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China's rise: Challenging the North-South technology transfer paradigm for climate change mitigation and low carbon energy☆

Frauke Urban

Centre for Development, Environment and Policy CeDEP, School of Oriental and African Studies SOAS, University of London, 36 Gordon Square, London WC1H 0PD, UK

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ABSTRACT

Historically, technology transfer from the global North to China played a large role in renewable energy pathways in China, particularly for wind energy, partly also for solar energy. Yet, the rise of China and other emerging economies means a shift away from a reliance on technology transfer and production capabilities to strengthening indigenous innovation capabilities. Drawing on evidence from the hydropower, solar and wind energy industry in China, the paper introduces the concept of 'geographies of technology transfer and cooperation' and challenges the North-South technology transfer and cooperation paradigm for low carbon innovation and climate change mitigation. The empirical evidence shows that for low carbon innovation, the conception that China is lacking behind in innovation capabilities is partly outdated. Instead, there is an increase in indigenous innovation capabilities, resulting in South-South technology transfer and cooperation as well as elements of 'reverse' South-North technology cooperation.

1. Introduction

Historically, technology transfer from the global North to China has played a large role in renewable energy pathways in China, particularly for wind energy, partly also for solar (Urban et al., 2015a; Lewis, 2013; Watson et al., 2014). Technology transfer of hardware occurred from OECD countries to China, as well as knowledge transfer of how to maintain and operate these technologies. This reliance on foreign technology imports has decreased in recent years as China has become a rising power at political, economic and technological levels.

This goes hand in hand with China's rising importance for global climate change and its dominant role in the climate change negotiations under the United Nations Framework Convention on Climate Change (UNFCCC). Climate change mitigation and low carbon energy transitions are strongly supported by the Chinese government (Zhang et al., 2017) as evidenced by China's ratification of the Paris Agreement, its strong support for global climate change mitigation even after the US' withdrawal, the country's plans to peak CO_2 emissions by 2030 and to increase the share of non-fossil fuels in primary energy consumption to 20% by the same year (Duan et al., 2016). At the same time, China is building up its indigenous innovation capabilities for climate-relevant technology and low carbon energy technology.

About a decade ago, Altenburg et al. (2008) found that China, as well as India, is in the process of a transition from production capabilities to innovation capabilities, yet it has not achieved this transition yet. Yet, the Chinese government referred to the Chinese wind and solar energy industry for several years as a "wind energy industry/solar PV industry with Chinese characteristics" (NDRC, 2012:1), meaning that low carbon technologies acquired through technology transfer from the global North by Chinese wind and solar PV firms had been amended, improved and turned into technologies that are more suitable for the Chinese market.

This paper analyses the latest empirical evidence to assess how far China has transitioned from a leader in manufacturing to a leader in innovation in low carbon energy technologies for climate change mitigation in the last few years. It combines empirical data from interviews, focus group discussions and site visits with patent analysis and document analysis.

This paper aims to assess the rise of China and the shift away from a reliance on technology transfer and production capabilities to strengthening domestic innovation capabilities. Drawing on evidence from the hydropower, solar and wind energy industry in China, the paper introduces the concept of 'geographies of technology transfer and cooperation' and challenges the North-South technology transfer and cooperation paradigm for low carbon innovation and climate change mitigation. Theoretically the paper adds value by expanding the current narrow framing of technology transfer and cooperation to a wider understanding that addresses various geographic directions of technology transfer and cooperation, exploring their characteristics and focusing on a cross-sector comparison across several major low carbon energy

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E-mail address: f.urban@soas.ac.uk.

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sectors. Empirically, the papers adds value by using a mixed methods approach, drawing on qualitative data from primary fieldwork as well as quantitative data from patent analysis to support these findings.

The paper finds that the conception that China is lacking behind in innovation capabilities is partly outdated for low carbon innovation. This is not limited to one industry or sector, but can be seen in evidence gathered from the hydropower, wind and solar energy sectors, thereby examining a broader trend for low carbon innovation. Instead, the paper finds a rise of South-South technology transfer and cooperation as well as elements of 'reverse' South-North technology cooperation with regards to low carbon energy technologies for climate change mitigation.

Section 2 presents the background and literature review, Section 3 presents the findings, Section 4 discusses the findings from the hydropower, solar and wind energy industry and Section 5.1 concludes the paper and raises some policy implications.

2. Background and literature review

The paper draws on the theories of international technology transfer for low carbon innovation (Ockwell and Mallett, 2012; Bell, 1990; Brewer, 2008). Rogers (2003) defines innovation as developing a new idea, product or service. Low carbon innovation is important for mitigating climate change and for enabling transitions to low carbon economies and societies. Achieving this requires the diffusion of low carbon technology innovation, which is a complex task and typically includes research and development (R&D), demonstration and deployment. The diffusion of low carbon technology innovation depends on several factors, including skilled labour, adequate incentives for firms, governments and other organisations to enable technology development and to help create markets for these technologies. (Ockwell and Mallett, 2013; Saviotti, 2005).

Less developed countries usually have lower capacities to create indigenous innovation, including in the energy sector (Ockwell et al., 2014; Ockwell and Byrne, 2015). This means they have a strategic disadvantage, as energy innovation is crucial for alleviating energy poverty, increasing energy security and for building an energy sector that reduces greenhouse gas emissions and is resilient to climatic shocks at the same time. Brewer (2007) hence calls for increasing technology innovation and its diffusion through international technology transfer, under the 'technology transfer paradigm'.

Technology transfer is here defined as per the IPCC's definition: a 'broad set of processes covering the flows of know-how, experience and equipment for mitigating and adapting to climate change […] The broad and inclusive term'transfer' encompasses diffusion of technologies and technology cooperation across and within countries. It comprises the process of learning to understand, utilise and replicate the technology, including the capacity to choose it and adapt it to local conditions and integrate it with indigenous technologies' (Hedger McKenzie et al., 2000, 1.4). This terminology refers to both technology transfer and technology cooperation.

In the past, technology transfer and cooperation was often limited to 'hardware', while other 'software' issues that are essential to create, operate and maintain technologies such as skills, knowledge and experience, were often excluded from the traditional understanding of technology transfer and cooperation (Urban et al., 2015a, 2015b). Also, for a long time the focus was on the traditional North–South model of technology transfer and cooperation. In recent years, partly due to the rise of emerging economies like China, India, South Africa and Brazil, this thinking has shifted towards a broader and more balanced understanding of technology transfer and cooperation. Hence, this term is here divided into four geographic flows: Technology transfer and cooperation (1) from North to South (e.g. EU to China), (2) from South to North (e.g. China to EU), (3) from South to South (e.g. China to Asia or Africa) and (4) from North to North (e.g. EU to US or vice versa) (Urban et al., 2015a, 2015b).

Types of technology transfer and cooperation include cooperative approaches between firms and/or countries such as foreign direct investment (FDI), overseas development assistance (ODI), licencing, joint ventures, mergers and acquisitions. Other forms of technology cooperation can include movement of skilled labour, networks and joint publications. Technology transfer and cooperation can be a short- or long-term process, formalised or informal, depending on its specific nature and the objectives of the parties involved in it. Technology transfer and technology cooperation can be horizontal, taking place between firms, or vertical, such as from R&D to commercialisation (Ockwell and Mallett, 2013). Urban et al. (2015a:236) distinguish between three flows of technology transfer and technology cooperation: "(1) capital goods and equipment, (2) skills and know-how for operation and maintenance and (3) knowledge and expertise for innovation/ technological change". Byrne et al. (2011, 2012) argue that a change in understanding is required from technology transfer to socio-technical transformations to enable countries in the global South to build up their indigenous innovation capabilities.

While technology transfer and cooperation has been a hot topic since the 1980s, not least as part of the UNFCCC climate negotiations, the focus has overtly been on North-South technology transfer and cooperation. In contrary, South–South technology transfer and cooperation is a rather under-researched and novel phenomenon. Urban et al. (2015a) argue that much of the literature and debates on technology transfer and cooperation is restricted to North–South technology transfer from high income countries to low and middle income countries. The rise of emerging economies like China, India, South Africa and Brazil as new economic, political, social and technological powers however challenges the pre-conceptions about technology transfer and rebalances the focus towards South–South technology transfer and cooperation. Yet, much of the literature on China's rise in the low carbon energy field is on catch-up strategies (e.g. Awate et al., 2012, 2014; Lewis, 2013; Gosens and Lu, 2013; Lema et al., 2013; Dai et al., 2014) or on analysing China's role for the Clean Development Mechanism (CDM) (e.g. Lema and Lema, 2016). While this is important much of China's South-South technology transfer and cooperation actually happens outside of the CDM. South-North technology transfer and cooperation from China to high income countries in the global North is even less researched, although a few authors have started to acknowledge the complex set of technology cooperations that Chinese and OECD firms are engaged in (Lema and Lema, 2012), yet empirical evidence in this field remains rare. This is where this paper adds value.

Urban et al. (2015a) developed a framework for characterising South-North technology transfer and cooperation. This paper uses an amended version of the framework and examines the following factors for China's role in technology transfer and cooperation for hydropower, wind energy and solar energy: 1. China investing in low carbon energy technology overseas (a South-South or South-North flow of capital), 2. China driving market access to overseas low carbon energy technology markets (South-South or South-North drivers for market access), 3. Technology and/or R&D leadership by Chinese low carbon technology firms (South-South or South-North technology/R&D leadership), and 4. China's approach to innovation capabilities (South-South or South-North origins of innovation such as patents, citations and other intellectual property rights (IPRs)). South-South and South-North technology transfer and cooperation could therefore be defined by taking into account the direction of flow of capital, the direction of drivers of market access, the direction of technology leadership (including R&D) and the origins of innovation (including patents).

3. Methodology and data

This paper is based on results from in-depths interviews, Focus Group Discussions (FGDs) and field visits conducted in China, Southeast Asia and the European Union (EU) between 2011 and 2016, as well as firm strategy analysis, literature review, policy analysis, data analysis and patent analysis. The paper analyses case studies from wind energy, solar energy and hydropower to assess how far China has transitioned from a leader in manufacturing to a leader in innovation in low carbon energy technologies for climate change mitigation in the last few years and to challenge the dominant North-South technology transfer paradigm. Wind energy, solar energy and hydropower are the most technically mature low carbon technologies, as well as the most commercialised technologies. Hydropower, wind energy and solar energy technologies have been commercially available to the mass market for several decades world-wide. They also make up the largest markets for renewable energy technologies world-wide. Hence these three technologies have been chosen as being worthwhile to study.

The paper uses case studies to explore these issues. The case study approach is based on Yin (2009); the analytical approach used is cross-case synthesis. Following Miles and Huberman (1994), our case selection criteria consider the significance of the case, its representativeness, its theoretical relevance, and data accessibility. The wind, solar and hydropower industries are analysed and systematically compared as they are the three most advanced and widely used low carbon energy technologies, globally and in China. It is important to look at different sectors to examine the issue of technology transfer as each sector has different dynamics. While some earlier work was conducted which focused on one specific sector only (see Urban et al., 2015a, 2015b, 2016), this paper does a cross-sector comparative analysis to synthesise, analyse and make sense of wider trends in the low carbon energy field. This cross-comparison can be helpful in more comprehensively understanding the role of China for global low carbon transitions and climate change mitigation.

Overall, the conducted fieldwork resulting in 101 in-depth, semi-structured interviews, 27 for the solar energy case, 24 for the hydropower case and 50 for the wind energy case and 16 FGDs (10 for the hydropower case and 6 for the solar energy case). The **FGDs** for hydropower were conducted with local communities that are affected by Chinese-built hydropower dams in Southeast Asia (with a focus on Cambodia), while the 6 solar FGDs were conducted with groups of users of solar energy and with solar energy firms. In the FGDs, an additional 6–10 respondents participated, hence in total another 128 people were surveyed, representing the views of 229 people in total when the number of interviews and FGD respondents are summed up. The in-depths qualitative **interviews** were conducted with 101 experts from energy firms, business associations, research organisations and academia, government agencies, regulators, financiers, NGOs and the local affected population (for large hydropower dams) in China, Cambodia and the EU (with a focus on Germany and Denmark). The interview and FGD questions were semi-structured, qualitative questions. The interviews were conducted in the local languages and then translated into English. Information which is not referenced in this paper is derived from the interviews or FGDs.

Information was triangulated to verify information and the validity of data sources. Additional quantitative data on the wind, solar and hydropower industry comes from various national, regional and global hydropower/wind/solar energy associations, International Rivers' database, the International Energy Agency IEA, the World Bank, the Intergovernmental Panel on Climate Change IPCC, the Chinese Statistical Yearbooks.

In addition, several site visits were conducted to leading wind and solar energy firms which showed us their wind and solar production lines, their trade exhibitions as well as ground-mounted solar PV farms and wind farms. Several visits to the Kamchay hydropower dam site in Kampot, Cambodia were conducted, which is operated by Sinohydro – PowerChina, as well as visits to the 5 affected villages Mortpeam, Prey Khmum, Ou Touch, Snam Prampir, and Tvi Khang Cheung whose residents are directly affected by the dam. The fieldwork was conducted between 2012 and 2016 in China, Cambodia and the EU.

For the wind and solar case studies, patent analysis and bibliometrics was also used. The author used an approach to patent analysis as first developed by Zhou et al. (2015). This methodology is based on key patent counts and network-based methodologies to analyse patent citations such as in peer-reviewed journals. Worldwide patent data was used for the international comparisons and adopted the Derwent Classification to categorise the key technologies. Worldwide patent data was applied to compare firms from developed and developing economies, with a focus on China and Northern-based firms. The worldwide patent data was retrieved from the Derwent World Patents Index (DWPI) and Derwent Patents Citation Index (DPCI) databases through the Thomson Innovation (TI) search engine. The DWPI and DPCI are databases with patent and citation data from 50 patent-issuing authorities around the world.

4. Results and discussion

This section discusses the characteristics of technology transfer and cooperation for the Chinese hydropower, solar energy and wind energy sectors, taking into account the following factors: flow of capital, drivers of market access, technology leadership, origins of innovation and types of technology transfer and cooperation today. The research acknowledges that historically there was a strong dependence on technology transfer from the global North to China, however this had changed considerably by the time the research was conducted. Table 1 summarises the findings. Table 1 addresses the following criteria of South-South and South-North technology transfer and cooperation: the direction of flow of capital, the direction of drivers of market access, the direction of technology leadership (including R&D) and the origins of innovation (including patents). Direction of flow of capital: China invested about US$32 billion overseas in renewable energy in 2016, both in the global South and North (IEEFA, 2017). Market access: This enabled Chinese firms to access markets in the global South and North. The top 5 markets for Chinese low carbon energy technology investment are the United States, Australia, Canada, Brazil and the United Kingdom (IEEFA, 2017). Technology leadership: China has technology leadership in the three leading low carbon energy industries, namely hydropower, solar and wind. This includes indigenous innovation, joint innovation based on joint ventures and acquired innovation based on firms acquired overseas. Origin of innovations: patents and citations for wind energy are steadily increasing, but are still below the number of those generated by firms in the global North. Patents and citations for

Table 1
Summary table indicating types of technology transfer and cooperation for specific low carbon energy sectors in 2017.

Sector	Flow of capital	Drivers of market access	Technology leadership (including R&D)	Origins of innovation (including patents)	Type of technology transfer and cooperation
Hydropower	South-South	South-South	South-South	South (China)	South-South
Solar energy	South-South, South-North	South-South, South-North	South-South, South-North	South (China for SWH and most PV technology; thin-film through acquired technologies)	South-South, South-North
Wind energy	South-South, South-North	South-South, South-North	South-South, South-North	North (mainly EU), South (China, sometimes through acquired technology)	South-South, South-North

Table 2
Latest hydropower technology in China and its status.

Hydropower technology	Status of technology
Impoundments (dam and reservoir)	Commercialised for mass market, cost-effective prices
Diversion (Run of the river)	Commercialised for mass market, cost-effective prices
Pumped storage	Commercialised for mass market, cost-effective prices
Reaction turbines (francis, propeller, bulb turbine, straflo, tube turbine, Kaplan, kinetic)	Commercialised for mass market, cost-effective prices
Impulse turbines (pelton wheel, cross-flow)	Commercialised for mass market, cost-effective prices
Arch dams, arch gravity dams	Commercialised for mass market, cost-effective prices
Gravity dams	Commercialised for mass market, cost-effective prices
Barrages	Commercialised for mass market, cost-effective prices
Rock-fill dams, concrete-face rock-fill dams, earth-fill dams	Commercialised for mass market, cost-effective prices

Chinese solar PV firms are at similar levels compared to Northern competitors and the large majority of patents for SWH are held by Chinese firms. These issues will be unpacked in the analysis below.

4.1. Hydropower and South-South technology transfer

Table 2 provides an overview of the recent technology and latest innovative developments in the hydropower sector in China.

While there is ample literature on North–South technology transfer and cooperation (e.g. Ockwell and Mallett, 2012; Watson et al., 2014; Bell, 2009; Brewer, 2008; Pietrobelli, 2000; Able-Thomas, 1996; Bell, 1990), there is limited literature on South–South technology transfer and cooperation. Empirical research on South–South technology transfer and cooperation is rare, particularly in the low carbon energy field.

This section elaborates South-South technology transfer by using a case study from the Kamchay Dam, the first large hydropower dam in Cambodia, which was financed and built by Chinese actors. Our research finds that Chinese dam-builders are actively engaged in South-South technology transfer and cooperation, as well as being global leaders in innovation capabilities in hydropower technology. While the paper draws on a case study from one Chinese-built dam in Southeast Asia, there is a global rise of South-South technology transfer from China to low and middle income countries in dam-building technology. It is estimated that there are about 330 Chinese-funded and Chinese-built overseas dams at various project stages, from already completed dams to those in the pipe-line. Most of these large dams tend to be in Southeast Asia (38%) and Africa (26%) (International Rivers, 2016; Urban et al., 2015b). Leading Chinese dam-builders are predominantly state-owned enterprises (SOEs), but also some private firms. The largest firms are Sinohydro (also known as PowerChina), PowerChina Resources Limited, China Huaneng Group, China Huadian Corporation, China Three Gorges Corporation etc. Smaller firms are usually made up of suppliers and grid operators like Dongfang, China Southern Grid, China State Grid. Chinese dam financiers include China Export-Import Bank (ExIm Bank), Chinese Development Bank (CDB), Sinosure, Industrial and Commercial Bank of China (ICBC) and Bank of China (BoC) (Tan-Mullins et al., 2017). Chinese dam-builders have built the world's largest dam, namely the Three Georges Dam in China and are internationally renowned for their hydropower engineering skills and expertise.

4.1.1. The Kamchay Dam and technology transfer

China is a main driver for South-South technology transfer for low carbon innovation and climate change mitigation in Cambodia as the following case study shows. There are very few OECD investors in low income countries such as Cambodia. The country is inexperienced in large dam-building and hydropower engineering in general, hence Chinese dam-builders and financiers play a very important role. The Kamchay dam was therefore supported at the highest level, by Prime Minister Hun Sen himself. Chinese hydropower dam technology is state-of-the-art (Urban et al., 2015b) and Chinese dam-builders are also known for delivering cost-effective dam technology within reasonable project time frames (Kirchherr, 2017).

The Kamchay Dam is the first large dam in Cambodia and its generating capacity is much needed in the energy-poor country. It is located in Kampot province, Southern Cambodia, it was built by Chinese SOE Sinohydro between 2006–2011 and is financed through a conditional loan by ExIm Bank. It has a generating capacity of nearly 200 MW, cost an estimated US$280 million and is part of a US$600 million aid package to Cambodia (International Rivers, 2016). Hence the financial arrangement for this technology transfer was partly FDI and partly ODA. The dam construction resulted in a number of environmental and social problems such as adverse effects on the livelihoods of the local population, the dam being built in Kampot National Park which resulted in habitat description and environmental damages in a protected area, late approvals of the Environmental Impact Assessment (EIA) and other issues. The Department of Environment in Kampot province argues that the dam has an expected annual output of 498 GWh and may be able to supply about 60% of Cambodia's energy demand in the wet season. Nevertheless, the generating capacity may be only 60 MW in the dry season, hence less than 1/3 of the nameplate capacity of 200 MW (NGO Forum Cambodia, 2013; Urban et al., 2015b).

For the Kamchay dam, Sinohydro successfully transferred advanced hydropower technology to Cambodia. The flow of technology transfer that occurred was therefore based on capital goods and equipment, which is greatly needed in Cambodia. In addition, Cambodia needs to gain access to skills and expertise for dam-building, as exemplified by the following quote:

> *"Lack of skills, experience and funds for the construction of large hydropower dams are the main barriers faced by most developing countries; while China can provide support in this regard." (Interview with representative from hydropower firm, 2013).*

However, there was very limited evidence of the transfer of skills, know-how and expertise for operation and maintenance and for developing domestic production or innovation capabilities at the Kamchay Dam. Our fieldwork revealed that approximately 3000–4000 Cambodian workers assisted the dam construction; however they were predominantly low-skilled labourers. The skilled work force composed of engineers and technicians was predominantly Chinese. Since the dam started operating in 2011 Sinohydro is employing almost exclusively Chinese workers to manage, operate and maintain the dam (Urban et al., 2015b).

The technology transfer between Sinohydro and the Cambodian government was horizontal. Vertical technology transfer and cooperation has not been observed at the Kamchay dam. An interesting finding is that the dam stays under the ownership of Sinohydro until 2050, hence for 44 years since the construction started as part of the BOT

(Build Operate Transfer) contract between Sinohydro and the Cambodian government. Only in 2050 will the ownership of the dam be transferred to the Cambodian government. Therefore, this can be considered a 'delayed' technology transfer (Urban et al., 2015b). Some of the technology cooperation elements, such as training of Cambodian technical and engineering staff, Cambodian staff exchanges to China, joint ventures or similar may happen towards the end of the 44 year agreement to enable the Cambodian actors to take over the dam operations.

In conclusion, large-scale hydropower technology was successfully transferred between Chinese dam-builders and Cambodian recipients evidenced by the construction of the Kamchay dam by Sinohydro; however knowledge transfer was very limited. Since Sinohydro is still operating and maintaining the dam, Cambodian authorities do not have much knowledge or experience yet in operating and maintaining the dam and there has been even less knowledge transfer with regards to building up indigenous innovation capabilities. While this is a case of South-South technology transfer, this is a missed case of China enabling Cambodia to fully embrace the potential of technological change that could go along with technology transfer and cooperation.

Yet, lessons can be learned from the Kamchay dam –Cambodia's first dam- for future dam-building in Cambodia and for future South-South technology transfer and cooperation. By 2017, another 5 Chinese-funded and Chinese-built dams had been constructed in the country, another 3 were under construction and another 4 are planned to be completed by 2020 (Clean Energy Info Portal, 2016). Table 3 shows an overview of the factors that are characterising South-South technology transfer and cooperation and analyses how this relates to the China-Cambodia hydropower case study. This research found that China invests in Cambodia's hydropower dam infrastructure (a South-South flow of capital), China is driving market access to Cambodia's and Southeast Asia's hydropower sector (South-South drivers for market access), there is R&D/technology leadership by Chinese dams firms as the technology originates from China (South-South technology/R&D leadership), as well as indications that the innovation capabilities rest with Chinese firms (South-South origins of innovation) as the patents are based on Chinese technology (Table 3).

4.2. Solar energy and South-North/South-South technology cooperation

Table 4 provides an overview of the recent technology and latest innovative developments in the solar sector in China.

Most of the literature on solar energy innovation in China acknowledges that historically the solar PV industry in China was partly dependent on technology transfer and cooperation although less than the Chinese wind industry (e.g. De la Tour et al., 2011; Lema and Lema, 2012). Indigenous innovation, favourable domestic policies and a strong national innovation system also played a large role in shaping the Chinese solar PV industry (Fu and Zhang, 2011).

This section analyses China's innovation capabilities in solar energy technology and its implications for South-North and South-South technology transfer and cooperation. Chinese solar energy technology is a complex and interesting case study, so far as various technologies are involved which relate to very different innovation capabilities and to different degrees of (in)dependence from overseas technology transfer and cooperation. This paper focuses on solar photovoltaic (PV) technology and on solar water heaters (SWH).

Solar photovoltaics (PV) are a technology predominantly developed in the US. Its development was promoted by state-regulated monopolies and government programmes in the USA, including NASA and the Department of Defense (Mazzucato, 2013). The breakthrough innovation of the world's first silicon PV cell occurred at Bell Laboratories, USA in 1954 (Leggett, 2009).

Similar to the world's top wind energy firms, Chinese solar energy firms rapidly climbed to the peak of global solar manufacturing performance. By 2015, 7 of the top 10 solar PV manufacturers were Chinese: Trina Solar, Yingli Green Energy, (Chinese-owned) Canadian Solar, Jingko Solar, JA Solar and Rene Solar (Renewables, 2015). The situation was very different a decade ago, when Chinese solar PV firms were absent from the world's top wind energy firms. This development is partly based on different forms of technology cooperation, particularly from the US, Australia, EU and Japan.

The development of innovation capabilities in the solar water heater industry in China was historically completely different. Flat plate collectors, predominantly of Canadian origin, were used in China in the

Table 3
overview of the factors that are characterising South-South technology transfer and cooperation for hydropower between China and the global South. Amended from Urban et al. (2015a).

Key factors of technology transfer and cooperation	Description – hydropower case study	Evidence found
South-South flow of capital	The capital for the technology cooperation comes from emerging economies, potentially influencing ownership of the project and strategic decisions.	Yes
South-South drivers for market access	Overseas market access is driven by firms from emerging economies, potentially opening up access to new markets.	Yes
South-South technology leadership/R&D leadership	Technology/R&D leadership is driven by Southern firms, leading to innovative designs and technologies that are more appropriate for new markets.	Yes
Innovation capabilities: South-South origins of innovation	The origins of innovation (such as patents and other IPRs) come from emerging economies.	Yes

Table 4
Latest solar technology in China and its status.

Solar technology	Status of technology
PV: Crystalline silicon cells	Commercialised for mass market, cost-effective prices
PV: Gallium arsenide-based single junction cells (GaAs)	R&D, mass production announced
PV: Multi-junction cells, mainly dual junction cells using different technologies	R&D, not yet commercially available at competitive prices
PV: Thin-film copper indium gallium selenide (Cu, In, Ga, Se2) (CIGS)	R&D, not yet commercially available at competitive prices, although mass production announced
PV: Dye-sensitised cells	Early stage R&D
SWH: evacuated tube	Commercialised for mass market, cost-effective prices
SWH: flat plate collectors	Commercialised, but less widely used

1980s, but did not operate well in the Chinese environment. Hence, Chinese engineers developed the evacuated tube technology, which is an indigenous, low-cost technology that is more adapted to the Chinese market and has been a huge demand success throughout China as the following section will elaborate.

4.2.1. Chinese solar energy firms and technology transfer and cooperation

While solar PV technology innovation originated mainly from the US, the Chinese solar PV industry pursued a strategy that depended partly on technology transfer and cooperation, but utilised a different strategy than the Chinese wind energy industry. Traditional technology transfer through ODA and FDI did play a minor role, as well as mergers and acquisitions, not only for key technology but also for manufacturing equipment. The movement of skilled labour was also very important (De la Tour et al., 2011). A case in point is Suntech and its founder Shi Zhengrong, once the richest man in China until the decline of the firm. Shi is an Australian-educated solar scientist who moved to China to set up Suntech, with considerable political support, particularly from the provincial government in Jiangsu.

In the 1990s and early 2000s, the government promoted a number of PV industry development strategies, mainly focused on the production of solar consumer goods for export to the US and the EU, and to other parts of Asia after the financial crisis (Fischer, 2012). From 2004–2008, China's solar PV policy shifted more heavily towards the overseas export market, gaining access to European and US markets and selling cost-effective solar PV technology in masses overseas (Zhang et al., 2014). To increase the quality of Chinese solar PV products for export, the government invested heavily in technology R&D, covering almost every link in the solar PV manufacturing chain, such as polysilicon, wafer, solar cells, PV modules, thin-film technology, energy storage, balance of system (BOS) components and system engineering as well as Concentrated Solar Power. Today, Chinese companies like Yingli Solar and Trina Solar have set up national PV key laboratories "with annual R&D investment of 592 million RMB and 610 million RMB respectively between 2009 and 2012." (Sun et al., 2014: 226). It is clear that boosting solar PV manufacturing became part of core government strategy and is central to its national climate and energy targets (Du, 2012). The Ministry of Science and Technology (MOST) has driven forward PV R&D, with an average annual investment of around 500 million yuan (around US$81 million) (Wang et al., 2013; Urban et al., 2016).

The prevailing PV technology in China is based on crystalline silicon cells, produced by leading firms like Yingli, Trina and JA Solar. Other innovations such as gallium arsenide-based single junction cells, multi-junction cells, thin-film solar cells based on copper indium gallium selenide (CIGS) and dye-sensitised solar technology are currently being developed in Chinese R&D labs (Urban et al., 2016). This is evidenced by the following quote: *"Lots of R&D is happening by Chinese firms in new technology development, such as dye-sensitised solar technology, but it's still at an early stage" (Interview with academic, 2015).*

Energy efficiencies have gone up from 14% to more than 30% for the latest cutting-edge technology in laboratory tests. This record is held by Chinese-owned AltaDevices, a US-based company acquired by Chinese thin-film company Hanergy in 2014 (Urban et al., 2016; NREL, 2016). Hanergy also acquired several other solar thin-film firms between 2012 and 2014 and is engaged in joint R&D activities with them, namely US-based MiaSole, German-based Solibro and US-based Global Solar. While the solar PV industry is still partly dependent on technology transfer and cooperation for cutting-edge innovation such as in thin-film technologies, like in Hanergy's case, the industry depends on the development of indigenous innovation for more mature solar PV technologies. *"Several Chinese solar firms also develop a range of applied solar innovations beyond solar PV and solar water heaters, such as solar panels for use in space, solar panels for use in electric vehicles and small-scale technologies such as solar cookers, solar lamps, solar bag packs for mobile phone charging" (interview with representative from solar energy firm, 2015).*

Patent data reveals that the Chinese PV industry has a stronger innovation capacity in patent portfolios, knowledge flow (measured in citations) and international collaboration, compared to the Chinese wind energy industry which has a weaker position in the global knowledge network (Zhou et al., forthcoming). Research on citations showed that Chinese solar PV firms Trina, Yingli, CSI and JA are highly referenced in international journals and have become global knowledge leaders. Patent data reveals that Chinese solar PV firms had lower numbers of patents registered pre-2007, and the global solar PV industry was then dominated by Japanese and US firms. This has however changed since 2007 as Chinese firms like Trina, Yingli, JA Solar and CSI Solar hold a comparable number of key patents compared with international competitors (Zhou et al., forthcoming). This indicates a transition from the early dependency on technology transfer and cooperation to an indigenous innovation model that contributes to global knowledge creation.

The case of solar water heaters is strikingly different. For SWH, technology transfer was important in the 1980s and early 1990s, but negligible afterwards. Solar water heaters were first developed in the 1970s in China. In the 1980s China began to produce flat plate solar water heaters that were based on technology transfer of a Canadian design (similar to the predominant design used in Europe today). However, the production was expensive and there were technical problems. In the 1990s, Chinese scientists at the Beijing Solar Energy Research Institute at Tsinghua University developed and patented the evacuated tube design (also called the vacuum tube): an example of indigenous, low-cost innovation. This follows a trend that we can also see in the wind energy sector, namely the emphasis on university-led R&D for renewables at national level in China. R&D in the evacuated tube design was heavily supported by the national government until it was commercialised in 1998. Himin Solar Energy Group, China's leader in solar water heaters, was the key player for commercialising the product and scaling up the business. Today, leading firms, such as Himin, still cooperate with the Chinese Academy of Sciences (CAS) and universities for R&D in solar water heaters. This requires a skilled work force for developing cutting-edge innovation, in addition to a low-cost work force for the assembly of solar water heaters. (Annini et al., 2014; Urban et al., 2016).

Today 95% of all the solar water heaters in China are of the evacuated tube design (Hu et al., 2012). It is estimated that Chinese firms hold 95% of the patents for core technologies of solar water heaters worldwide (CGTI, 2011). It is a low-cost indigenous innovation that suits local needs. Today, more than 85 million solar water heating systems are being used in China (Weiss et al., 2015). There is also export to OECD countries and Asia and Africa (Urban et al., 2016).

The case study of solar energy, particularly solar water heaters defies the idea that China's innovation capabilities are lacking behind. For solar water heaters, China is undoubtedly the world's largest innovator and is focussing particularly on the domestic market, although some overseas exports exist. For solar PV, the bulk of China's market is export-oriented, although the domestic market has been growing in recent years. With regards to innovation, the solar PV industry has mixed roots, but today is innovating also domestically. The picture is equally complex with regards to technology transfer and cooperation in the Chinese solar energy industry. There is evidence for South-South and South-North flow of capital (although this paper hasn't focused explicitly on this subject), South-South and South-North drivers for market access such as in the EU, US, Asia and Africa. There is also evidence of joint technology/R&D leadership by Chinese solar firms, such as in the Hanergy- AltaDevices case, and there are strong indications that the innovation capabilities rest with Chinese firms, such as the fact that 95% of the patents for core technologies of solar water heaters worldwide rest with Chinese firms (CGTI, 2011). Table 5 shows an overview of the factors that are characterising South-South and South-North technology transfer and cooperation for solar energy.

Table 5
overview of the factors that are characterising South-South and South-North technology transfer and cooperation for solar energy between China and other parts of the world. Amended from Urban et al. (2015a).

Key factors of technology transfer and cooperation	Description – solar case study	Evidence found
South-South and/or South-North flow of capital	The capital for the technology cooperation comes from emerging economies, potentially influencing ownership of firms/projects and strategic decisions.	Yes
South-South and/or South-North drivers for market access	Overseas market access is driven by firms from emerging economies, potentially opening up access to new markets.	Yes
South-South and/or South-North technology/R&D leadership	Technology/R&D leadership is driven by Southern firms, leading to innovative designs and technologies that are more appropriate for new markets.	Yes
Innovation capabilities: South-South and/or South-North origins of innovation	The origins of innovation (such as patents and other IPRs) come from emerging economies.	Yes, especially for SWH

4.3. Wind energy and South-North technology cooperation

Table 6 provides an overview of the recent technology and latest innovative developments in the wind sector in China.

For the past three to four decades, the focus in the wind energy literature was on technology transfer from the global North to the global South. Recent literature highlighted the importance of Chinese wind energy firms catching up with regards to wind firms in the global North (e.g. Lewis, 2013; Gosens and Lu, 2013; Lema and Lema, 2012; Lema et al., 2013; Dai et al., 2014). Yet, until recently the dominant paradigm of North–South technology transfer and cooperation has not been substantially challenged, despite the rise of emerging economies such as China and India. Urban et al. (2015a) however introduced the concept of ‘reverse’ or South-North technology cooperation from emerging economies in the global South, like China and India, to the global North, by examining evidence from the wind energy industries in China, India and the EU. This case study examines the wind energy industry in China and its engagement with Northern, OECD firms to challenge the North–South technology transfer and cooperation and to assess the innovation capabilities of Chinese wind firms.

4.3.1. Chinese wind energy firms, technology transfer and cooperation

China has been the world's largest wind energy market for several years. It had a cumulative installed capacity of nearly 170 GW in 2016, representing about 35% of the global wind market (GWEC Global Wind Energy Council, 2017). Chinese wind energy firms only became global leaders after the implementation of the Kyoto Protocol when the Chinese wind industry experienced a quick growth in manufacturing capacity, installed capacity and access to international wind markets (Urban et al., 2015a). This was mainly due to technology transfer and technology cooperation with European wind energy firms. The ten largest Chinese wind energy firms are currently Goldwind (about 27%), Envision (about 9%), Mingyang (about 8.5%), Guodian United Power (about 8%), and CSIC (just under 8%), Shanghai Electric (about 7%), XEMC (just over 5%), DongFang (about 5%), Windey (about 3%) and Huachuang (also about 3%) (GWEC, 2017).

In the past, some of the leading Chinese wind energy firms built their expertise on technology transfer and cooperation from European (mostly German) wind energy firms by means of licencing and joint ventures. Goldwind conducted joint R&D with Vensys and licenced technology from Jacobs/REpower, Mingyang conducted joint R&D with Aerodyn, Guodian United Power licenced technology from Aerodyn and Sinovel licenced technology from Fuhrländer (Urban et al., 2015a). However, the research also indicates elements of South-North technology cooperation, particularly the Goldwind-Vensys collaboration.

German wind engineering firm Vensys developed from a small R&D-focused university-spin off at the University of Saarbrücken to a global leader in the wind industry after the acquisition by Chinese Goldwind in 2008. Today, Goldwind is the world's largest wind manufacturer and it operates with Vensys’ technology. Benefits for Vensys included being able to access to Chinese market and draw on Goldwind's network, scaling-up rapidly and supplying the world's largest wind energy market. Benefits for Goldwind included access to Vensys technology, IPRs, components, profits and markets. German and Chinese technology cooperation resulted in joint R&D and joint technology, particularly with regards to larger turbines in the multi-megawatt scale and even up to 10 MW, which is historically rare for China as usually smaller gear-driven turbines have been developed. Vensys however is a champion of the Permanent Magnetic Direct Drive (PMDD), for which rare earths are used – an advantage as China holds large resources of it (Urban et al., 2015a).

> The following quotes shed some light on the technology cooperation between Vensys and Goldwind: *“Licensing only poses risks of IPR infringements, it provides only limited financial benefit and it offers only limited contacts. Joint ventures and acquisitions in contrast enable getting access to global networks, contacts and support from larger players, access to new markets and higher financial benefits and reducing the risks of financial losses. In relation to Goldwind it gave Vensys access to the Chinese market and contacts.” […] “Another innovation at Vensys is that they modify their products for various offshore markets, particularly relating to the rotor design and climatic conditions. For example, for China, the modifications are for high and low temperates, for sandy conditions and for low wind speed areas. These modifications are researched and developed partly by Vensys and partly by Goldwind. This is due to the fact that the R&D expertise and facilities are greater at Vensys than abroad. There is an exchange of expertise and training programmes for Goldwind engineers at Vensys.” (Interview with representative from*

Table 6
Latest wind energy technology in China and its status.

Wind energy technology	Status of technology
Gear-driven turbines	Commercialised for mass market, cost-effective prices
Permanent Magnetic Direct Drive (PMDD)	Commercialised for mass market, cost-effective prices
Offshore turbines	Commercialised, several offshore wind farms operating
Large wind turbines (> 5 MW)	Commercialised for mass market, cost-effective prices
Low-wind speed turbines	Prototypes launched, mass production announced
Wind turbines adapted to extreme conditions (extreme heat & cold & typhoon wind speeds)	Prototypes launched, mass production announced
Vertical axis turbine	Small-scale types commercialised, cost-effective prices
Hybrid systems (hydro-wind, solar-wind)	R&D, not yet commercially available at competitive prices
Floating offshore turbines	Early stage R&D

wind firm, 2012).

"Vensys considers innovation just as the Chinese do: licensing and acquisition results in ownership of innovation and modification of existing technologies is innovation." (Interview with representative from wind firm, 2012).

Patents held by Goldwind rose from 3 in 2007, just before the Vensys acquisition in 2008, to more than 170 in 2012 thanks to the technology acquired from German firm Vensys, which after the acquisition counts as patents for Chinese firm Goldwind (see also Zhou et al., 2015). The acquisition and joint R&D also made Goldwind the largest wind turbine manufacturer in China and worldwide, overtaking Vestas in 2015, and relying on advanced, high quality, cost-efficient technology. The key to this success is collaborative research with German R&D firm Vensys. In addition to producing PMDD turbines of the size 1.5 MW (onshore), 2 MW (onshore), 2.5 MW (onshore), 3 MW (onshore/offshore), 6 MW (offshore) and 10 MW (offshore), the two firms conduct joint R&D for amending wind turbines for the local conditions in China, such as low wind speed areas, turbines that can withstand desert conditions like extreme heat, dryness and sand exposure (Urban et al., 2015a). In addition, through Vensys Goldwind is operating on all continents (except Antarctica) and in the key markets of China, India, Germany, Poland, Portugal, Canada, USA, Brazil, Educador, Egypt, Cyprus, Sri Lanka, South Africa and Australia (Vensys, 2017).

Despite this drive for global innovation, the patent analysis indicates that the majority of patents are still owned by EU-based firms like Vestas, Enercon and Siemens; despite Goldwind and Mingyang owning a growing number of patents (see also Zhou et al., 2015).

In conclusion, elements of South–North technology cooperation in wind energy technology can be evidenced between China and Europe, such as South–North flows of capital (e.g. for acquiring EU-based firms like Vensys), drivers for market access have been seen, as well as evidence of joint technology/R&D leadership, while the origins of innovation (e.g. patents) seem to stay mainly in the global North. Nevertheless this analysis concludes that the technology cooperation between China and Europe has become more complex and increasingly Southern-led. However, it is too early to speak of 'reverse' technology cooperation, as the patents and IPRs are mainly acquired through acquisitions and not through independent innovation. See Table 7 for details.

5. Conclusions and policy recommendations

For many decades, China was treated as a technology follower, rather than a technology leader. Several decades after the country's political opening and with a rapidly growing economy, research suggested that China was still in the process of technological catching up and not yet an innovator (Altenburg et al., 2008). With regards to climate-relevant technology and low carbon innovation this was correct in the past, as technology transfer from the global North to China played an important role for many decades. However, in recent years the conception that China is lacking behind in innovation capabilities is partly outdated. This research suggests that the tide has turned with regards to climate-relevant technology and low carbon innovation, particularly for solar energy and hydropower technology. Drawing on in-depths interviews, focus group discussions, field visits and data analysis, this research challenges the North-South technology transfer paradigm. This paper presents three case studies from hydropower, solar energy and wind energy to argue that China is already engaged in South-South as well as South-North technology transfer and cooperation in these fields. The research shows that there are different variations of technology transfer and cooperation happening for these three sectors, as well as broader, more systematic trends that can be observed across the wider low carbon energy sectors.

For solar water heaters, China has been an innovator for more than two decades, not just a leader in production. Chinese firms are reported to hold 95% of the patents for core technologies for solar water heaters (CGTI, 2011). Also for solar PV, Chinese firms are increasingly global leaders in patenting core technologies and leaders in global knowledge networks.

For hydropower, China is already engaged in South-South technology transfer of its own technology to low and middle income countries in Asia and Africa. Chinese firms are the world's largest dam builders in terms of the size of dams built, the global coverage, the investment sums and they also use state-of-the-art technology at competitive costs. Chinese state-owned enterprise Sinohydro is reported to have a global market share of over 50% of the international hydropower market (International Rivers, 2017).

For wind energy, there are signs that the dynamics of technology cooperation are changing between the global North and the global South. While the majority of technology patents still rest with international wind energy firms such as Vestas, Enercon and Siemens, Chinese wind energy firms like Goldwind and Mingyang are catching up with patenting.

Hence across these three low carbon technologies, there is a rise of South-South technology transfer and cooperation as well as elements of 'reverse' South-North technology cooperation. The old model of the North-South technology transfer and cooperation paradigm is outdated when we refer to China and low carbon technologies. In the future there needs to be more research and policy emphasis on different 'geographies of technology transfer and cooperation', diversifying from the classical North-South paradigm and acknowledging that the reality of low carbon innovation and technology development is far more complex with regard to China than some of the current literature assumes.

There are a complex set of reasons why differences can be seen among these three sectors with policy, technology and demand factors being amongst the most important drivers that explain these differences.

One major reason is linked to policy: the development and application of hydropower technology was strongly supported by the

Table 7
overview of the factors that are characterising South-North technology transfer and cooperation for wind energy between China and Europe. Amended from Urban et al. (2015a).

Key factors of technology transfer and cooperation	Description – wind case study	Evidence found
South-South and/or South-North flow of capital	The capital for the technology cooperation comes from emerging economies (a reverse flow of capital from South to North), potentially influencing ownership of the firm and strategic decisions.	Yes
South-South and/or South-North drivers for market access	Overseas market access is driven by firms from emerging economies, potentially opening up access to new markets.	Yes
South-South and/or South-North technology/R&D leadership	Technology/R&D leadership is driven by Southern firms, leading to innovative designs and technologies that are more appropriate for new markets.	Yes
Innovation capabilities: South-South and/or South-North origins of innovation	The origins of innovation (such as patents and other IPRs) come from emerging economies.	Partly

Chinese government for many decades. The tradition of grand visions for water engineering projects stems back to the time of Mao Zedong. Even today, many leaders of the Chinese government are engineers, including water engineers, such as China's former leader Hu Jintao (general secretary of the communist party 2002–2012). Hence, indigenous innovation and state-of-the-art hydro technology was supported by the government for many decades. This, together with the Chinese 'Going Out' policy has increased the opportunities for South-South technology transfer in the hydropower sector. For solar PV, the policy focus was mainly on the export market for many years, predominantly for the European Union and the United States. It is only since the financial crisis in 2008 that a re-orientation towards domestic markets, as well as non-OECD overseas markets in Asia, Africa and partly Latin America has happened. This explains while South-South technology transfer as well as South-North technology cooperation is more pronounced in this sector. For SWH there was very little policy support or coordinated financial incentives available after the commercialisation of the evacuated tube design by Chinese scientists (post the 1990s), yet indigenous innovation flourished due to a self-reliance on domestic engineering and science skills. Today Chinese firms such as Himin Solar are operating in more than 30 markets around the world, both in the global South such as in Algeria, Argentina, Brazil, Egypt, India, Madagascar, Malaysia, Mexico, Namibia, Nigeria, Pakistan, Senegal, South Africa, Tunisia, Vietnam as well as in the global North such as in Australia, Canada, Germany, New Zealand, the United Kingdom, the United States etc (Himin, 2017). Hence South-South and South-North technology transfer is actively promoted for solar energy. With regards to wind energy technology, the Chinese government has actively created a domestic market by the means of coordinated policy and financial support over many years. The introduction of a local content requirement, which was 50% from 2004 to early-2005 and 70% from mid-2005 until its abolishment in 2009 meant that foreign firms only had access to the Chinese wind energy technology market if their production capacity was in China. As a result many foreign firms, such as Vestas, entered joint ventures with Chinese firms (Urban et al., 2012). This explains why there is much more of an emphasis on South-North technology cooperation in the wind energy sector than there is for the hydro and solar sectors.

Another major reason to explain the differences among these three sectors is the technology itself. Solar energy technologies, particularly SWH, are far less complicated technologies than wind turbines. It is often argued that a wind turbine consists of 100,000 components, all of which require advanced engineering skills to produce. This is why countries such as Germany, which are traditionally strong in electrical engineering due to expertise from other sectors (car manufacturing, household electronics) were able to develop state-of-the-art wind technology quicker and better than some of their competitors. A modern hydropower dam requires advanced technology too, however not to the same level as a wind turbine. Also, much of the Chinese hydroelectric engineering skills were build up over many decades, starting with small scale, less technologically advanced hydropower schemes and slowly building up in size and scale over the decades.

A third major reason is demand. The characteristics of China's energy demand and its geographic conditions result in a huge energy demand which is concentrated in urban centres, mainly along the coast in Eastern China. The small-scale and decentralised nature of SWH and PV panels does little to meet the gigantic energy needs of China's urban centres. In addition, limited roof-space in urban areas results in unfavourable conditions for highly individualised solar PV installations. Hence, the need for expanding to overseas markets both in the global South and the global North. For wind energy, large-scale wind farms in Inner Mongolia, Gansu and Xinjiang are helping to meet the demand in Western China and beyond, with some efforts of feeding into regional grids and long-distance electricity transport. There is therefore less need to look overseas for new markets, yet this is happening to some extent. For hydropower, the sector has nearly reached its saturation point domestically with many major rivers in China being already dammed. The Chinese government therefore actively encourages hydropower firms to 'go out' to access under-explored overseas markets with un-met energy demand, particularly those in Southeast Asia and in Africa. This is one factor driving South-South technology transfer and cooperation in the hydropower sector.

5.1. Policy recommendations

As this research finds, China has greater innovation capabilities in low carbon energy technologies than assumed in the past and hence the country could play a more active role for climate change mitigation and low carbon transitions, both domestically and internationally. This has implications for future science and technology policy-making at the local, national, regional and international level, as well as for international technology initiatives such as the UNFCCC Technology Mechanism and the Technology Framework included in the Paris Agreement. This results in the following two policy implications:

1. In recent years, China has emerged as a global climate leader at the domestic and international level, which is particularly strongly visible since the Trump administration announced to withdraw the US from the Paris Agreement. Meanwhile, China has the capabilities to not only be a leader in terms of climate policy, but to also be a leader in climate-relevant technology and innovation. This means that China can take on a leading role for facilitating technology transfer and cooperation of climate-relevant technologies with the global South and the global North, not only as a host country or a recipient of technology, but also as an innovator and technology supplier. Internationally, the role of China could be strengthened for the UNFCCC's Technology Mechanism, including for the Technology Executive Committee (TEC) and the Climate Technology Centre and Network (CTCN), as well as strengthening China's role for the Technology Framework embedded within the Paris Agreement. China could also take on a global leadership role, leading a group of innovative emerging economies from the global South such as China, India, South Africa and Brazil, and exploring within the UNFCCC and beyond their role for Southern-led technology transfer and cooperation for the benefit of these countries and the wider international community.
2. Bilaterally, China could engage more strongly in South-South and South-North technology transfer and cooperation, which it already does with many African and Asian countries, as well as some countries in Latin America and Europe. In terms of global policy implications, firms and governments around the world are already looking for partnerships and technology cooperation with China, particularly in the energy sector as China can deliver advanced low carbon technology at competitive prices. Firms in the global North could encourage more South-North technology cooperation with China by setting up joint ventures, such as in the wind and solar energy sectors which may also enable Northern firms to access the Chinese market (see the example of Goldwind-Vensys for a win-win situation). This fits well within the Chinese government's 'Going Out' strategy that has encouraged SOEs and private firms to engage in overseas markets since 2001. This strategy enables Chinese firms to access new markets, create employments, cooperate on state-of-the-art technology development and gain further global political and economic power while safeguarding the global climate. Finally, this approach could help accelerate global low carbon transitions and climate change mitigation, for which China has global importance.

Finally, this paper has cross-synthesised findings from three low carbon energy technology sectors: wind, solar and hydropower. It comes to the conclusion that for these technologies China is no longer only a technology follower, but a technology leader with a world-wide reach. A transition from production capabilities to innovation capabilities has therefore happened in China's low carbon energy technology sectors.

As other emerging economies may follow similar trends, it is useful to broaden our understanding of technology transfer and cooperation, to move away from the prevailing focus on North-South technology transfer and instead to examine various 'geographies of technology transfer and cooperation' and their dynamics, characteristics and outcomes.

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