory 70% local content requirements, almost all major global wind power firms established production in China, a minority through joint ventures (Lema and Ruby, 2007). Leading national players, Sinovel, Goldwind and Dongfang all initiated production through licensing foreign technology from European design houses in the early 2000s. As the companies' in-house design capabilities have matured, the relationships to foreign licensors developed into co-design relationships (Lema et al., 2011). Unconventional transfer strategies by Chinese national champions seeking to engage in the development and design process were successful because foreign technology partners were not manufacturing competitors but rather specialised technology design houses achieving new business ventures through co-design relationships.

Unconventional mechanisms helped to achieve turbines of comparable size (and sometimes sophistication) as those currently under development by global competitors (Lema et al., 2011). Goldwind achieved strong overseas R&D capabilities through its acquisitions of German Vensys (as well as key suppliers), and both Donfang and Sinovel cooperated with foreign technology companies. A number of smaller Chinese companies have independent design of wind technology and all major Chinese wind turbine manufacturers have undertaken considerable in-house R&D for own solutions with the support of government R&D grants (Tan, 2010). For instance, Sinovel has a newly established 'National Offshore Wind Power Technology and Equipment R&D Center' and is approaching the frontier with Sinovel's new own-designed 5 MW offshore turbine.

Local technology agreements with local centres of excellence have not played a strong role for national champions, but other national companies have local technology linkages to centres of excellence, such as Shenyang University of Technology.[6]

With a slow take off in the 1980s, the Indian market has now become the fifth largest in the world (BTM, 2010). The domestic industry developed through conventional and unconventional transfer of technology. Production facilities have been set up by foreign wind turbine and key component manufacturers both as joint ventures and wholly owned subsidiaries (Mizuno, 2007). While there are more than 30 Indian wind turbine manufacturers, the uncontested national wind power champion is Suzlon and is responsible for almost half of the installed capacity in India (C-WET, 2009). Suzlon entered the business through license agreements to manufacture turbines and blades from Aerpac and Enron Wind. However, Suzlon moved away from the license strategy and acquired AE-Rotor (blades), Hansen Transmissions (gearboxes) and REpower (offshore turbines and R&D). It also established a joint venture with Austrian Elin to co-design wind turbine generators. Suzlon now has state-of-the-art technology and R&D facilities in Germany and has become the world's fifth largest turbine manufacturer (BTM, 2010). In addition to conventional (licensing) and unconventional (foreign acquisition, joint R&D and overseas in-house R&D) technology transfers, Suzlon is also embarking heavily on in-house R&D in India (Lewis, 2007).

Substantial contributors to the development of the Indian wind energy industry are interactive learning in the local innovation system, for instance with quality testing and standard setting provided by the Centre for Wind Energy Technology. Although there is still a gap to the world

Table 2. Technology transfer and localised innovation in wind power (summary).

Technology transfer		Other mechanisms
Conventional mechanisms	Unconventional mechanisms	Localised innovation
Trade (capital imports): Was of considerable importance in early stages. Now relatively unimportant as most turbines are based on high degrees of locally produced components *Inward FDI:* Was of high importance for industry formation. Spillover effects to local industry are not documented. *Joint ventures*: Were of some importance at the industry level during formative phase and continue to play a role, but mostly in the supply base. Few champions engaged in local joint ventures (Suzlon). *Licensing*: Was very important for 'take off' for local turbine manufacturing and continues to play a role (Goldwind, Sinovel, Dongfang, Suzlon)	*Joint R&D:* has become very important as initial technology licensing arrangements have evolved into co-design partnerships (Goldwind, Sinovel, Dongfang, Suzlon) *Foreign acquisitions*: are now central to the technological learning and innovation strategies of key national champions (Goldwind, Suzlon). *Overseas R&D (OFDI)*: is now undertaken on a significant scale in champion firms (Goldwind, Suzlon)	*In-house R&D*: is now undertaken by all national champions, including for offshore deployment (Goldwind, Sinovel, Dongfang, Suzlon) *Local technology linkages*: have become increasingly important, as national industries and institutional support structures have matured (Suzlon)

technological frontier, Kristinsson and Rao (2008) argue that the 'innovation system' performs an important supportive role in the catch-up process (see also Rajsekhar et al., 1999; Mizuno, 2007).

China and India have both developed globally leading national wind power champions. In both countries, the industry formation phases from the 1980s were characterised by capital imports and the industries emerged as a combination of FDI and licensing strategies by local companies. However, as the national champions have entered a catch-up phase they began to mix transfer strategies and localised innovation and shifted towards unconventional technology transfer (Table 2).

3.2. *The solar PV sector*

Both China and India have rapidly built national solar PV industries with notable catching up, but China is taking the lead with major global-scale companies and technological capabilities (Fu and Zhang, 2011).

China's PV industry has moved from component supply to production of complete panels and has become the world's largest producer of solar PV cells (Liu et al., 2009; Fischer, 2012; Kirkegaard et al., 2010). With a 98% export share, foreign markets drive Chinese companies and the success is one of export-oriented technological upgrading (Fu and Zhang, 2011). However, the home market is picking up through subsidies of 50–70% of total solar PV investments (Climate Group, 2009; Howell et al., 2010).

By 2009, three Chinese national champions reached global sales top 10 (Hirshman, 2010; Climate Group, 2009). The Chinese leader, Suntech Power, emerged with a mix of local technology and international technology transfer and managed to become second in the world. World-

class technological expertise was developed with in-house R&D combined with various mechanisms – licensing, a joint venture, overseas FDI and acquisitions, and collaboration with the University of New South Wales (BCG, 2010). Suntech also has local technology cooperation linkages with research institutions, such as Sun Yat-sen University and Shanghai University of Technology.

Trina Solar have established a government supported R&D 'State Key Laboratory' and cooperates with key suppliers as well as local universities and research institutions. The company has reported to invest 10 billion Yuan in R&D over five years, corresponding to about 5% of expected revenue. In addition to local innovation, Trina has strong international technology linkages including R&D cooperation with MIT in the US, Australia National University and Singapore's national institute for applied solar energy research.

Yingli Solar's trajectory is similar. On the one hand Yingly has in-house R&D, local R&D cooperation and acquisitions backwards in the supply chain. On the other hand, it has research agreements with centres of excellence and technology companies in The Netherlands and has opened a facility in Singapore to do overseas in-house R&D.

India's solar PV sector has transformed from mainly public supply and demand in the 1970s to private technology and production capacity by the late 1980s (Bhargava, 2009; Kathuria, 2002). When demand from state-owned enterprises ceased in the 1990s, solar producers sought export markets which now take about 75% of PV output (Srinivasan, 2005; Mallett et al., 2009).

Moser Baer is one major player that has used unconventional technology transfer strategies such as strategic and equity alliances with foreign solar technology companies, in addition to conventional licensing of thin film photovoltaic technology. Moser Baer also undertakes significant overseas in-house R&D in The Netherlands as well as jointly with various overseas research institutions. Within India, Moser Baer has close linkages to research institutions, including the National Chemical Lab, the National Physical Laboratory and the Indian Institute of Technology Kanpur.

HHV Solar use in-house R&D as the primary source of technology and also engage in crystalline and thin film solar cell and module technology, of which the majority is locally developed (ISA, 2008). TATA Power has followed a more conventional technology transfer route. Since 1989, it has engaged in a joint venture with British BP Solar for marketing a wide range of solar photovoltaic solutions in India.

Indian manufacturers have used licensing or external, expired patents for mono- and multi-crystalline silicon cells (Mallett et al., 2009). However, Indian companies have also used a wider range of mechanisms including joint ventures, R&D cooperation, foreign acquisitions and in-house R&D. Links to foreign technology-firms are strong, but Mallett et al. (2009, p. 73) argue that 'Indian firms actively drive the process and so play more a leadership role in the technology transfer process'. Collaboration with national research institutions and in-house R&D has proved important to pick up and refine technologies, produce at a low cost and engage in own patenting.

Both countries have experienced a mix of conventional and unconventional technology transfer with an emphasis on the latter in recent years (Table 3). Localised innovation has been a very strong contributor to technological capabilities in this sector in India and China (Fu and Zhang, 2011). Most firms are predominantly export oriented, have played an important role in global supply chains driving down costs and contributed to mitigation at a global level (Fischer, 2012).

3.3. *Electric and hybrid electric vehicles*

With a number of preferential policies, China aims to become the leading producer of plug-in hybrid and electric passenger vehicles with about 5% of China's new vehicle sales by 2015.

Table 3. Technology transfer and localised innovation in Solar PV (summary).

Technology transfer		Other mechanisms
Conventional mechanisms	Unconventional mechanisms	Localised innovation
Trade (capital imports): has played a limited role as these industries focus on exports for global markets. *Inward FDI:* has not been important to industry formation but is beginning to occur in the catch-up phase, especially in China. *Joint ventures*: are not significant in the industrial structure but have played a major role in the Indian take-of (TATA BP Solar). Some companies are using overseas joint ventures to access technology and foreign markets (Moser Baer). *Licensing*: was very important for the take off and continues to play some role during to access advanced PV technologies such as thin film (Suntech; Moser Baer).	*Joint R&D:* has played a role in the overall industry formation although with a practical impact for few champion firms (Moser Baer). *Foreign acquisitions*: has become important to access advanced foreign technology by leading champion firms (Suntech; Moser Baer) *Overseas R&D (OFDI)*: was of limited importance during the take of, but champion firms are increasing overseas R&D and cooperation with research institutions (Suntech; Moser Baer).	*In-house R&D*: has been and continues to be very important in almost all champion firms in combination with conventional and unconventional technology transfer strategies (Suntech, Yingli, Trina Solar; Moser Baer, HHV Solar). *Local technology linkages*: had a limited practical impact during take off, but has now become important to complement in-house R&D (Suntech, Trina, Yingli; Moser Baer).

The government has within a decade provided about 2 billion Yuan in R&D and demonstration support and a tenfold increase in public R&D and demand side support for the coming decade has been reported (Watson et al. 2011). China is already the leading producer of rechargeable batteries – a key technology, in the electric vehicle value chain (IEA, 2009; MOF and MOST, 2009). Q2

There are important examples of conventional technology transfer in this sector. Joint ventures emerged largely as a response to the combination of two circumstances. First a 'market pull' was driven by mandatory emissions standards – currently stricter than those in the US. Second, government legislation dictates that entry by foreign auto companies requires Chinese majority share joint ventures.

China's largest auto manufacturer, state-owned SAIC has established electric car joint ventures with an US lithium-ion battery company and with Volkswagen. Also, SAIC established a joint development facility in China assisting in designing General Motors's hybrid and all electric vehicle technology. Another international linkage is SAIC's overseas R&D through its acquisition of a UK company. SAIC is also developing an electronic drive system through in-house R&D (Wang, 2009).

Several companies have relied on in-house R&D rather than technology transfer to develop electric and hybrid vehicles, especially small-car versions (People's Daily Online, 2009; IEA, 2009). Chery Auto have developed and commercialised a small electric car based on own technological resources.

BYD acquired a small Chinese car manufacturer and started intensive in-house R&D to combine its lithium-ion battery technology with car making. BYD's all localised innovation approach introduced the first plug-in hybrid electric vehicle in 2008. BYD has now established a R&D joint venture in which it will bring together Daimler's car platform and BYD's battery and

electric motor technology to co-design electric vehicles under a joint brand (BYD, 2010). Thus for BYD, technology transfer has intensified *after* the building up of an in-house innovation platform.

A number of Indian electric and hybrid vehicle manufacturers have road-ready or demonstration models, including three leading car companies: REVA, TATA Motors and Bharat Heavy Electricals Limited. These companies are not at the technological frontier of the global market but are evolving through a mix of mechanisms, including in-house R&D, licensing, joint ventures and joint development with foreign firms.

An example of a non-transfer route is Bharat Heavy Electricals Limited which has developed electric buses, vans and special purpose vehicles for the government sector through in-house R&D (Awasthi, 2009). On the other hand, Tata Motors has used an unconventional technology transfer strategy by acquiring a majority stake of a Norwegian lithium-ion battery technology developer to utilise this foreign technology in Tata's car platform to design an electric car (Mallett et al., 2009).

REVA, an Indo-US R&D joint venture, brought together electric vehicle expertise from both organisations, but was established to conduct in-house R&D in combination with external R&D collaboration (Bajaj, 2009; Menon, 2009). REVA now markets own-brand electric vehicles and reportedly has more electrical vehicles on the global market than any other player in the industry. REVA started as a R&D joint venture, a strategic *licensee* of patents coupled with an intensive in-house R&D (about 7% of annual turnover) with the result of building strong technology with which it now carries out R&D collaboration and has become a *licensor* (Maini, 2005).

China and India's electric and hybrid auto industries are younger than wind power and solar PV and reflect that the global market is less developed. The sector is also special in that local technology linkages are less developed, but companies have very strong in-house R&D. The Chinese case has some foreign technology linkages (especially joint R&D) but is less a 'transfer' case than a 'localised innovation' case. India's trajectory emerged closer to conventional technology transfer with joint ventures and licensing, although unconventional transfer mechanisms such as joint R&D, foreign acquisitions and overseas R&D are also, if not more, important during catch-up (Table 4).

Table 4. Technology transfer and localised innovation in Electric and Hybrid vehicles (summary).

Technology transfer		Other mechanisms
Conventional mechanisms	Unconventional mechanisms	Localised innovation
Trade (capital imports): has played a limited role because manufacturing is highly localised. *Inward FDI:* has played some role although the core technology tend to be nested in and around the headquarters of large car manufacturers *Joint ventures*: are important to link smaller companies to foreign technology companies (SAIC; REVA) *Licensing*: Does occur but is not very important for champion firms across the board (REVA)	*Joint R&D:* has become very significant for some companies and it seems that top companies especially in this sector are partners with equal or superior technological capabilities in partnerships (BYD; REVA) *Foreign acquisitions*: is not a common strategy across the board but has served as an entry strategy in some cases (TATA) *Overseas R&D (OFDI)*: is rather limited but is sometimes used in combination with foreign acquisitions (TATA)	*In-house R&D*: is carried out by all identified national champions and appears to be the central strategy of most champions firms (BYD, Chery Auto, SAIC, REVA, TATA, BHEL) *Local technology linkages*: have played fairly a limited role in this sector with no apparent evidenced of R&D relationships between firms and local institutions

Table 5. Importance of different technology transfer mechanisms over time.

Group	Specific organisational arrangement	Formative phase	Catch-up phase
Conventional mechanisms	Trade(imports)	****	**
	FDI/Joint ventures	****	***
	Technology licensing	****	****
Unconventional mechanisms	Joint R&D with MNC	**	****
	Overseas R&D lab	**	****
	Cross-border M&A	**	****
Localised innovation	Local technology linkages	**	****
	In-house R&D	****	*****

Source: Drawing on tables 2-4 in this section. Note: This table is meant as a summary and does not reflect the full complexity and variety. We have used the following classification system to describe the organisational arrangements:
* = low
** = low and medium
*** = medium
**** = medium and high
***** = high

3.4 *Summary of the insights*

Three main conclusions arise from the analysis in this section: First, these three key green technology sectors in India and China are managing the transition from simple production to innovation capability. While there are differences between sectors, the technological gap between China and India and so-called advanced economies is now small and decreasing.[7]

Second, unconventional technology transfer mechanisms were very important in most cases and this importance tended to increase over time. The crucial ingredients were rarely knowledge embodied in 'hardware'. In recent years, the crucial ingredients were people-embodied knowledge, acquired through R&D networks and overseas investments in firms and technology alliances. However, the unconventional mechanisms played a more important role in the catch-up phase than in the take-off phase. Licensing often performed as a stepping stone. The cases reveal that it is a matter of sequence. This is illustrated in Table 5, showing the relative importance of different mechanisms in the formative and catch-up phases.

Third, technology transfer was only one element in the development of these green technology champions. Endogenous technology creation was crucially important as (i) a prerequisite (in creating absorptive capacity), (ii) a complement and (iii) an alternative to technology transfer. There is also evidence which suggests that localised innovation has increased in importance. It has interacted with learning in global innovation networks (for example cooperation with design houses) and it has partly substituted such networks (for example, creation of own designs). The next section draws out some of the central implications of these three conclusions.

4. The relevance of technology transfer

In this section we discuss the relevance of our empirical findings with respect to the notion of technology transfer in the low carbon policy debate. We argue that this debate has taken its point of departure in a 'narrow view' of technology transfer. This view derives from the early transfer literature and conventional economics (Krugman, 1979; Grossman and Helpman, 1995; Romer, 1994; Jian-Ye, 1990) and discernible in numerous climate change reports and studies (Ueno, 2009; Commission on Growth and Development, 2008; IPCC, 2007; World Bank, 2010). In Table 6, the narrow view is contrasted with a 'broad view' which derives from innovation studies (Lundvall et al., 2002; Nelson, 2011) and the literature on technological learning and catching up (Fu et al., 2011; Lall, 1993; Ernst and Kim, 2002).

Table 6. Contrasting perspectives on technology transfer.

	Narrow View	Broad View
1: Developed and developing countries	• The global economy is divided between innovating (developed) and non-innovating (developing) economies.	• The simple distinctions between innovating and non-innovating economies is misleading
2:Technological innovation and diffusion	• The notion of technological innovation refers to global novelties (new to the world innovations);these are usually derived from science, research and experimental development • Innovation and diffusion are separate and distinguishable processes	• Innovation consists not only of global novelties but also of incremental improvements (e.g. new to the firm or country); these are often made in the organisations that undertake production. • The distinction between innovation and diffusion is blurred and often misleading
3: Cross border interaction	• The content of technology transfer consists mainly of tangible assets and skills and know-how for operation and maintenance • Technology transfer is essentially a process of one-way flows between exporters and importers of technology • The organisational arrangements for technology transfer are largely confined to 'conventional mechanism'.	• Effective 'transfer' of technology is likely to include not only artefacts but also people-embodied knowledge as well as organisational assets • Effective transfer is an interactive process • Different organisational arrangements are needed for different types and degrees of knowledge and capability acquisition
4: Localised innovation – recipient efforts and investment in capability	• Technology transfer (importing) involves merely choosing adopting, and occasionally adapting technologies • Technology transfer and localised innovation are alternatives	• Technology transfer is usually much more creative and complex than simply choosing, purchasing and adopting technology • Effective transfer rests on recipient efforts and investments in capability within firms and in innovation systems. • Technology transfer and localised innovation are complementary activities; these are combined in the process of technological learning

Sources: Drawing on Bell (2009, 39–42) and references cited in sections 2 and 5.

The argument is not that elements of the broad view are absent in the climate technology debate. As will also be discussed, the broad view is slowly gaining ground. However, the narrow views' conceptions of developed vs. developing countries (row 1) and innovation vs. diffusion (row 2) has important implications for the thinking of cross-border interaction (row 3) and localised innovation (row 4). The remainder of this section discusses the dimensions of Table 6 in relation to our analysis.

4.1 *The distinction between developed and developing countries*

There is overall agreement on the crucial role of technology in climate change mitigation and the increasing importance of mitigation in emerging economies. However, we argue that the

dominance of the 'narrow view' of technology transfer in the policy debate means that core 'discourses' becomes overly simplified. The World Bank's report on 'Development and Climate Change' illustrates this tendency:

> *Developed countries* have produced most of the emissions of the past and have high per capita emissions. These countries *should lead the way* by significantly reducing their carbon footprints and stimulating *research into green alternatives*. Yet most of the world's future emissions will be generated in the *developing world*. These countries will *need adequate funds* and *technology transfer* so they can pursue lower carbon paths—without jeopardizing their development prospects. (World Bank, 2010, pp. 13–14, emphasis added)

This passage illustrates how the narrow view draws on a stark distinction between those who 'lead the way' and those who need 'technology transfer'. This rests on the notion that 'most technologies are still mainly developed and first deployed in the industrialised world' (Schneider et al., 2008, p. 2931; see also IPCC, 2007; Ueno, 2009; Tomlinson et al., 2008, p. 56). Such a binary worldview of innovating and non-innovating economies is evident in much of the influential literature on technology transfer (Commission on Growth and Development, 2008; World Bank, 2008, 2010).

However, as was shown in the previous section, China and India – countries that still have relatively low per capita incomes compared to OECD countries – have now acquired considerable technological capacity (Stamm et al., 2009, p. 22). This means that the distinction between innovating (developed) and non-innovating (developing) countries is deceptive for the technology debate. While this is particularly true in the context of emerging economies, it applies more broadly. To bring this out, it is necessary to consider critically the meaning of the terms 'innovation' and 'diffusion'.

4.2 *Technological innovation and diffusion*

The narrow view tends to equate innovation with novelties. The World Bank (2010) quote above highlights the important role of formal 'research into green alternatives'. Drawing implicitly on the linear model of innovation, the narrow view tends to see research as the key route to create 'new to the world' innovations required to tackle global warming (World Bank, 2008). It further distinguishes the innovation process (in developed countries) – undertaking research and creating new products – and then the subsequent diffusion activity of *transferring* the results to developing countries. In short, innovation and diffusion are two separable processes.

Our analysis questions this view. The firms in India and China drew heavily on flows of transferable technology which were 'diffused' from developed countries, but this was in itself an innovative process. It created technological solutions that were 'new to the firm' and it involved creative interaction and reshaping of external knowledge. This means that the process of adopting and adapting technologies was not a simple process of 'diffusion' in the way this process is sometimes conceptualised. Acquiring capabilities involved a pervasive occurrence of creative change in recipient organisation which is best described as a process of innovation. In short, innovation and diffusion was not separate processes.[8]

The analysis also suggests that while 'research into green alternatives' may play an important role in advancing the frontier, the research lab is not the only locus of innovation. 'Innovation' is more than 'science'. This analysis has suggested that in building green technology capabilities, scientific research was only one element among a number of mechanisms involved. In fact, research within the science sector was not central to the catch- up process in these sectors and countries.

It is worth noting the differences in policy emphasis that follow the contrasting views. Because of the capability gap, proponents of the narrow view believe it is most efficient if OECD countries with stronger capabilities engage in technological innovation, and developing countries merely use the 'results'. This implies that innovation in developing countries is costly and inefficient so technology transfer (diffusion) is preferable until developed country status is reached. It tends to underemphasise the importance of supporting innovation in developing countries because 'actual installation of mitigation technologies can reduce emissions, regardless of their origin' (Ueno, 2009, p. 3).

By contrast, the broad view maintains that support for innovation is important because efficient 'diffusion' involves creative shaping of technologies also in developing countries. The formation of green technology sectors in China and India relied much less on simply purchasing equipment and simple know-how than on a creative process of knowledge absorption that is essentially a learning and innovation process. The resulting policy focus is one that is primarily concerned with supporting technological learning.

The typical conceptualisation of innovation and diffusion in the climate change technology debate has important follow-on implications with regard to the thinking about cross-border interaction and localised innovation and we discuss them in the remainder of this section.

4.3 *Cross-border interaction*

Some of the technology transfer discussion seems to be mainly about shipping ready-to-use equipment to developing countries and combining this with knowledge for operation and maintenance – not with the deeper capabilities which is fundamental to technologic change.

The report on technology transfer by the Intergovernmental Panel on Climate Change (IPCC) states that climate change mitigation: 'will require rapid and widespread transfer and implementation of technologies, including know-how for mitigation of greenhouse gas emissions' (IPCC, 2000, p. 3, emphasis added). The IPCC emphasises the transfer of *know-how* as opposed to *know-why* which is required for effective innovation (Lundvall and Johnson, 1994).

Also in line with the narrow view is the UNFCCC's (1992, Article 4.5) emphasis on facilitating 'transfer of, or access to, environmentally sound' technology and know-how. The discourse of the UNFCCC largely emphasises flows to developing countries of embodied technology and skills required to operate imported technology (Ockwell et al., 2010), i.e. flows i and ii as defined in Section 2.

Developing economies seem to be viewed mainly as *consumers* of technology which is developed in the North (UNFCCC, 1992, 2002; World Bank, 2010). As discussed, this policy approach draws on a concept of diffusion, which is distinct from innovation, and therefore on the mechanisms thought central to the envisaged one-way technology 'hand-off'.

This relates closely to the 'mechanisms' discussed in this paper. A large number of studies see conventional mechanisms as the main vehicles of technology transfer (e.g. Less and McMillan, 2005; Ueno, 2009; World Bank, 2008; Popp, 2011). As stated by Schneider et al. (Schneider et al., 2008): 'The main channels of private sector technology transfer are trade, licensing, and foreign direct investment' (Schneider et al., 2008, p. 2931).

All of these one-way mechanisms have been involved in the development process in the green technology sectors in China and India. However, they have primarily been important to industry formation. They have been less significant in contributing to core skills and capabilities that have been essential to the technological prowess and the cost innovation (Zeng and Williamson, 2007) which lies behind technological upgrading and fast deployment of wind-power and green vehicles (electric two-wheelers in China), and export of solar PV panels.

Firm centred cross-border interaction is under-emphasised in the technology transfer debate but has been of central importance in the cases reviewed. The critical factor was flows of knowledge, experience and expertise for generating and managing technological change (flow iii). Such knowledge is inherently difficult to 'move' across space because it is often tacit and built up in an interactive, cumulative and path dependent way (Ernst and Kim, 2002). However, 'thick' linkages that facilitate two-way flows (interaction) make 'transfer' possible.

It is interesting to note the dynamic nature of cross-border interaction. For instance, relationships that started out as one-way licensing arrangements have changed into co-design arrangements. FDI investments that were originally focused solely on producing and selling technology developed in OECD countries are now platforms for technology R&D relevant for the global market. Overall the cases suggested that conventional forms of cross-border interaction were important in early stages of formation. In later stages, a combination of conventional and unconventional forms was utilised. The core insight in this respect is that different organisational arrangements are needed during different stages of technological learning. Networks and mechanisms become more complex and demanding over time as sectors mature (Dantas and Bell, 2011; Fu and Zhang, 2011).

4.4 *Localised innovation*

This subsection continues the discussion of our findings in relation to the narrow view, but we turn the attention the role of internal effort and investment and localised innovation in firms ('in-house R&D') and innovation systems ('local technology linkages').

The analysis suggested that overall, China and India did not rely solely (or even mainly) on external green technology. In the three sectors, in-house effort and investment in innovation was a key determinant of the speed and depth of technological learning. The trajectories of national champion firms have integrated internal technology development efforts with the acquisition of skills and knowledge from outside in a cumulative process. Leading firms are increasingly global and they perform a key function in pulling together local and global knowledge flows for creating and putting green technology in use. The important role of localised innovation is unsurprising, but it is not always given sufficient attention.

However, a substantial body of literature (Ernst and Kim, 2002; Lall, 1993; Bell, 2009) has shown the limitations of the idea that 'technology importers' only need to choose and absorb technology that is available elsewhere. As stressed earlier, the innovation literature has shown that this process is not at all trivial and involves significant investments in knowledge, experimentation and organisational routines.

But rapid development also depended on implementation of green technology support mechanisms such as feed-in tariffs (creating demand) and public investment in training and R&D (helping supply). Over time, local technology linkages such as collaborative R&D between firms and research institutes became important elements of the upgrading model, particularly in wind and solar but also, to some extent, in green vehicles.

The analysis provides two main insights. First, global linkages ('technology transfer') and local innovation systems were not alternatives as is sometimes implied. Local and global flows were supplementary 'mechanism' in both the formation and catch-up phases. Second, capability building in firms was a prerequisite for local linkage formation – not the other way around. Champion firms benefited from linkages with national research institutions but as with international technology transfer, the key point is about sequencing and evolution. R&D linkages – local and global – only became important once the sectors were beyond the formation phase.

Technology 'transfer' can hardly be understood in isolation because the use of external *technologies and local learning* were *complementary* elements that were combined in the

technological upgrading process. These points may seem trivial to innovation scholars. However, they are of great importance in relation to climate policy and will be discussed further in the concluding section.

5. Conclusion

The starting point for this paper was the connection between the mounting shift from production to innovation capability in China and India (Altenburg et al., 2008; Ely and Scoones, 2009) and the debate over the global transfer of green technology (Ockwell et al., 2008; Schneider et al., 2008; IPCC, 2007). It is often sometimes argued that the rise of China and India in green technology is overstated (Watson 2011). We agree that there is a gap to the frontier and that the catch-up is uneven among sectors and countries. However, the gap is now relatively small and decreasing. As China and India transcend from users to producers and innovators of green technology, this has increasingly important implications for the global low carbon technology transfer debate and policy process.

5.1 *How much mileage is left in technology transfer?*

The implication of the analysis in this paper is that there is limited *practical mileage* left in the conventional approach to technology transfer in the chosen sectors in India and China. The conventional narrow technology transfer focus on trade in capital equipment, traditional FDI and licensing (e.g. Schneider et al., 2008) is increasingly obsolete in these countries. The notion of technology transfer was introduced by economists more than 50 years ago, a time when it was difficult to see beyond trade, FDI and licensing. While these channels are still important they are used in new ways and they are increasingly being supplemented and surpassed by new mechanisms.

China and India's cross-border technology relations have evolved significantly over the last 10years with the effect that unconventional mechanisms such as investment in internal R&D, global R&D collaboration and outward knowledge-seeking FDI are increasingly important. While the notion of technology transfer is inherently problematic, the limits of the concept are-deepened by the way globalisation and economic development in China and India have changed the ways technological capability accumulation now takes place in these countries.[9] Both countries seek to take full advantage of these changes by making their own investments.

Our analysis is relevant beyond China and India because it suggests that there is also limited *analytical mileage* left in the conventional technology transfer concept. In reality, technology can be 'transferred' only in a very narrow sense and only provided that one adopts a narrow and outdated notion of technology development, learning and innovation. Capabilities are *built* and *acquired* rather than *transferred* (Bell, 2009; Lall, 1993). The emphasis on *transfer* of mitigation technology could be complemented and sometimes replaced by international *collaboration* and local *innovation.*

5.2 *Technology and climate change policy*

The findings of this analysis have important implications for the technology transfer debate, not least under the UNFCCC. The UNFCCC approach to technology transfer is mainly focused on the provision of information regarding available climate change mitigation and adaptation technology, rather than practical transfer mechanisms and learning (Thorne, 2008; Ockwell et al., 2010).[10] Although tackling climate change requires catching up and innovation in green technologies in the developing world, this receives inadequate attention in the technology transfer

discussion. The analyses in this paper lead us to suggest that the international technology approach of the UNFCCC and other multilateral organisations needs reorientation in three important ways.

First, our main argument is that the international dimension of technological learning requires more than information of available technology alternatives and financial support to mitigation. However, the core UNFCCC agreements (UNFCCC, 1992, 2002) largely reflect a narrow view of technology and its global mobility; overall the debates in the negotiation rooms are similarly narrow in scope. A discourse shift is slowly underway within the UNFCCC, but has not moved far into the sphere of policy formulation. There has been little and inadequate negotiation over the definition of 'technology collaboration', what it should achieve and the mechanisms to underpin it. Policies and initiatives need to go beyond the typical focus on framework conditions for trade, FDI and arms-length licensing (e.g. World Bank, 2010). New sources and organisational arrangements are becoming increasingly important for technological learning in many countries, in particular in China and India.

Second, the emerging focus on localised learning and innovation in UNFCCC policy (2007, 2010) could be strengthened and integrated into the framework with equal weight as international technology collaboration. So far the framework has had only little focus on local capability formation overall (Ockwell et al., 2010). Where capability formation and strengthening has been an explicit goal within bilateral and multilateral arrangements, it has tended to focus on support for public sector R&D institutions. By contrast, private sector organisations have been underemphasised because the targeted strengthening of firms remains controversial. In fact, the global climate technology discussion largely ignores the established insight that 'for countries aiming to catch up, developing the capabilities for learning and innovation *in firms* is the heart of the challenge' (Nelson, 2011, p. 48, emphasis added). Specialised R&D organisations can play a very important role, but firm capability remains a central prerequisite for interactive learning and innovation (Bell, 2009; Lall, 1990).

Third, the distinction within the UNFCCC framework (1992) between Annex 1 Countries (developed) and non-Annex 1 Countries (developing) does not seem conducive to progress with respect to technology arrangements for climate change mitigation. Policies that work for China and India may be very different for countries with other needs. Particularly in least developed countries more basic capability building remains important in many green technology sectors. So far, the BASIC countries (Brazil, South Africa, India and China) have only been an informal negotiation group within the UNFCCC process. However, the pressing question is whether it is now time to introduce new country classifications into the framework.

5.3 *Limitations and issues for further research*

In this paper we have questioned the relevance of the conventional approach to technology transfer in green technology sectors in China and India. In assessing the scope and weight of our key points, it is important to have in mind that we have focused mainly on national champions and that the focus on three 'new' sectors was narrow. For example, it remains an open question whether a similar conclusion would be reached in studies of mainstream power generation such as higher efficiency coal fired power generation, carbon capture and storage or energy efficiency technologies in buildings and industrial production. Some of the greatest opportunities for low carbon innovation are perhaps in materials-intensive and energy-intensive sectors. In these areas, China and India still seem to be lagging considerably behind levels of efficiency in OECD countries (IEA, 2010).

These reservations need to be acknowledged but the insights of this paper do nevertheless have implications that should be explored in further research. There is a global trend in which

innovation is decomposing and decentralising within and beyond multinational corporations and specialised technology firms (Lema et al., 2012). The question is how decomposed and open innovation (Lema, 2010; Srinivas, 2011) affect the building up of advanced green innovation capabilities in the developing world. This paper suggests implicitly that these trends have been a precondition for unconventional technology transfer, but further research should address this question directly.

Moreover, a key question for research is whether technologies developed under national policy agendas and factor endowments specific to emerging economies will be more adequate for least developed countries in Africa and Asia than those developed in the OECD countries (Stamm et al., 2009, p. 22).

Research into these issues is needed because much of the previous debate has been over the *scale* of innovation capability building as opposed to the *direction* (Bell, 2009). The notion of technology transfer implies an adherence to given technological paths, but the key need is for new trajectories (Altenburg and Pegels, 2012). As China and India gradually move 'beyond' catch-up, these countries may already be pushing the green technological frontier in new directions.

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Notes

1. We recognise in our introduction that effective mitigation will require changes in a much wider range of sectors including conventional energy and transport systems, heavy industry, construction, etc, but it is not the focus of this paper.
2. It is important to emphasise that – even as ideal types – these mechanism classifications are not absolute categories. There is a continuum between conventional and unconventional mechanisms.
3. However, it needs to be stressed that there is also large degree of variability – meaning that there is no straightforward relationship between the different mechanisms and the acquisition of different types of capability. It depends on strategic intent and the way the transfer mechanisms are organised and managed.
4. Firm-internal R&D is an imprecise proxy for firm-internal technological activity. The reason for focusing on R&D – rather than a broader array of technological activities (including non-R&D activities) – is merely operational. We did not conduct fieldwork but relied on information in the press and on websites. Such sources often mention R&D projects, but rarely other types of innovative activities.
5. The analyses in this section draw on existing literature and company sources in the public domain. The micro-level components of the analyses and the underlying information about individual companies are based on company websites and documents unless otherwise cited.
6. Some foreign companies also engage in local R&D. Vestas have established an R&D centre Beijing, tapping into the wind competences being built in China and signalling commitment to technology development in China (Lema et al., 2011).
7. This corresponds with patent data. In renewable energy and electric and hybrid vehicles, China and India are increasing patenting activity and have shown a strong growth in patent applications from 1999 to 2008, although from low levels. What is also worth noting is that China and India have higher shares of renewable energy in overall patent applications than the OECD average (OECD 2011). However, the available data does not show a shift from patenting by foreign subsidiaries to national companies (Lee et al., 2009; UNEP, 2010).
8. This issue is not just definitional. The emphasis on the narrow view comes at the cost of neglecting the important role of incremental and other types of innovation that clearly mattered for climate change mitigation in these cases. The key process was not about adopting technological breakthroughs but

more about adopting (and increasingly contributing to) incremental innovations, such as those that improve key performance indicators in the wind or solar power technology industries.

9. Prospects of gaining increased access to enormous markets in India and China seem to have motivated foreign players to 'share' their knowledge collaborative relationships. They may be less motivated to do so in smaller countries with less bargaining power.
10. Recent Conference of the Parties (COPs) introduced the planned establishment of a Climate Technology Centre and Network and a Technology Executive Committee. However, the details of these initiatives have not yet been specified in detail.

References

Altenburg, T., and Pegels, A. (2012) Sustainability-oriented innovation systems – managing the green transformation. *Submitted to Innovation and Development*, forthcoming 2012.

Altenburg, T., Schmitz, H., and Stamm, A. (2008) Breakthrough China's and India's transition from production to innovation. *World Development*, 36, pp. 325–34. **Q5**

Awasthi, S.R. (2009) Development of reneable energy technoloogies in India: The role of BHEL. *Akshay Urja Renewable Energy. A newsletter of Ministry of New and Renewable Energy*, 2, pp. 26–33.

Bajaj, V. (2009) The tiny leader of the pack. *New York Times*, October 28. **Q6**

BCG (2010) Sunrise in the east: China's advance in solar PV-and the competitive implications for the industry. Boston Consulting Group.

Bell, M. (1990) Continuing industrialisation, climate change and international technology transfer (Brighton: Science Policy Research Unit, Sussex University).

Bell, M. (2009) Innovation capabilities and directions of development *STEPS Working Paper* (Brighton: STEPS Centre).

Bhargava, B. (2009) Overview of photovoltaic technologies in India. *Solar Energy Materials and Solar Cells*, 67, pp. 639–646. **Q7**

BTM (2010) , World market update 2009. BTM Consult Ringkøbing, Denmark.

BYD (2010) , Green tech for tomorrow. Annual report 2009. BYD Company Limited.

C-WET (2009) *Manufacturers-wise wind electric generators installed in India (As on 31.03.2009)* available at: http://www.cwet.tn.nic.in accessed May 2010.

Climate Group, T. (2009) China's clean revolution II: Opportunities for a low carbon future.

Commission on Growth and Development (2008) The growth report: Strategies for sustained growth and inclusive development. World Bank on behalf of the Commission on Growth and Development, Washington, DC.

Dantas, E., and Bell, M. (2011) The co-evolution of firm-centered knowledge networks and capabilities in late industrializing countries: The case of petrobras in the offshore oil innovation system in Brazil. *World Development*, 39, pp. 1570–1591. **Q8**

Ely, A., and Scoones, I. (2009) The global redistribution of innovation: Lessons from China and India. *STEPS Working Paper* 22, STEPS Centre, Brighton.

Ernst, D., and Kim, L. (2002) Global production networks, knowledge diffusion and local capability formation. *Research Policy*, 31, pp. 1417–1429. **Q9**

Fischer, D. (2012) Challenges of low carbon technology diffusion: Insights from shifts in China's photovoltaic industry development. *Innovation and Development*, forthcoming 2012.

Fu, X., Pietrobelli, C., and Soete, L. (2011) The role of foreign technology and indigenous innovation in the emerging economies: Technological change and catching-up. *World Development*, 39, pp. 1204–1212. **Q10**

Fu, X., and Zhang, J. (2011) Technology transfer, indigenous innovation and leapfrogging in green technology: The solar-PV industry in China and India. *Journal of Chinese Economic and Business Studies*, 9, pp. 329–347. **Q11**

Grossman, G.M., and Helpman, E. (1995) Technology and trade, in: M.G. Gene and R. Kenneth (eds) *Handbook of International Economics.* (Elsevier). **Q12**

Hirshman, W.P. (2010) Surprise, surprise (Cell Production 2009: survey). *Photon International*. **Q13**

Howell, T.R., Noellert, W.A., Hume, G., and Wolff, A.W. (2010) China's promotion of the renewable electric power equipment industry (Washington: Dewey & LeBoeuf LLP for the National Foreign Trade Council).

IEA (2009) Technology roadmaps electric and plug-in hybrid electric vehicles. International Energy Agency, Paris.

IEA (2010) Energy technology perspectives 2010: Scenarios & strategies to 2050. International Energy Agency, Paris.

IPCC (2000) Methodological and technological issues in technology transfer. Intergovernmental Panel on Climate Change. Working Group III, Cambridge.
IPCC (2007) *Mitigation of climate change* (Cambridge, NY: Cambridge University Press).
ISA (2008) Solar PV industry: Global and Indian scenario. India Semiconductor Association, New Delhi.
Jian-Ye, W. (1990) Growth, technology transfer, and the long-run theory of international capital movements. *Journal of International Economics*, 29, pp. 255–271. **Q14**
Kathuria, V. (2002) Technology transfer for GHG reduction – A framework with application to India. *Technological Forecasting and Social Change*, 69, pp. 405–430. **Q15**
Kirkegaard, J.F., Thilo, H., Lutz, W., and Matt, M. (2010) Toward a sunny future Global integration in the solar PV industry. Peterson Institute for International Economics.
Kristinsson, K., and Rao, R. (2008) Interactive learning or technology transfer as a way to catch-up? Analysing the wind energy industry in Denmark and India. *Industry and Innovation*, 15, pp. 297–320. **Q16**
Krugman, P. (1979) Model of innovation, technology-transfer, and the world distribution of income. *Journal of Political Economy*, 87, pp. 253–266. **Q17**
Kulkarni, J.S. (2003) A southern critique of the globalist assumptions about technology transfer in climate change treaty negotiations. *Bulletin of Science Technology Society*, 23, pp. 256–264. **Q18**
Lall, S. (1990) *Building industrial competitiveness in developing countries* (Paris, France: Organisation for Economic Cooperation and Development).
Lall, S. (1993) Promoting technology development: The role of technology transfer and indigenous effort. *Third World Quarterly*, 14, pp. 95–108. **Q19**
Leadbeater, C. (2007) *The atlas of ideas. Europe and Asia in the new geography of science and innovation* (London: Demos).
Lee, B., Iliev, I., Preston, F., and Royal Institute of International Affairs (2009) *Who Owns Our Low Carbon Future? : Intellectual property and energy technologies* (London: Chatham House).
Lema, R. (2010) Adoption of open business models in the west and innovation in India's software industry. *IDS Research Reports*, 2010, pp. 1–144.
Lema, R., Berger, A., Schmitz, H., and Song, H. (2011) Competition and cooperation between Europe and China in the wind power sector. in: *IDS Working Papers*, 2011, pp. 1–45.
Lema, R., Quadros, R., and Schmitz, H. (2012) Shifts in innovation power to Brazil and India, *IDS Research Report* (Brighton: Institute of Development Studies, University of Sussex).
Lema, A., and Ruby, K. (2007) Between fragmented authoritarianism and policy coordination: Creating a Chinese market for wind energy. *Energy Policy*, 35, pp. 3879–3890. **Q20**
Less, C.T., and Mcmillan, S. (2005) , Achieving the successful transfer of environmentally sound technologies: Trade-related aspects. OECD Publishing.
Lewis, J.I. (2007) Technology acquisition and innovation in the developing world: Wind turbine development in China and India. *Studies in Comparative International Development*, 42, pp. 208–232. **Q21**
Liu, L.-Q., Wang, Z.-X., Zhang, H.-Q., and Xue, Y.-C. (2009) Solar energy development in China – A review. *Renewable and Sustainable Energy Reviews*, 14, pp. 301–311. **Q22**
Lundvall, B.-Å. (1992) *National systems of innovation : towards a theory of innovation and interactive learning* (London: Pinter).
Lundvall, B.-Å., and Johnson, B. (1994) The learning economy. *Journal of Industry Studies*, 1, pp. 23–42. **Q23**
Lundvall, B.-Å., Johnson, B., Andersen, E.S., and Dalum, B. (2002) National systems of production, innovation and competence building. *Research Policy*, 31, pp. 213–31. **Q24**
Maini, C.K. (2005) REVA electric car: A case study of innovation at RECC. *International Journal of Technology Management*, 32, pp. 199–212. **Q25**
Mallett, A., Ockwell, D., Pal, P., Kumar, A., Abbi, Y., Haum, R., Watson, J., Mackerron, G., and Sethi, G. (2009) UK-India collaborative study on the transfer of low carbon technology. Phase II Final Report. SPRU and TERI.
Menon, N. (2009) Chetan Maini is charged about the prospects of electric car REVA. *The Economic Times*, 28 March 2009. **Q26**
Mizuno, E. (2007) *Cross-border transfer of climate hange mitigation technologies: The case of wind energy from Denmark and Germany to India* (Ph.D. Dissertation). Massachusetts Institute of Technology.
MOF & MOST (2009) Information about the promotion experiments with models of energy efficient and new energy cars (in Chinese), Directive 2009/6. Ministry of Finance and Ministry of Science & Technology, available at: <http://www.gov.cn/zwgk/2009-02/05/content_1222338.htm>.
Nelson, R.R. (2011) Economic development as an evolutionary process. *Innovation and Development*, 1, pp. 39–49. **Q27**

Ockwell, D., Watson, J., Mallett, A., Haum, R., Mackerron, G., and Verbeken, A.-M. (2010) Enhancing developing country access to eco-innovation: The case of technology transfer and climate change in a post-2012 policy framework. *OECD Environment Working Papers*, OECD.

Ockwell, D.G., Watson, J., Mackerron, G., Pal, P., and Yamin, F. (2008) Key policy considerations for facilitating low carbon technology transfer to developing countries. *Energy Policy*, 36, pp. 4104–4115. **Q28**

People's Daily Online (2009) China's new energy vehicles head for the world. *People's Daily*, 11 February. **Q29**

Popp, D. (2011) International technology transfer, climate change, and the clean development mechanism. *Review of Environmental Economics and Policy.* **Q30**

Rajsekhar, B., Van Hulle, F., and Jansen, J.C. (1999) Indian wind energy programme: Performance and future directions. *Energy Policy*, 27, pp. 669–678. **Q31**

Reddy, N.M., and Zhao, L. (1990) International technology transfer: A review. *Research Policy*, 19, pp. 285–307. **Q32**

Romer, P.M. (1994) The origins of endogenous growth. *Journal of Economic Perspectives*, 8, pp. 3–22. **Q33**

Rui, H., and Yip, G.S. (2008) Foreign acquisitions by Chinese firms: A strategic intent perspective. *Journal of World Business*, 43, pp. 213–226. **Q34**

Schneider, M., Holzer, A., and Hoffmann, V.H. (2008) Understanding the CDM's contribution to technology transfer. *Energy Policy*, 36, pp. 2930–2938. **Q35**

Shamsavari, A. (2007) , The technology transfer paradigm: A critique. Kingston upon Thames, UK Faculty of Arts and Social Sciences, Kingston University.

Srinivas, K.R. (2011) Role of open innovation models and IPR in technology transfer in the context of climate change mitigation, in: J. Haselip, I. Nygaard, U. Hansen and E. Ackom (eds) *Diffusion of Renewable Energy Technologies: Case studies of enabling frameworks in developing countries* (Denmark: UNEP Riso Centre).

Srinivasan, S. (2005) Segmentation of the Indian photovoltaic market. *Renewable and Sustainable Energy Reviews*, 9, pp. 215–227. **Q36**

Stamm, A., Dantas, E., Fischer, D., Ganguly, S., and Rennkamp, B. (2009) Sustainability-oriented innovation systems: Towards decoupling economic growth from environmental pressures? *Discussion Paper – DIE Research Project 'Sustainable Solutions through Research'*, German Development Institute / Deutsches Institut für Entwicklungspolitik, Bonn.

Stern, N.H. (2007) *The Economics of Climate Change: The Stern review* (Cambridge, UK; New York: Cambridge University Press).

Tan, X.M. (2010) Clean technology R&D and innovation in emerging countries – Experience from China. *Energy Policy*, 38, pp. 2916–2926. **Q37**

Tomlinson, S., Zorlu, P., and Langley, C. (2008) Innovation and Technology Transfer (London: E3G and Chatham House).

Ueno, T (2009) Technology transfer to China to address climate change mitigation. **Q38**

UNEP, E. a. I (2010) Patents and clean energy: Bridging the gap between evidence and policy. United Nations Environment Programme (UNEP), European Patent Office (EPO), and International Centre for Trade and Sustainable Development (ICTSD), Munich.

UNFCCC (1992) United Nations framework convention on climate change. United Nations.

UNFCCC (2002) The Marrakesh accords. United Nations Framework Convention on Climate Change.

UNFCCC (2007) Bali action plan, decision 1/CP.13. United Nations Framework Convention on Climate Change.

UNFCCC (2010) Outcome of the work of the ad hoc working group on long-term cooperative action under the convention, 1/CP.16. *Cancun Agreements* (Bonn: United Nations Framework Convention on Climate Change).

Wang, G. (2009) Shanghai auto group on move in developing new energy cars. *Xinhua News*, 2009, pp. 11–03. **Q39**

World Bank (2008) Technology diffusion in the developing world. International Bank for Reconstruction and Development, Washington, DC.

World Bank (2010) World development report 2010: Development and climate change. World Bank, Washington, DC.

Zeng, M., and Williamson, P.J. (2007) *Dragons at Your Door: How Chinese cost innovation is disrupting global competition* (Boston, MA: Harvard Business School Press).