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Denmark – China

SDC International Report 2020

Cooperating for Energy Transition

Edited by Birte Holst Jørgensen, Stine Haakonsson, Hong Zhao and Guangchao Chen

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Content

Preface 5

Part I: Cooperating for energy transition

Chapter 1 / Introduction and background 8

Chapter 2 / Sino-Danish cooperation in the energy transition 10

Part II: Sino-Danish energy outlook for technologies and systems

Chapter 3 / Energy scenarios and policies 24

Chapter 4 / Mapping wind resources and extreme winds: Technical and social aspects 33

Chapter 5 / Smart energy systems in China and Denmark 42

Chapter 6 / Power electronics-based large-scale integration of renewables in power grids 50

Chapter 7 / Solar thermal energy. 58

Chapter 8 / District heating for China's energy transition: Lessons from Sino-Danish collaboration. 65

Chapter 9 / Digitalisation for energy efficiency and flexibility 72

Part III: Transforming the energy system through policy and innovation

Chapter 10 / Catching up through green windows of opportunity 82

Chapter 11 / Sustainability-driven innovation in China: The case of Windoor. 92

Chapter 12 / Energy transitions in urban China: Drivers, developments and challenges 98

Chapter 13 / China's pragmatic experimentalism towards sustainable transition: Wind power and Sino-Danish collaboration. 104

Chapter 14 / Financing the global low-carbon energy transition: China's dual role domestically and overseas 110

Chapter 15 / Small hydropower sustainability evaluation in the Road and Belt Initiative 119

Abbreviations. 130

Preface

An ancient Chinese proverb says that "when the wind of change blows, some people build walls, others build windmills". 2020, the Chinese Year of the Rat, has been a year of dramatic winds of change caused by COVID-19, forcing countries around the globe to lock down major parts of their economies and introduce restrictions on movements within and between countries. This has also impacted university cooperation at the Sino-Danish Center (SDC). Professors and students alike have made an enormous effort to create an inspiring and active learning environment so that students can graduate on time and with their customary high ranking degrees. Researchers have continued their research, even labs opened after a time, but they have missed the enriching experience, normally open to international scholars, of working at partner institutions across our two countries. However, research cooperation does not recognize borders and SDC researchers have continued to collaborate. This collaboration began over ten years ago and has developed into a thriving research environment where tangible results are produced by dedicated professionals. This first "SDC International Report 2020. Cooperating for Energy Transition" is the fruit of such collaboration. The idea emerged before the pandemic and took off shortly after the Chinese lockdown in January, rapidly developing over the following months, by which time Denmark had also entered lockdown. Our report has been drafted, scrutinised and redrafted in accordance with academic norms of peer review and interaction. SDC has refused to envisage COVID-19 distancing as a physical wall. Instead we build bridges, which hopefully will lead to more windmills, an ambition compatible with the Energy Transition, a topic highly relevant both for the future and to this first SDC International Report.

Morten Laugesen
Danish Director

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Part I
Cooperating for energy transition

1

Introduction and background

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This report highlights research from the Sino-Danish Center (SDC), the fruit of a consolidated and strong bilateral partnership for collaboration in science, technology and innovation between universities in China and Denmark. In 2020, SDC celebrates its ten-year anniversary, making it a perfect moment to present some of the academic outcomes of this partnership. This volume constitutes a collection of research that brings to the fore one of the most important global challenges facing the world today: the energy transition. Addressing this challenge and achieving the sustainable development goals calls for international collaboration, and as the chapters in this report illustrate, bringing together scholars from different disciplines, backgrounds and geographies offers a holistic perspective for a sustainable transition. Moreover, the report simultaneously addresses the development, context, implementation and dissemination of energy transition solutions.

We intend to draw attention to the work of two SDC research clusters: Sustainable Energy and Social Science. A prerequisite for understanding how a sustainable energy transition can materialize is an analysis of how these two areas interrelate. Indeed, the transition 1) may be facilitated by policies, drivers and strategies at different levels (international, national and regional), 2) can be organized in ways that ensure common goods are safeguarded across generations, and 3) is subject to technological development, selection and integration. Technology and societal change are two sides of the coin when addressing the challenge of climate change.

The Covid-19 virus, which has been changing the world as we write, is a current and germane example of the relevance of interdisciplinary and international collaboration. Workshops and conferences have moved online along with our teaching programmes, and we were unable to make visits throughout 2020. Covid-19 has become an international crisis, with an enormous impact on people's welfare, health and economic activities. In terms of the energy transition, Covid-19 is also a reminder of the indispensable role of electricity in modern life. With entire countries locked down, system operators faced new challenges in balancing supply and demand. Covid-19 can be considered a testing ground for international governance and collaboration, and a beacon to future demands for a sustainable and reliable energy system that is based on generating electricity from renewables and is underpinned by flexible, smart and resilient networks.

The energy sector is in the midst of unprecedented global change driven by rapidly evolving technologies, changing customer demands and new business opportunities. China and Denmark are at the forefront of this development, both in terms of research and implementation. Since the 1980s, Denmark has been a bona fide pioneer in energy transition, and over the past two decades, China has become a global leader in the large-scale deployment of renewable energy technologies and new grid concepts. Both China and Denmark have committed to the Paris Agreement and its central goal to keep global warming well below 2°C. Though their roadmaps differ, both countries have set ambitious targets to increase renewable energy as a percentage of total energy consumption by 2030.

With high annual economic growth rates and a constant rise in energy consumption, China faces a substantial challenge to maintain the balance between energy supply and demand in a sustainable and affordable way. In 2016, China introduced policies to promote a cleaner and greener economy. These policies established specific targets for environmental management and protection, clean energy and emissions control, and the development of green industries. With the Nationally Determined Contributions (NDC), China has committed to a CO_2 emissions peak and a reduction in carbon intensity of 60-65% by 2030 (compared to 2005). The government also introduced the 'New Normal', marking a shift in national policy towards an economy with moderate but higher quality growth. It is expected that the next Five-Year plan, and the medium and long-term plans, all of which will be launched in 2021, will reaffirm this direction and set even higher national targets.

In June 2018, the Danish government signed an energy agreement setting the goal of reaching 55% renewables in total energy consumption and 100% renewable electricity by 2030. This will be mainly generated by new offshore wind parks. In 2019, Denmark introduced a binding de-carbonization target and consequently the 2030 benchmark was updated to a target of reducing emissions by 70% below the 1990 level (excluding international shipping and air travel). Danish policies also encompass energy efficiency improvements, a broad electrification strategy, a ban on the sale of all new diesel and petrol cars from 2030, and cooperation with other North Sea countries to further exploit offshore wind energy potential.

Future energy systems in Denmark and China will be smart, efficient and integrated. New technology will play a significant role in achieving national energy consumption targets and providing a smooth transition to a low-carbon energy system. Research, development and education across the fields of Energy and Social Science are crucial in addressing challenges related to the planning, development, integration, operation and optimisation of energy systems; these systems should be accessible, reliable and resilient, and steadily increase the share of renewable energy sources. SDC researchers from China and Denmark across the Energy and Social Science research fields have taken on the task of closely monitoring and contributing to this development. The following chapters show how the dual perspectives of technical and societal transformations complement each other, constituting the Yin and the Yang in the transition of the two countries' energy systems.

Chapter 2 provides an overview of Sino-Danish research collaboration in relation to energy transition. The remaining chapters are organised into two main sections. Part II, 'Sino-Danish energy outlook for technologies and systems' focuses on technical and engineering aspects of energy transitions from a systems perspective. Chapter 3 examines the development and deployment of energy scenarios in Denmark and China. Chapters 4 to 9 focus on specific technologies: Wind mapping (Chapter 4), smart energy solutions (Chapter 5), integration of renewables into the grid (Chapter 6), solar thermal power (Chapter 7), district heating (Chapter 8) and digitalisation (Chapter 9). All these technologies benefit from a substantial level of collaboration across the two countries and a high level of complementarity in the knowledge base. Part III, 'Transforming the Chinese energy system through policy and innovation' addresses changes related to energy transition at multiple levels, including business, consumers, national and international governance, policy and socio-economic transformation. Chapter 10 analyses the industrial development of Chinese manufacturers and their role in the deployment of renewable energy in the Chinese market. Chapter 11 looks at urban development and the construction of new satellite housing areas, while Chapter 12 explores the upgrading of urban energy and mobility. This is followed by an examination of China's new role, both internally (Chapter 13) and as a financial actor in the region (Chapter 14). Finally, Chapter 15 assesses sustainability of small hydropower.

The chapters are written by teams of leading international researchers responsible for projects embedded in the SDC research themes of Sustainable Energy and Social Science. Each chapter is founded on internationally recognized research and is fully referenced. Indeed, the chapters have been subject to a peer review process involving leading international experts in line with the highest standards of academic quality. The four editors are the Principal Coordinators of SDC in China and Denmark.


Industriens Fond

2

Sino-Danish cooperation in the energy transition

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Introduction

The sustainable energy transition is a critical shift to secure the future of the planet and the existence of human beings. Both sustaining current living standards of the global middle class and improving the lives of people still living in poverty are at stake. The transformation of our energy systems towards a sustainable, more efficient and affordable model encompasses energy production, transmission and consumption. The impact of institutional drivers and barriers, and who uses energy and at what cost, are also key factors. Moreover, this transformation comprises different scales, from the household to national policy, and from international markets and technology transfer networks to international governance of energy and climate.

The global political agenda on climate change is driving this unprecedented transformation of energy systems, facilitated by a rapidly evolving techno-economic system, changing customer demands and new business opportunities. Innovation and large-scale adoption of clean energy technologies, which complement other emission-based policies, are key to decarbonising the energy sector and combatting climate change (WEF 2020; IRENA 2020). While policy innovation and implementation often takes place locally and nationally, international cooperation is critical given the urgency of energy and climate challenges (Gluckman et al. 2017). In September 2020, Xi Jinping, the Chinese President, announced China's objective to achieve a carbon neutral energy system by 2060, with a carbon emissions peak in 2030. Alongside this target, Xi Jinping made an appeal for international collaboration, "We call on all countries to pursue innovative, coordinated, green and open development for all, seize the historic opportunities presented by the new round of scientific and technological revolution and industrial transformation, achieve a green recovery of the world economy in the post-COVID era and thus create a powerful force driving sustainable development" (Speech at UN General Assembly, 22 September, 2020). Meanwhile, in Denmark, the stated political objective is to reduce carbon emissions by 70% by 2030.

Cooperation on sustainable energy has increasingly traversed geographies. Though at different scales and following slightly different paths, China and Denmark are among countries with ambitious goals for a sustainable energy transition. Denmark has long been a forerunner in sustainable energy transition, while China is currently leading the world in investments. At the beginning of the century the two countries established energy-related cooperation and the transfer of knowledge, practice and technologies (see below). Today, this collaboration goes beyond the governmental and diplomatic sphere with the market nurturing innovative systems from both countries for developing new energy solutions (Haakonsson & Slepniov 2018; Haakonsson et al. 2020).

In this chapter, we examine the rationales for international energy-related cooperation in general, and for Sino-Danish cooperation in particular. We explore the development of the strategic partnership between the countries, and the visions and driving forces related to sustainable energy technologies. We scrutinize the complex network of collaborative R&D efforts between Denmark and China and put this in the context of international energy technology cooperation.

International energy R&D cooperation

The transition towards a sustainable, affordable and reliable energy system will require nothing short of a revolution in energy technology. It necessitates a radical change in how we organize our societies, encompassing infrastructure, institutions and markets along with technological improvements. Existing technologies need to improve and be deployed in a more astute way, particularly in energy efficiency, alongside the introduction of radically new technologies and concepts. The scale of the energy challenge and the heterogeneity and complexity of energy systems demands a broad offering of new energy technologies, and an acceptance that some may not succeed. Technology leaders should adopt a push and pull strategy to accelerate the development cycle from research to market deployment. Finally, while economic development is dependent on reliable and affordable energy systems, huge opportunities exist for technology providers on the global market. Meanwhile, new concepts such as the 'post-growth society' are emerging, and will engender changes in mobility, interconnectivity, smart cities, the sharing economy and bottom-up initiatives in sustainable development.

The question is not whether to engage in international cooperation on energy transition, but to what degree, where and how. A good starting point are initiatives directly linked to industry innovation through research and development (R&D). Although international energy R&D cooperation has been high on the political agenda in times of energy crisis and other global challenges, it seldom goes beyond knowledge exchange and memorandums of understanding (Edler 2010; Gray et al. 1985). National technological capacities tend to be associated with international competitiveness, technological potency and consequent negotiating strength (Gray et al. 1985; Grin et al. 2010; Mazzucato 2015; Geels and Schott 2007). Balancing government strategies for competitiveness and transition with firm ambitions for scaling up in international markets is challenging. Different political systems may have conflicting objectives, making international cooperation even more difficult (Mitchell 2010) and shaping governments' innovation and energy policies, an area high on the agenda in terms of national security.

Benefits of international R&D cooperation

International R&D cooperation brings a number of benefits (Gray et al.1985; Georghiou 1998; Boekholt et al. 2009; Archibughi et al. 1999; Kuemmerle 1999) that can be grouped into two major categories. *Narrow or direct benefits* for science and research activities undertaken by the science community aim to stimulate cross-fertilisation, enlarge the scale and scope of research activities, improve the capabilities of researchers and institutions, harvest synergy effects and complementarity, set the standards of future technologies, secure access to state-of-the-art knowledge and attract resources for science, technology and innovation. Taken together, these contribute to scientific and knowledge competences and competitiveness, as well as industry level dynamic capabilities and absorptive capacity. *Broader or indirect benefits* for other political and economic objectives provide the means for addressing global challenges, such as climate change, while seeking to improve national competitiveness, foreign relations and development policies. Often, trade-offs have to be made between conflicting policy goals, not least in energy policy.

Narrow/direct benefits of international cooperation

The direct, scientific benefit of international cooperation mainly relates to the potential to improve scientific quality, scope and critical mass by connecting resources and knowledge across national borders. The concept is embedded in the scientific norms of communalism, universalism, disinterestedness and organised skepticism (CUDOS). Scientists build on merit review, critical thinking, diversity of thought, and transparency and knowledge exchange with peers. It is a mutual exchange, though not simultaneously and not necessarily with the same peers. The benefit is both to secure access and attract state-of-the-art resources and knowledge (Boekholt et al. 2009).

Access to expertise, knowledge or skills aims to enhance scientific or technological excellence, reaching across national boundaries. This is clearly the case for a small country such as Denmark where competences may be under the threshold for critical mass and/or limited to specific areas. It is also the case for a large country such as China that seeks to improve its leadership in science and technology. China's rise on the global stage is also reflected in the fields of research and higher education. Since the late 1980s, China has sent tens of thousands of young scientists and engineers on research stays in leading universities abroad, but while many in the past chose to remain abroad, there has been a concerted effort by the Chinese government in recent years to encourage them to return home (Basu et al. 2018). Today China has the second largest R&D budget in the world after the USA, the second largest pool of researchers after the EU and has surpassed the USA in numbers of scientific publications (d'Hoodge et al. 2018). Recent scholarly work also highlights the potential of internationally organized and dispersed innovation. Indeed, the current stage of globalization involves new forms of global organized innovation networks (Ernst 2002; Barnard and Chaminade 2017; Gu et al. 2016).

Access to unique sites and specialized facilities is a further benefit of cooperation. A good example is how Danish researchers working on energy-related fusion technology have, under the auspices of the Sino-Danish Center for Education and Research, established a long-term cooperation with researchers from the Chinese Academy of Sciences' Institute of Plasma Physics (IPP). This provides them with access to the Experimental Advanced Superconducting Tokamak, EAST, an experimental superconducting tokamak magnetic fusion energy reactor in Hefei. Such partnerships mean the costs and risks of expensive research infrastructure are shared; examples are the CERN in Switzerland, the ITER tokamak facility in Southern France and the European Spallation Source (ESS) in Southern Sweden. Research and development that necessitates large-scale science infrastructure is increasingly organised into global networks. The Huairou Science City Park, which is under construction just north of Beijing, is a good example.

Indirect/broad benefits of international cooperation

In addition to the direct benefits of international cooperation, indirect benefits are associated with broader economic, political and cultural objectives. Competitiveness is becoming a very important driver at both national and supranational/regional levels. The EU aims to use international cooperation in research and innovation to not only improve excellence in this area, but to strengthen economic and industrial competitiveness - outward strategies provide access to new markets while inward strategies attract businesses and resources to individual countries. Meanwhile, Chinese innovation policy has shifted along similar lines over the past decades, moving from leveraging indigenous innovation to exploring international collaboration and strategic alliances (d'Hoodge et al. 2018; Fu and Mu 2014).

Opening up to new markets is particularly promising for companies in the renewable energy industry. Opportunities for new energy technologies are booming in emerging markets where economic growth relies on a secure, affordable and sustainable energy system.

R&D cooperation also benefits exports as it may contribute to opening up to and providing access to important actors in the energy sector, such as governmental institutions in charge of implementing, operating and maintaining infrastructure and sustainable investments. Global competition among technology providers is fierce and irrespective of national barriers, energy costs define whether an investment is remunerated in the longer term. Over the last decade, there has been a market tendency towards auction systems for renewable energy infrastructure. Energy technology systems are complex and comprise a wide variety of knowledge-intensive technologies and standard components, all of which rely on a process of smooth integration into the local energy system.

Attracting knowledge and inward investment is another driver of international cooperation. In a Research and Innovation (R&I) assessment of Denmark, enhanced international cooperation is highlighted as a mechanism to increase the relatively low number of new doctoral students and the quality and availability of research and innovation skills (Knudsen et al. 2018). Indeed, the work of innovation centres in global technology hotspots facilitates cooperation and attracts universities and companies. These centres are often aligned with the *Invest in Denmark* programme that aims to attract foreign direct investments (FDI), including R&D-intensive companies that wish to link up with key players in Denmark, in areas such as renewable energy. Today, most countries have scientific officers within their diplomatic teams to facilitate and nurture international science collaboration.

The magnitude of addressing global energy and climate challenges is perhaps the single most important driver in international energy technology cooperation and therefore is helpful in seeking to understand the dynamics of international collaboration in general. The climate challenge is simply too great to be tackled by one country alone, and the involvement of countries with different R&D knowledge bases and financial resources is essential to secure successful outcomes (Boekholt 2009). This cooperation is evident in all phases of the value chain from basic research to deployment of known technologies that have to be adapted to local systems and contexts.

Barriers in international energy technology cooperation
While international cooperation is expected to bring about direct economic, societal and technological benefits, there are barriers that need to be addressed. Access to promising new energy technology and systems markets does not mean that market share is evenly distributed (Georghiou 1998). Emerging markets such as China do not open up their markets to foreign products and direct investment without implementing measures to protect the competitiveness and development of their domestic industry and knowledge base. Since 2006, China has implemented industrial innovation policies that favour indigenous technologies at the expense of imported technologies. These policies include a mandate to replace imported technology in core infrastructure, the use of public procurement to block products not designed, developed or produced in China, a requirement for imports to pass product testing and approval regimes, the use of domestic patent rules, and the leveraging of Chinese industrial and technology standards as market barriers to foreign technology. Consequently, many Chinese firms have developed to a size and standard that is fast closing the gap on foreign technology (Fu 2015; Lema et al. 2020), presenting a huge challenge to incumbent companies from the so-called advanced economies.

Another barrier is the rise in institutional complexity that results from collaboration, termed in the business literature as the 'liability of foreignness'. Different cultures, national innovation systems, structures and priorities make it difficult to successfully match research communities and identify the relevant funding agencies, as well as to agree on appropriate administrative and monitoring mechanisms for project development. National systems follow procedures and rules developed over time to support their respective research communities. Often, restrictions exist for foreign access to national programmes, making it more difficult to align administrative regimes. Further, development expenditure is often considered as an investment, and therefore not adequately compensated. In addition to formal institutional differences, less visible differences around traditions, work practices and culture make establishing close collaboration a long-term investment – at both the individual and the institutional level.

From a narrow national funding agency perspective, management of international cooperation is cumbersome, time-consuming and is obliged to demonstrate a reasonable return on investment. Public R&D expenditure is seldom a governmental priority in times when populations expect tangible and short-term economic and welfare benefits. This makes it even more difficult to spend R&D resources on international research cooperation instead of national research projects (Stamm et al. 2012).

Even though the World Trade Organization (WTO) introduced a binding agreement on intellectual property rights (IPR) (TRIPS Agreement), or patent protection, the perception persists that international cooperation faces serious challenges. The purpose of IPR is twofold, to foster the development of new technologies while facilitating their diffusion across and within countries. It aims to boost the private economic incentive to invest in innovation, and promote the creation and transfer of technology. Conversely, IPR also holds back the development and diffusion of new technologies as it

MISSION INNOVATION

Mission Innovation(MI) is a global initiative of member countries from five continents, 24 countries and the EU, working to accelerate clean energy innovation.

China and Denmark were among the founding countries of MI. When world leaders came together in Paris in December 2015 to undertake ambitious efforts to combat climate change, a group of countries launched MI to dramatically accelerate global clean energy innovations with the objective of making clean energy widely affordable.

As part of the initiative, participating countries committed themselves to doubling their governments' clean energy research and development investments over five years, while encouraging greater levels of private sector investment in transformative clean energy technologies.

MI complemented another global initiative, Clean Energy Ministerial (CEM), established in 2009 and focused on deployment measures for a global clean energy economy.

China and Denmark hosted ministerial meetings of CEM and MI, in Beijing in 2017 and in the Oresund Region in 2018, respectively.

Member countries cooperate on a number of innovation challenges of common interest.

Danish and Chinese researchers also engaged with Sino-Danish Center (SDC) to cooperate closely on Smart Grid innovation challenges, which China co-leads together with Italy.

http://mission-innovation.net

increases costs and has the potential to limit availability. The literature on IPR reveals its systematic impact on technology transfer and licensing for middle-income countries (emerging economies), for which the risk of imitation in the absence of IPR is relatively high. Though concerns exist around the lack of enforcement of IPR in emerging countries, recent empirical analysis has found that IPR is not a barrier to the diffusion of energy technologies, and that theft of intellectual property in new energy technologies is exaggerated. Indeed, IPR should be seen as an important administrative aspect of international cooperation that needs to be addressed early (Anadon et al. 2015).

Finally, international cooperation is vulnerable to changes in financial and political commitment. It can be exposed to partner withdrawals and cutbacks in funding, as countries tend to change strategy over time, at times opening up, at other times closing in. This has clearly been demonstrated by the Trump administration that has downsized or cancelled financial and political engagement in international R&D cooperation. Both its engagement in Mission Innovation and the US-China energy collaboration have been impacted.[1] The development of institutionalized country-level partnerships has become a critical tool in sustaining collaboration, inspiration and co-creation, particularly for smaller countries.

In conclusion, international cooperation has the potential to increase the scope and scale of research and can therefore develop solutions more effectively and efficiently to crucial challenges and problems – particularly those related to the transition of energy systems. International R&D cooperation is also characterized by differing and overlapping policy objectives, ranging from national competitiveness to trade, foreign investment, development aid and science diplomacy, together comprising a comprehensive package of external action (EU Commission 2012). While some barriers can be overcome by drafting careful agreements, others are related to transaction costs and should be resolved through organizational and procedural measures. An example follows of a broad international R&D cooperation, involving China and Denmark.

Sino-Danish energy cooperation

Sino-Danish cooperation is founded on long-term diplomatic relations. Denmark is the only country to have an unbroken diplomatic presence in China since 1908. On 11th May 1950, Denmark and China consolidated their relationship by establishing embassies and ever since Danish recognition of the Peoples Republic of China and its national territory (the One-China policy) has remained unchanged. China's increasing integration into the international community has led to dialogue and cooperation across all areas of common interest.

1 www.energy.gov/ia/initiatives/us-china-clean-energy-research-center-cerc

In 2008, the two governments signed an agreement to establish a Strategic Partnership in areas of common interest. Most importantly, the intention was to strengthen political dialogue between the two governments to foster cooperation in areas such as climate, energy, environment, research, innovation and education. In 2017, this cooperation was upgraded through the China-Denmark Joint Work Programme 2017-2020.

Government-to-government initiatives in the energy area included the Wind Energy Programme (WED), 2007-2010, which targeted capacity building in wind energy to contribute to China's energy supply. The Renewable Energy Programme (RED), aimed at enhancing capacity for renewable energy development in China, ran from 2009-2013. A key component was the establishment of China's National Renewable Energy Centre to support the Chinese government and society in promoting renewable energy development. This led to the founding of the China Renewable Energy Center (CNREC), which today is a leading Chinese government think tank for renewable energy policy. Government-to-government energy cooperation has further been strengthened by a number of Memorandums of Understanding (see box below for details) that seek to enhance Sino-Danish cooperation between companies, organizations and institutions, and thereby facilitate Danish stakeholders' entry into the Chinese energy market and vice versa.

Sino-Danish scientific and research cooperation is deeply embedded at multiple levels and embraces individual researchers, universities and research council systems. Researchers – often supported by grants and support mechanisms – cooperate with peers across universities from the two countries. Universities build international alliances with partner universities on research and education. For example, Copenhagen University is a member of the International Alliance of Research Universities (UERU) together with Peking University and nine other international universities. Until recently, Copenhagen University also had a close partnership with Fudan, one of the world's leading universities. The research council systems in both countries have made joint calls for proposals and supported research projects. For example, the National Science Foundation of China (NSFC) and the Danish National Research Foundation have supported three Centres of Excellence in the energy sector, focusing on solar, materials and fuel cells.

Following the launch of the Danish Strategic Action Plan, existing mechanisms to facilitate and strengthen researcher mobility and institutional collaboration were further complemented by new initiatives to overcome barriers and generate direct and indirect benefits. These included joint research and innovation proposals by MOST and Innovation Fund Denmark, the Danish International Network Programme. The Danish strategy for science cooperation is described below.

Overview of Memorandums of Understanding between the Danish Ministry of Climate, Energy and Utilities and Chinese energy authorities

1. National Energy Administration (NEA)Underlines and supports cooperation with CNREC, 2012-
2. Ministry of Housing and Urban-Rural Development (MoHURD)
   Cooperation on energy efficiency in buildings, 2014
3. National Energy Conservation
   Cooperation on energy efficiency, 2014-
4. Ministry of Science and Technology (MoST)
   Cooperation on development and demonstration projects, 2012-
5. National Development and Reform Commission (NDRC), 2013-
   Promotes a mutually beneficial partnership between Denmark and China in the field of climate and energy planning, and promotes the transition to low carbon economies

Danish strategy for Sino-Danish science cooperation

The Danish strategy for science cooperation between China and Denmark highlights the enormous value of Sino-Danish research and higher education cooperation to the Danish society and its position in the global knowledge economy.

It has three aims:

- facilitating access to Chinese partners
- attracting Chinese talent to Danish stakeholders in China and Denmark
- improving Danish researcher and student access to, and insight into, Chinese educational systems and R&D environments

The strategy outlines 11 actions for strengthening research and higher education cooperation with China and also contributes to the Danish government's China Strategic Action Plan. The establishment of the Sino-Danish Center for Education and Research was highly prioritized in the strategy.

Source: Strategi. Vidensamarbejde mellem Danmark og Kina 2008)

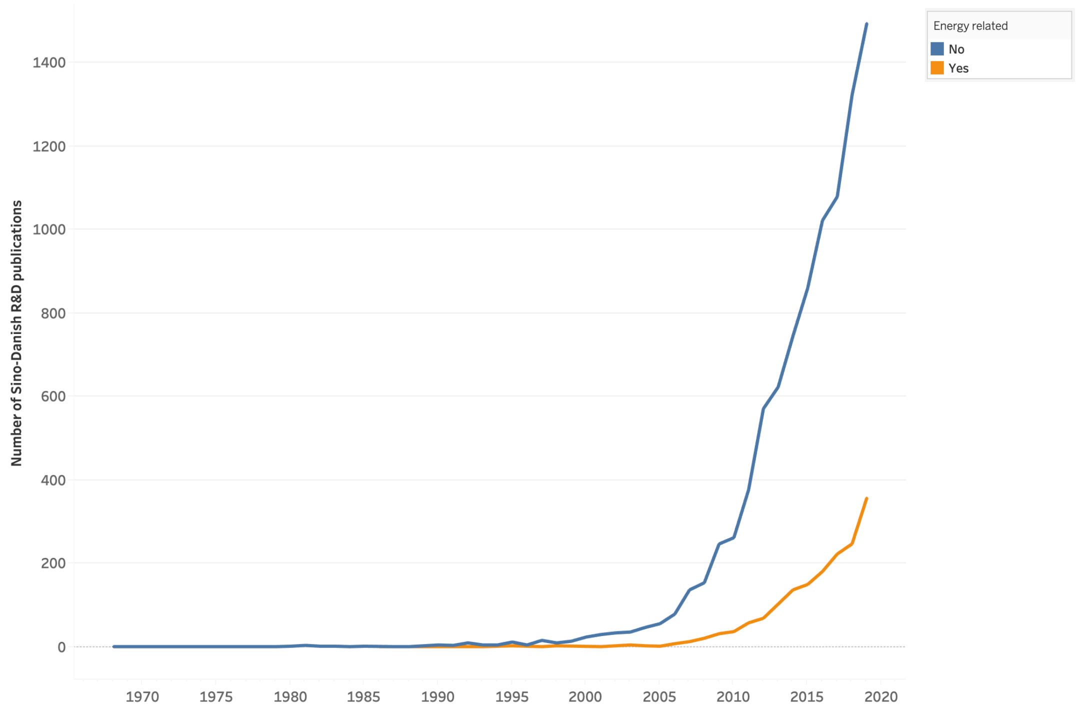

Figure 1 Total collaborative co-publication article outputs over time.

With strong political support from both sides, the Sino-Danish Center (SDC) was established in 2010 and is a partnership between all eight Danish universities, the Chinese Academy of Sciences (CAS) and the University of Chinese Academy of Sciences (UCAS). The overall objective is to promote and strengthen collaboration between Danish and Chinese learning environments and increase the movement of students and researchers between the two countries. Activities include research collaboration within seven focus areas, including sustainable energy, affiliated Masters programmes and training of PhD students. In the field of energy technology there is a dedicated sustainable energy research area as well as a more generic social science area with a strong focus on renewable energy.

Research directly linked to energy technology includes a broad range of topics that have emerged over time as relevant for cooperation. Initially, the Sino-Danish research community focused primarily on the supply side of energy systems, including fusion, solar, wind, bioenergy (thermal and biological) and, over time, energy systems analysis. Following a number of researcher-practitioner seminars on technological solutions for system integration of renewables, a new targeted approach was agreed upon to address the challenges related to the development, integration, operation, management and optimization of accessible, reliable and resilient energy systems, with an increasing focus on renewable energy resources.

In addition to the technological and energy system projects, a considerable amount of Sino-Danish research collaboration focuses on societal impacts of energy transition. This involves company and industry level research on innovation, technology transfer and learning; collaboration on policy-related issues of transformative innovation, innovation policy and the socio-economic consequences of energy transition; macro initiatives related to the digital transformation, use of artificial intelligence and machine learning; and long term strategies such as the Belt and Road Initiative and the changing world order. New emerging projects integrate differing levels of analysis and disciplines, such as projects on sustainable smart cities and zero-energy houses, dispersed green technologies and end-user involvement.

Sino-Danish R&D output

As part of this report, we conducted a bibliometric study to better understand the complex network of collaborative R&D efforts between Denmark and China (Parraguez 2020). We analyzed the key characteristics of the evolving Sino-Danish collaborative research eco-system across multiple locations, organizations, topics and individuals. While the study furnishes information on Sino-Danish cooperation in general, its focus is technological projects related to the sustainable energy transition. Scientific co-publication provides some insights into research collaboration. Figure 1 reveals a general increase in collaboration. However, as this figure exclusively shows peer reviewed co-publications, this is not a measure of all Sino-Danish research collaboration since most of this is not necessarily co-published.

Figure 1 shows that co-publication dates from the 1970s and increases significantly from 2005 onwards, with consistent annual growth of around 20%. Energy-related records numbered 1,850 or 15% of all publications.

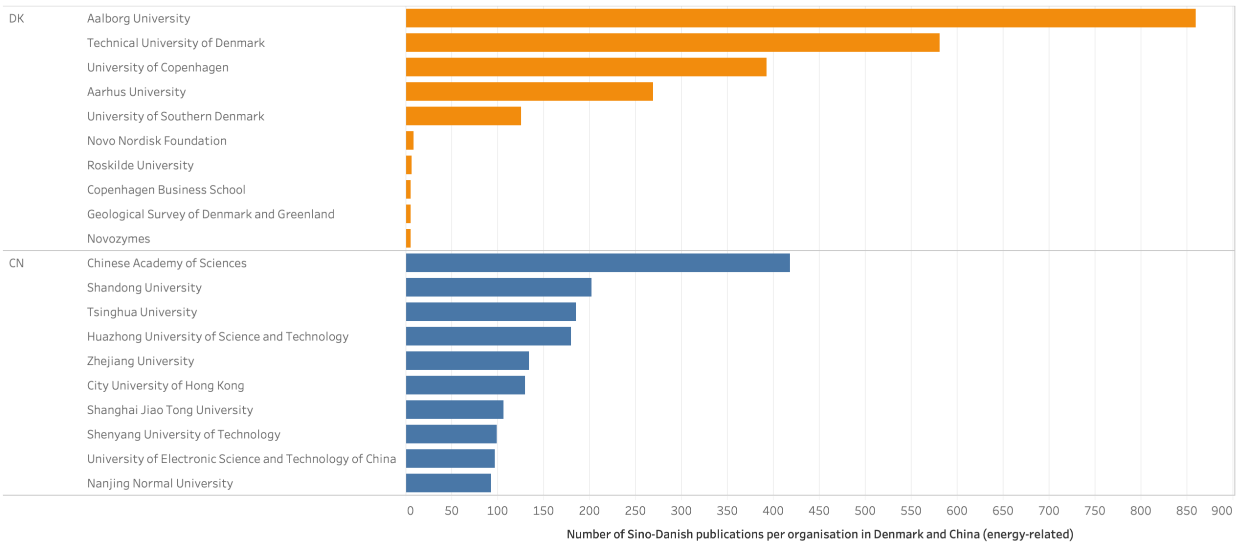

Figure 2 Top ten organisations in China and Denmark with scholars involved in energy-related scientific co-publication

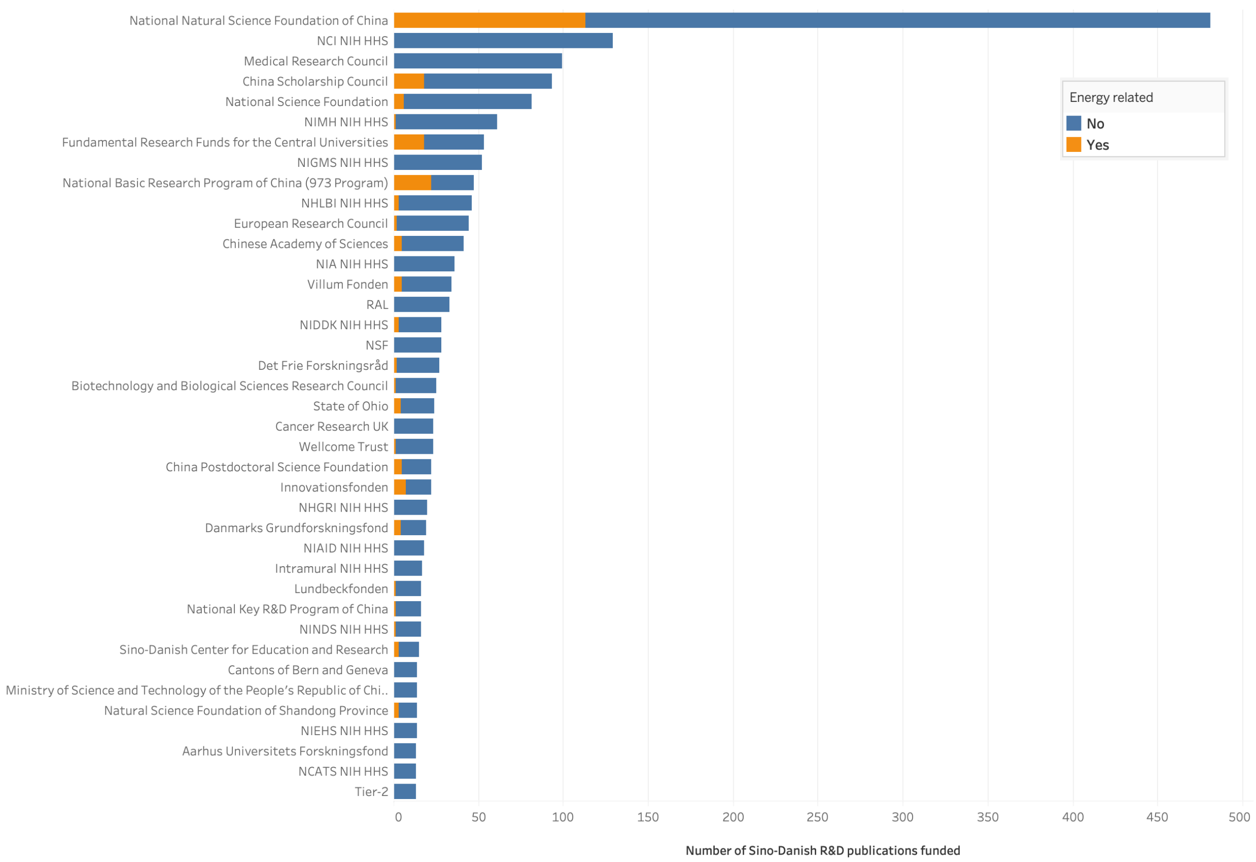

Figure 3 Funding sources mentioned in the acknowledgements sections of Sino-Danish co-publications

The top five organizations involved in overall Sino-Danish co-publication are, in order, the University of Copenhagen, the Chinese Academy of Sciences, Aarhus University, the Technical University of Denmark and Aalborg University. The same institutions comprise the top five within energy-related technology, but due to the strong engineering focus of energy research, the order differs: Aalborg University, the Technical University of Denmark, the Chinese Academy of Sciences, the University of Copenhagen and Aarhus University.

Chinese organizations are by far the largest source of funding. The National Natural Science Foundation of China is the top funding organisation, both for general and energy research. Likewise, the China Scholarship Council and the National Basic Research Programme of China (973 Programme) contribute financially to Sino-Danish collaboration. The Danish Villum Foundation is ranked at 14 in terms of funding, with only a small funding contribution to energy-related research, while the Innovation Fund Denmark is ranked at 24, producing - proportional to its size - a substantial volume of energy-related research.

Sino-Danish collaboration is not limited to bilateral relations but plays out globally, as illustrated in the networks of co-authors in Figure 4. Researchers co-publish internationally and seek out their peers at international conferences, during individual research stays or via university alliances and public support mechanisms, nurturing a broader scope of high quality networks. The leading country for both general and energy specific co-publication activities is the USA with 4352 and 431 records respectively. The United Kingdom ranks second with 2889/203 records, followed by Germany with 2377/148 records.

However, when analysing technical sciences broadly, China leads in Danish scientific co-publications, surpassing marginally Germany and the USA. Figure 5 contains data from 2014 to 2019 and shows co-authored publications in the technical sciences (engineering, environmental science, etc.) between Denmark and other countries (see https://deffopera.dk/).

The analysis identified four main clusters covering engineering+, materials, applied social and earth sciences, and human factors, the latter being much smaller. Each cluster was divided into sub-topics. The engineering factor in energy is clearly dominant, but chemistry and materials science are also significant. Economics stands out within applied social and earth sciences.

The complex connections between topics within energy are illustrated in Figure 6, showing the clusters and sub-groups of co-published papers where Sino-Danish collaboration was involved. The network has a node for each topic identified in the bibliometric analysis. The connections between topics reveal where those topics appeared on the same paper.

The respective topic tree maps of targeted topics such as wind energy, bioenergy and climate change vary substantially. For wind energy, engineering+ is dominant, with Aalborg University (AAU) leading, followed by the Technical University of Denmark (DTU). For bioenergy, waste management, biogas and biomass (within applied social and earth sciences) are dominant, with DTU leading followed by Aarhus University and the University of Copenhagen. For climate change, applied social and earth sciences, in particular environmental resource management and natural resource economics, are dominant, with Aarhus University leading followed by the Chinese Academy of Sciences.

In conclusion, the bibliometric analysis of Sino-Danish cooperation demonstrates that it accelerated from 2005 and has since experienced exponential growth. However, it is challenging to verify the impacts of multiple and simultaneous interventions and to attribute specific

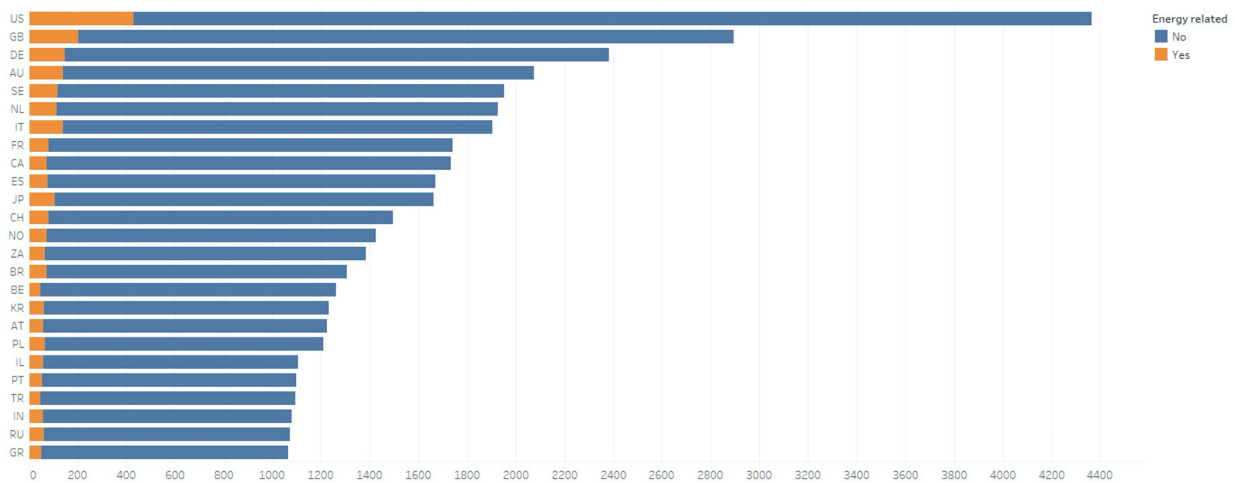

Figure 4 Total co-publication records as per third country partners involved in Sino-Danish R&D collaboration

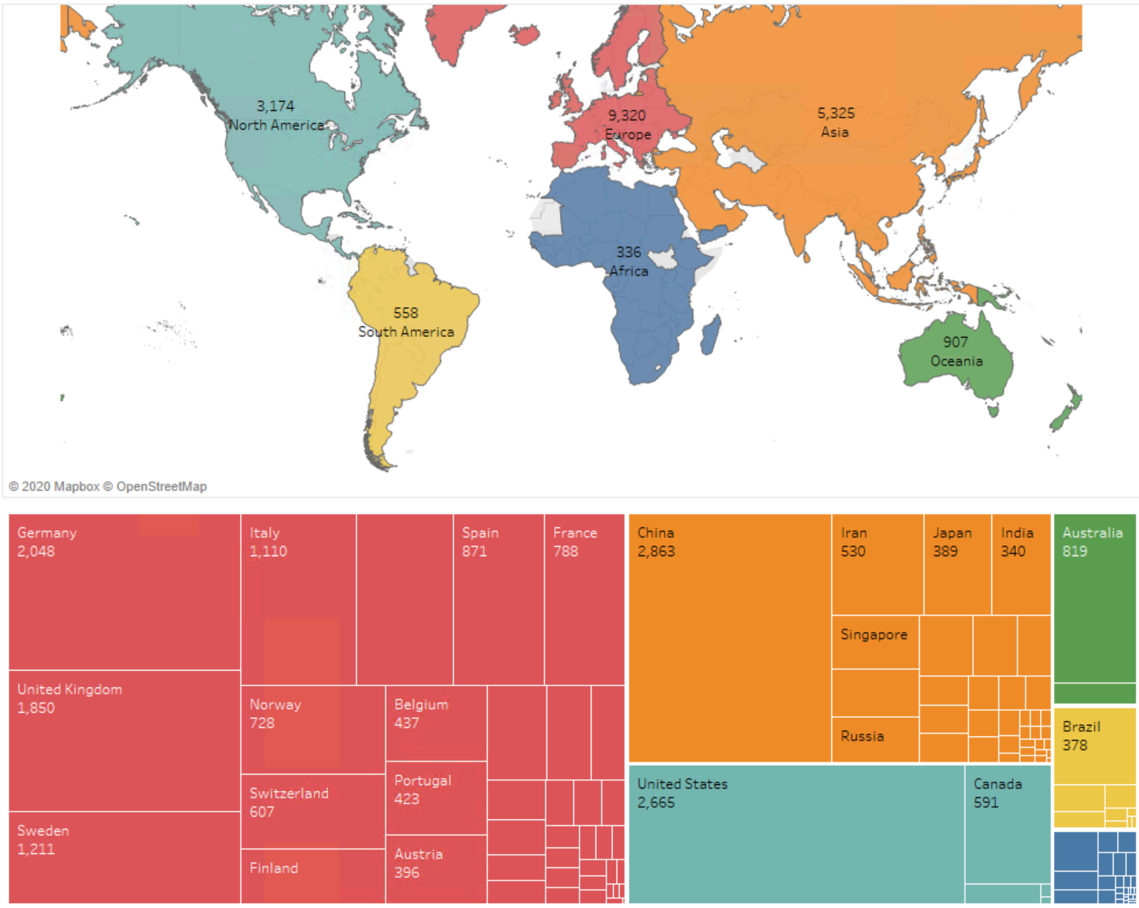

Figure 5 Total global records of scientific co-publication within technical sciences

outputs to collaboration. Researchers and institutions are involved in many international partnerships and receive funding from multiple sources, often for the same project. This growth has been aided by governmental support mechanisms and facilitating frameworks on both sides - unilateral, bilateral, and also multilateral in terms of the EU, the International Energy Agency (IEA), etc. The longer-term impacts of strategic partnerships and targeted support mechanisms are not yet evident. Due to its scale[2], China is the leading funding source of Sino-Danish cooperation. This is also true of the energy area, even though Danish research councils and private foundations have also supported Sino-Danish research. It is also significant to note that cooperation encompasses global scientific communities in the USA, the United Kingdom and Germany. Due to the role of engineering in energy technologies and systems, topic areas are dominated by engineering+ disciplines, though generic topics such as materials also play a central role in cooperation. Social science is mainly limited to disciplines such as socio-economic transformation, sociology, political science, business management and economics, and social development. Technical and social sciences are increasingly important in the energy transition as it necessitates a more complex systemic and user-centric approach driven by multiple disciplines and co-creation across themes and space. However, co-publication mapping does not corroborate this need. Sino-Danish cooperation would benefit from incentives and mechanisms that support such an approach, with an emphasis on technology for people and not the other way round.

Conclusion – the reciprocity of cooperation

Given the urgency of the energy and climate challenge, innovation and large-scale adoption of clean energy technologies are the key actions to hasten the energy revolution. International cooperation is particularly critical if this transformation is to be dramatically accelerated. Both China and Denmark have set ambitious goals to transform their domestic energy systems and both countries collaborate internationally to gain mutual benefits such as access to knowledge, people and resources and access to promising markets and positioning on the global scene. International cooperation increases both the scope and the scale of research and is therefore seen as more effective and efficient in developing solutions to pressing challenges and problems related to the energy system. International cooperation is difficult and sometimes associated with

2 The Chinese Mid to Long-Term S&T Development Plan (2006-2020) set a goal of doubling national R&D investment to 2.5% of GDP by 2020 and China is on track to achieve this goal (Basu et al. 2018).

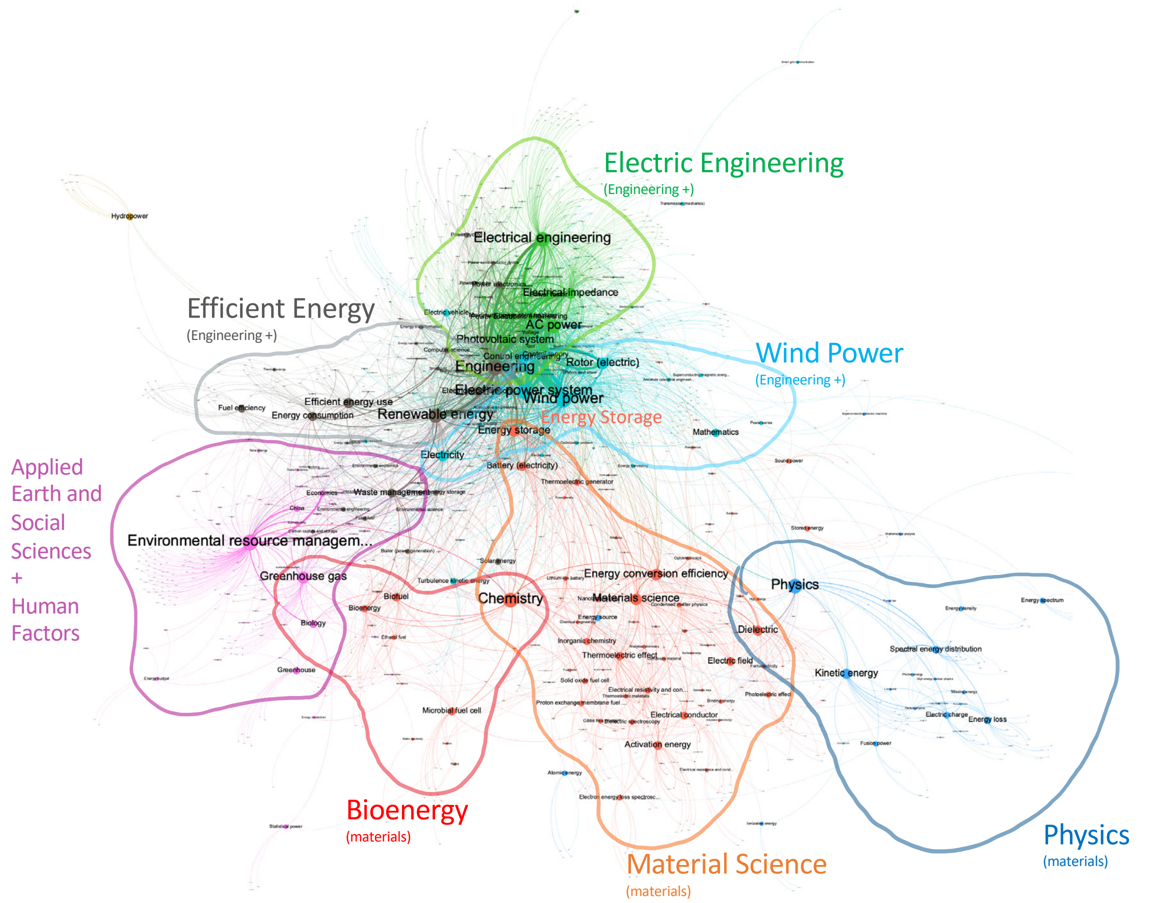

Figure 6 Annotated network view of the connections between energy transition topics. Each node is a topic, the connections between nodes show where topics were used in the same publication. The colours show lower level clusters, specialized technological areas.

transaction costs related, for example, to robust IPR arrangements and investments into the building of networks and markets. As collaboration evolves and the model for undertaking Sino-Danish projects is fine-tuned, a potential pathway is set out for higher levels of engagement in other areas and in addressing other global challenges. Covid-19 is a good example of such a challenge.

For a small, open economy such as Denmark, international cooperation with a large country such as China is decisive for the further development of scientific disciplines and knowledge and the economic competitiveness of the energy industry in global markets. China offers a scale of markets, resources and expertise that cannot be matched by a small country. China is also leading in key areas for the energy transition, such as digitisation, artificial intelligence and batteries. However, as a member of the EU, Denmark constitutes an entry point for China into the EU and its markets. Denmark is a leader in terms of transforming the energy system, with the highest global share of renewables and a competitive science and engineering wind technology sector (ATV 2020). This has been driven by a combination of ambitious and protective policies, good framework conditions and strong research communities within renewable technologies.

In times of a global health and climate crisis, international cooperation is vital to accelerate the energy transition. The IEA has identified key principles to compress the innovation cycle and deliver on net-zero emission targets (IEA 2020) and most of them are shared by Sino-Danish energy cooperation.

1. Energy sectors have identified and prioritized cooperation areas and have adapted to local requirements and conditions.

2. Both China and Denmark have doubled public energy R&D over the last 5 years and enabled market-led innovation.

3. Cooperation addresses all links in the knowledge value chain from basic research to demonstrations and market initiation.

4. Both countries have enabled knowledge infrastructures such as access to public and private finance and networks.

5. Both countries engage in the broader international community to exchange and create new knowledge, preventing knowledge gaps and creating cross-border synergies.

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Part II
Sino-Danish energy outlook for technologies and systems

3 Energy scenarios and policies

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Introduction

Climate concerns present a complex challenge for policy-makers, as decisions taken today can have lasting impacts on the future of the planet. This is particularly relevant when discussing the development of energy systems, where the pressing need to reduce greenhouse gas (GHG) emissions requires a deep decarbonization of the system. The climate targets of the Paris Agreement show that the green energy transition requires a novel scope and scale compared with past developments, passive measures no longer being enough to reach climate targets: the active decarbonisation of energy systems is required.

Due to the rapid pace of technological development, energy systems of the future will hardly resemble those that exist today at all, whether in terms of the technologies they use, the flexibility of their sources or the way they are operated. The development of new markets for energy and energy services, digitalization, novel technologies for energy generation and storage and the smarter operation of assets are only some of the drivers that will challenge policy-makers and planners into taking decisions requiring a fundamentally different approach compared to previous strategies for energy-system development.

In this context, the modelling of future scenarios has become an extremely significant tool in planning for the transition to renewable energy. In general, scenario analysis is a tool that helps in taking a long-term view in a world of great uncertainty by describing hypothetical possible futures and their corresponding pathways (Schwarz 2012). Beyond the characteristics they have in common, in the context of energy scenarios it is relevant to divide them into three categories: predictive, explorative, and anticipative (Dannemand and Rasmussen 2014). These different categories are linked to the research question that the scenarios attempt to answer, and therefore care must be taken to ensure an appropriate fit between the conclusions taken from a scenario and type of scenario used.

Predictive scenarios aim to describe the most plausible future, utilising the current context and observed trends. Predictive energy scenarios are often used when describing the expected evolution of an energy system if current policies are maintained in what is called a 'business-as-usual' scenario.

Explorative scenarios not only take into account the current context, they also aim to explore a series of possibly uncertain futures based on different assumptions, usually rooted in a qualitative but occasionally also quantitative assessment of different drivers. One example is exploring the effects of different possible policy measures on the evolution of the energy system and on climate, where the policies are determined by a qualitative assessment of possibilities, and the modelling provides a quantitative assessment of the effects of their implementation.

Anticipative scenarios (also called 'normative scenarios') work in a different direction, that is, by establishing a future definitive vision and working backwards to identify one or more pathways that can connect the existing context with the selected future scenario. As a result, they do not identify the effects of specific decisions today, but instead provide information on which decisions need to be taken to achieve a specific future state. In the field of energy, one of the most typical uses is to identify which policies need to be taken in order to achieve specific targets, for example, limiting global warming below 1.5°C.

The main objective of long-term energy-planning models is to deliver support to strategic, operational and political decisions for future energy systems (IRENA 2019). In this manner, the effects of existing policies can be analysed, the effects of introducing new policies can be estimated, and new policies can be drafted in order to achieve a specific target.

Policy ambitions for energy transition in China and Denmark

China

China is focusing on building an energy system for the future, a development that will address the issues of energy security, energy efficiency and the promotion of a clean energy supply.

China has the ambition to develop an 'ecological civilization' as its main characteristic by 2035 to 2050. The concept of ecological civilization, which was written into the Chinese constitution in 2018, seeks to complement the three core dimensions of the concept of sustainable development – the environmental, economic and social dimensions – with specific features of Chinese political civilization, aspects of Chinese governance and core elements of the country's sustainable economic development agenda (Kuhn 2019).

China has committed itself to the Paris Agreement and the targets to avoid dangerous climate change by keeping global warming to well below 2°C and pursuing efforts to limit it to 1.5°C. Its current Nationally Determined Contributions (NDCs) are committed to having CO_2 emissions peak at the latest by 2030, to reach a non-fossil-fuel (i.e. renewables and nuclear) share of primary energy consumption of 20% (calculated by the special Chinese coal consumption substitution method (Lewis et al. 2015)), and to reach a reduction in carbon intensity of 60-65% by 2030 compared to 2005 (NDRC 2015). However, these targets are nowhere near sufficient to reach the goals of the Paris Agreement (Climate Action Tracker 2019).

At the 19th National Congress of the Communist Party of China in 2017, President Xi Jinping confirmed that China would promote revolutions in energy production and energy consumption, in the development of energy technology and in forging a holistic energy system while at the same time strengthening international cooperation to ensure energy security, including access to energy resources (Jinping 2017). The country's plans emphasize shifting economic development from high growth to high-quality growth, a paradigm shift that also applies to the energy sector. Prompted by important milestones in 2020, 2035 and 2050, China aims to develop a 'clean, low-carbon, safe and efficient energy system' (*The 13th Five-Year Plan for Economic and Social Development of the People's Republic of China* 2015).

Denmark

Denmark has a history of a high level of ambition in de-fossilising its energy sector, with a heavy emphasis on building up a supply of renewable energy, aggressive energy-efficiency measures and a focus on developing specific technologies (as exemplified by its leading the way in developing offshore wind), while maintaining a constant view regarding sector coupling (Ropenus and Jacobsen 2015), that is, exploitation of the synergies created by integrating operations and planning across sectors (as, for example, heat and power). Despite this extensive history, the country has increased and renewed its ambitions to decarbonize Danish society further.

In 2019, Denmark passed a new Danish Climate Act (*Aftale Om Klimalov* 2019). This Act is the first legally binding piece of climate legislation, which introduces the goals of reducing GHG emissions by 70% by 2030 compared to 1990 and of achieving carbon neutrality by 2050. This is an extremely ambitious strategy since, as of 2020, emissions have been reduced by 38% compared to the baseline of 1990, meaning the remaining 32% need to be abated in the coming decade. Consequently, to achieve the Climate Act's targets, Denmark must reduce its carbon emissions at a rate much higher than yet seen.

According to analysis carried out by the Danish Council on Climate Change, this 70% reduction in GHG emissions, while ambitious, is fully necessary if Denmark is to play its part in limiting the rise in global temperatures due to climate change to below 1.5 degrees C. In line with this necessity, it must be understood that such a broad and ambitious transition will come with associated economic costs. Nonetheless, analysis shows that, by implementing measures to achieve the 70% GHG emissions reductions target in a cost-effective manner, the goal can be achieved while maintaining associated costs below 1% of Denmark's GDP over the next ten years, compared to a 'business-as-usual' scenario.

Energy scenarios for China

China's energy planning is mainly related to the preparation of national and provincial five-year plans. The five-year plans set targets for the development of the energy system for the next five years, including specific targets for power-supply capacity, share of non-fossil fuels, etc. (National Energy Administration 2016). In a scenario context, the five-year energy plans work as a combination of a prediction and a (mandatory) anticipation (Nielsen and Karlsson 2007), for which the targets are minimum aspirations for the planned development.

The longer-term planning is dealt with by energy strategies, for example, (NDRC 2017). The energy strategy has a time horizon to 2030 and it is based on the same methodology as the five-year energy plan, with targets for key indicators and policy measures to implement the development. Compared with the five-year plan, the targets are less binding. Neither the five-year plans nor the energy strategies are completely supported by quantitative and comprehensive scenario analyses.

In general, sophisticated energy system-specific models for China are relatively few and recent (CNREC 2018, p. 346). These models have mainly been developed by universities, think-tanks, research institutes and energy sector-owned institutions (CNREC 2018, pp. 346–348; Lawrence Berkeley National Laboratory 2020).

CREO scenarios: Methodology, assumptions, and main results

Since 2011, the Energy Research Institute of the NDRC (ERI) and the China National Renewable Energy Centre (CNREC) have developed an energy model for a tool for holistic and quantitative analyses of the future development of the Chinese energy system. The models have been developed in close collaboration with the Danish Energy Agency, the US National Renewable Energy Laboratory, and other international partners.

The energy-system modelling tool consists of interlinked models covering the energy sector of Mainland China. The END-USE model, based on the Long-range Energy Alternatives Planning (LEAP) model, uses bottom-up analyses for Agriculture; Construction; Residential, Commercial and Government Buildings; Industries; and Transport. These sectors are further divided into relevant subsectors. The goal of the analysis is the primary energy demand of these sectors and subsectors. End-uses are driven by assumed developments in key activity levels specified for each subsector. These are physical or behavioural drivers specific to the subsector, or the subsector's economic value-added when no other driver is available. Transformation and resource activities, apart from district heating and power, are also covered by LEAP, including upstream refinery activity. Power and district-heating sectors are modelled in EDO (Electricity and District-heating Optimization).

The EDO model is a fundamental model of power and district-heating systems, built on the Balmorel model (Wiese et al. 2018).The power system is represented at the provincial level, taking the interprovincial grid constraints and expansion options into account. The model includes thermal power (including CHP), wind, solar (including CSP), hydro, power storage, heat boilers, heat-storage facilities, heat pumps, etc. It also covers demand-side flexibility in industry, options for charging electric vehicles and the option of a fully integrated coupling with the district-heating sector. The model can represent the dispatch in the Chinese power system on an hourly basis, taking into account the technical limitations of thermal power plants and interprovincial exchanges of power, as well as the dispatch in provincial, regional or national markets for power, based on least-cost marginal price optimization. Its key characteristics are related to the detailed representation of the variability of load and supply (e.g. from VRE sources), as well as flexibility and flexibility potentials, which can operate optimally and be deployed efficiently in capacity-expansion mode.

The results from the two models are combined in an integrated Excel-based tool, which provides an overall view of the energy system, combining fuel consumption from the power and heating systems from EDO with direct consumption by end-use sectors and other transformation sectors from LEAP (CNREC 2019, p. 14).

The energy model is used to prepare long-term energy scenarios to illustrate how China can transform its energy system into a clean, low-carbon, safe, energy-efficient, and cost-efficient system by 2050. These scenarios are analysed and presented in the yearly China Renewable Energy Outlook Report (CNREC 2019) from Energy Research Institute in the form of two main scenarios: the Stated Policies Scenarios and the Below 2°C Scenario.

The two scenarios represent two different scenario methodologies, the predictive and the anticipative (Nielsen and Karlsson 2007). The predictive scenario, called the 'Stated Policies Scenario', shows what the full and firm implementation of energy-sector and related policies announced in the 13th Five-Year Plan and at the 19th Party Congress would look like in the long run. The central priority is the effort to build a clean, low-carbon, safe and efficient energy supply. The scenario also envisages the NDC climate emissions target peaking before 2030, the effects of the Blue-Sky Protection Plan, aspects of the Energy Production and Consumption Revolution Strategy, and the National Emissions Trading Scheme. In aiming to achieve the 2050 timeline, policy trends are extrapolated to set appropriate policy drivers (Zhongying and Sandholt 2019).

The anticipative 'Below 2°C Scenario' sets out the road for China to achieve its ambitious vision for an ecological civilization, a goal included in the Chinese constitution since 2018, and a clean, low-carbon, safe and efficient energy system, and to illustrate the role China could play in fulfilling the Paris Agreement. The main driver is a hard target for energy-related CO_2 emissions through a strategy with renewable electricity, electrification, and sectoral transformation at its core. The target is set at a total of 200 million tons of energy-related CO_2 emissions between 2018 and 2050.

The model results indicate a cost-effective pathway for the building of China's ecological civilization, driven by the large-scale deployment of a green power supply, wide improvements in energy efficiency to drive down overall energy demand and electrification as well as market reforms. These pillars of the energy revolution show that, according to the Below 2°C scenario, by 2050 the Chinese energy system may have a share of non-fossil fuels of 65%, based on an electrification rate of 66%, and up to 35% lower costs of power, while achieving a GDP in 2050 that is 4.2 times the GDP in 2018.

Key policy measures for the energy transition in China

The scenario analysis in the China Renewable Energy Outlook 2019 (CNREC, 2019) sets out a clear three-point strategy for the energy transition in China: 1) energy efficiency in end-use sectors; 2) electrification of key sectors (industry, transport, buildings); and 3) green energy supply, based on wind and solar power. This strategy is backed by the following key policy drivers:

- Promotion of renewable energy
- Coal control
- Promotion of energy-efficient measures
- Development of efficient power markets
- Power-system flexibility
- Carbon-pricing and efficient carbon control.

In the near term, the scenario analysis provides specific key recommendations to policy-makers to achieve a cost-effective energy transition that will not undermine the growth of the Chinese economy but will move away from the requirement for heavy subsidies for renewable energy. The 2019 version of the report highlights the need to go from an energy transition to an energy revolution in order to build the ecological civilization, as well

Deep dive on waste as case

The broader modelling of the Chinese energy system, as done in, for example, the China Renewable Energy Outlook, is capable of informing and being informed by deeper sector- or technology-specific analyses. One example is the analysis of waste management and energy generation carried out by Shapiro-Bengtsen et al. (2020).

Using waste fractions in modern energy facilities addresses waste management problems while providing energy services. For example, waste incineration reduces the need for landfill and contributes heat and power to the energy system. In respect of municipal solid waste (MSW), resource availability is the key to planning sufficient treatment capacity. China has gone from treating two thirds of collected MSW to treating 99% in just ten years (MoHURD, 2020). Some of this has been due to extensive investments in MSW incineration (MSWI) capacity, and China is well on its way to reaching its 2020 target of being able to incinerate 216 Mt of MSW nationally (NDRC & MoHURD 2016). In 2018 China's MSWI capacity increased by 22% compared to the previous year, resulting in 45% of the collected 228 Mt of MSW being incinerated (MoHURD 2020). However, investments in treatment capacity must be in line with the MSW to be treated. As these are long-term investments, long-term scenarios can help guide decisions. Even in the short term, there is a risk of provinces over-investing in MSWI capacity (Shapiro-Bengtsen et al. 2020).

Based on econometric analysis, Shapiro-Bengtsen et al. (2020) have projected mixed MSW and sorted food-waste development, using urban population and household income variables and setting out policy scenarios for the provinces extending to 2050.

Increasing the sorting of waste is in line with the vision of China as an ecological civilization that makes efficient use of its resources. Sorting of MSW has already started in several cities, one of them being Shanghai, which has shown positive results (Huanbao 2020). With more food waste being sorted out of general waste, the levels of mixed MSW should decline, while the lower heating value (LHV) of mixed MSW should increase. The LHV of Chinese MSW is typically not high enough to sustain combustion and is therefore often co-fired with coal (Guo et al. 2018). If food waste were to be separated from mixed MSW, the need for co-firing with coal could be eliminated in five years (Shapiro-Bengtsen et al. 2020). These sorting schemes are therefore most relevant to include in planning for waste treatment capacity. More sorting puts pressure on other treatment facilities, as the sorted food waste should be treated in, for example, anaerobic digesters. If the extensive investments in MSWI capacity were to continue while China is increasing its resource efficiency, there is a risk of the country becoming locked-in to incineration, where sorting and specialized treatment of MSW fractions is not encouraged.

as stressing the importance of the 14^{th} Five-Year Plan for 2021-2025 in accelerating the energy transition. Key recommendations for the 14^{th} Five-Year Plan period are:

- Set ambitious but realistic end-targets for the period: achieve 19% of non-fossil energy by physical energy content, target a reduction of energy intensity of actual GDP by 21%, and reduce CO_2 emissions targeting a reduction of real GDP CO_2 intensities of 27%.
- Leverage the cost reductions in wind and solar and scale up the pace of RE installations, including averaging annual additions of wind 53 GW and solar 58 GW.
- Ensure supporting RE policies, such as strong RE purchasing requirements, after the transition from subsidy to market prices. This could be achieved through an extension to the quota system or the facilitation of green PPAs.
- Internalize fossil fuel damage and/or abatement costs through the refined ETS mechanism.
- Pursue electrification with a focus on industry to reduce coal consumption and transport as a counter to the growing consumption of oil products.
- Avoid new coal-power plants and conduct orderly prioritized closures of inefficient plants and coal mines.

Energy scenarios for Denmark

Scenarios for different developments of the energy sector are a large part of the discussion of the future of the Danish energy sector and have been for many years. Scenario creation is not limited to government agencies, but also covers universities, organizations, independent counsels, sector partnerships and system operators providing their views on possible developments and recommendations for the entire energy sector in whole or in part.

To create a baseline, and as part of Denmark's National Energy and Climate Plan to be submitted to the EU, the Danish Energy Agency annually prepares Denmark's Energy and Climate Outlook (DECO) with inter-ministerial support (Danish Energy Agency 2019). DECO consists of a technical assessment of Danish energy consumption and production, GHG emissions and their evolution up to 2030 from a frozen-policy perspective, that is, with no new policies being introduced. The purpose of DECO is to describe where Denmark stands and what challenges it faces in meeting its energy and climate obligations and policy targets. It is therefore an important planning tool in setting Danish energy and climate policy, as well as an important reference for assessing the impacts of new policy initiatives.

The overall picture shown in DECO 2020 was that, under the current set of policies, Denmark's GHG emissions are expected to be reduced by 44% in 2030 compared with the UN base year of 1990.

However, the Danish Climate Act of 2019 (*Aftale Om Klimalov* 2019) sets a legally binding target to reduce GHG emissions by 70% by 2030. As part of the Act, the Danish Council on Climate Change (an independent council) must present its professional assessment of whether the initiatives in the Danish government's annual Climate Action Plan are sufficient to reduce emissions (Danish Council on Climate Change 2020).

In its scenario for a 70% reduction in GHG emissions, the Danish Council on Climate Change proposes a large package of sector-specific instruments paid for by a tax on GHG emissions. They also emphasize that Denmark will not reach the 70% target without pursuing new and less well-known parts of the transition, specifying CO_2 capture and storage, transport and agriculture as crucial in reaching the target.

As part of the Climate Action Plan, the government has created thirteen joint private-public climate partnerships, each representing a sector. The partnerships have now presented their initial recommendations to the Danish government on how to reach the 2030 target, which, as with other energy scenarios, is part of the ongoing political discussions for the Climate Action Plan.

Another relevant scenario analysis for Denmark is the Power and Gas Sector Outlook for Infrastructure Planning (PGSO-IP), prepared annually for use by Energinet (the Danish Power and Gas Transmission System Operator) as a basis for Energinet's planning of the Danish power and gas infrastructure. The PGSO-IP describes developments in the Danish energy system up to 2040. It is based on the best and, as far as possible, most robust hypothesis regarding developments in the energy system so as to safeguard against systematic under- as well as over-investment in the transmission grid, both of which would cost society more compared with the appropriate level of development (Danish Energy Agency and Energinet 2018).

The PGSO-IP describes how a long-term green transition might unfold, so it encompasses any additional measures needed for this development to happen. Therefore, while in the short term the methodology is similar to that utilized by DECO, the modelling of later years is based on Danish policy commitments and the targets laid down by the Danish Climate Act and Energy

Deep dive into the gas case

Large shares of variable renewable energy will need to be integrated to meet the targets of the Paris Agreement (IPCC 2019; UNFCC 2015). This integration will require increased flexibility in energy systems in terms of consumption, storage, transmission, and generation. To facilitate this, sector coupling between the power, heating, industry and transport sectors can assist in achieving low-cost solutions (Brown et al. 2018). A recent Danish research project, FutureGas, has analysed how Denmark can achieve ambitious climate targets in the future with sector-coupling of the above-mentioned sectors and with a focus on the role of gas (Münster et al. 2020). Three GHG emission scenarios have been analysed: Early Sprint reaching 375 Mt CO2eq by 2050, Marathon reaching 435 Mt CO2eq, and Late Sprint reaching 708 Mt CO2eq. All three scenarios achieve climate neutrality by 2050 and have similar costs for a system using between 400 and 650 PJ fuel per year (see Figure 1). The analysis was performed with the linear optimization model TIMES-DK (Balyk et al. 2019) for all GHG emissions in Denmark, and the results were soft-linked to Balmorel (Wiese et al. 2018) modelling the power, heating and process heat sectors in Denmark, as well as the power and district heating sectors in neighbouring countries, thus facilitating the optimization of investments and electricity transmission between countries. Both models perform least-cost optimization of investments and operation. Modelling assumptions can be found on the project's homepage (www.futuregas.dk).

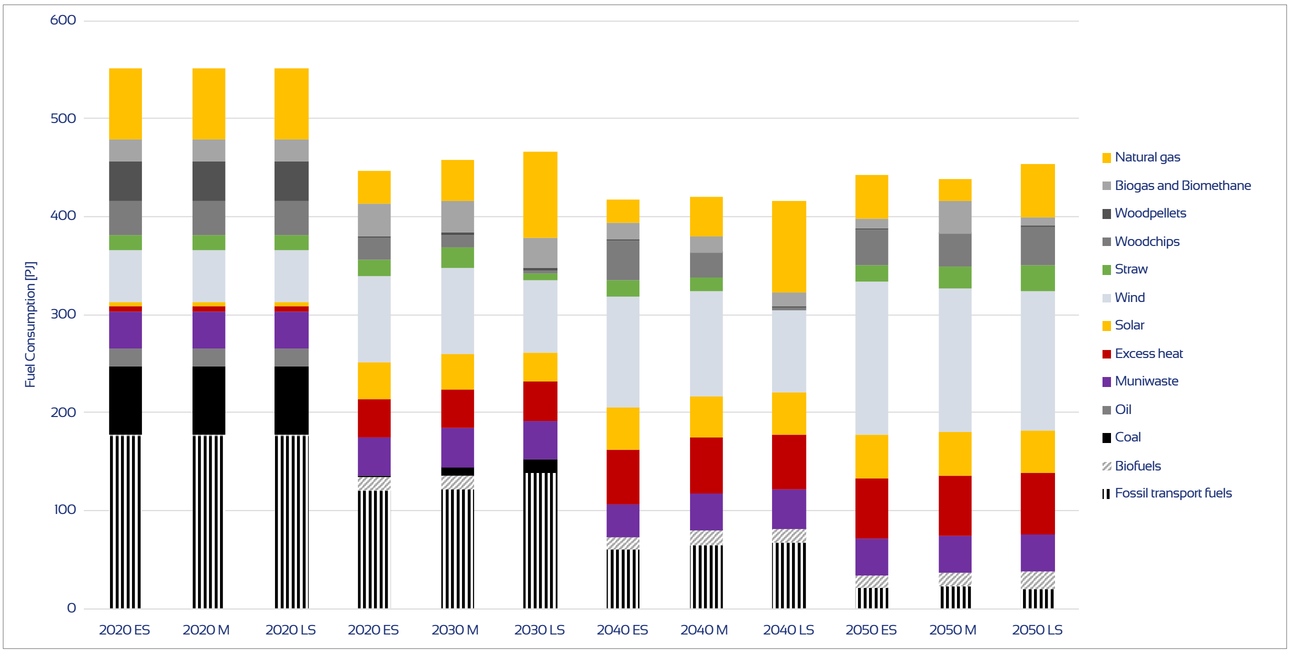

Figure 1 Potential fuel consumption in Denmark in 2020-2050 in the Early Sprint (ES), Marathon (M) and Late Sprint (LS) scenarios..

Agreement[1]. It is important to stress that the power and gas sector outlook has been prepared specifically to provide Energinet with the best possible basis for grid-planning, investment decisions, security of supply analyses, etc.

Broader scenarios are, once again, supported by deeper sector-specific analyses, such as the analysis carried out for the gas sector by the FutureGas project, described as an example in this chapter.

Figure 1 shows high shares of wind, which, together with solar PV, is the main source of power. District heating (which is assumed to continue constituting around two thirds of the demand for heating) is mainly produced from electricity (one third), excess heat from industry (one third) and the incineration of municipal solid waste (MSW) (one sixth). The last part of the demand for heating is supplied as individual heating, which is found to shift mainly towards electricity consumption using heat pumps. Process heat and transport are the two sectors that are most difficult to decarbonize. Process heat is mainly produced using gas and solid fuel. The transport sector shifts to electric and hybrid vehicles but also uses oil and biofuels for heavy transport. Substantial shares of electrofuels utilising hydrogen can be found in 2050 (around one third of demand) if production of fuels for international travel (aviation and ships) is included and imports of biomass and biofuels are restricted or expensive.

1 For example, Denmark's National Energy and Climate Plan related to the EU Climate and Energy Package and the Winter Energy Package.

For most scenarios, the demand for gas falls by 2050, but may increase in an intermediate period if low caps on CO2 and low fuel prices prevail as in the Late Sprint scenario. Gas is mainly used for process heat, but it also provides flexibility for the power and heating sectors. When including the option of carbon capture and storage, some natural gas is kept in the system, but local resources are available to cover the full consumption using green gases such as biomethane from upgraded biogas. In the transport sector, green gases are mainly used as a feedstock for the longer-term production of liquid bio-/electrofuels.

The scenario results illustrate how ambitious climate targets with high shares of wind and electrification and with low additional costs can be achieved if the synergy potentials available from sector coupling are utilized in smart energy systems linking the power, heating, industry and transport sectors.

Key policy measures for the energy transition in Denmark

On 22 June 2020, the Danish government announced the Climate Agreement on the Energy Sector and Industry (*Klimaaftale for Energi Og Industri Mv. 2020*, 2020), which sets out an initial set of specific policy initiatives to implement the targets laid down in the Danish Climate Act, with recommendations from the (Danish Council on Climate Change 2020).

Denmark will use two tracks to accomplish this goal:

1. The implementation track, where known and already commercially available measures and technologies see wider adaptation and use.

2. The development track, where new technologies are developed and quickly implemented as soon as they fulfil expectations regarding their costs and effectiveness.

The implementation track will apply climate technologies to all sectors of the Danish economy. Previous climate strategies, as in most other countries, have focused on energy use and energy production. The new climate strategy aims to transform the methods currently used in transport, farming, industry and more by developing more effective policies to ensure the broad and swift application of existing solutions that have not yet been completely implemented. One of the major areas of transformation is agriculture, which has previously been ignored in climate strategies, but is expected to produce 25% of the accumulated GHG emissions in 2030 (Danish Energy Agency 2019).

The technological advances and improvements to processes to combat climate change are improving rapidly. These developments should not be ignored, but nor will Denmark place all its hopes in futuristic technology scenarios that may not ever bear fruit. Some examples of technologies being considered are the broad deployment of Power-to-X in conjunction with a dedicated energy-island project in the North Sea, as well as various energy-storage methods.

The strategy looks at technologies and methods that are in their commercial infancy, but which are likely to be implemented within the next decade. Quite possibly some of these will never be commercially viable, so the strategy takes this into account by suggesting more methods than needed and weighing them in terms of the probability of their implementation. Thus, the strategy can afford several of these technologies and tactics faltering without the 70% reduction goal being compromised.

A delicate balance must therefore be achieved between developing new promising technologies, ensuring the efficient deployment of existing solutions and retaining awareness of the social costs associated with the energy transition. As presented in the Climate Act (*Klimaaftale for Energi Og Industri Mv. 2020*, 2020), offshore wind will be a main technology, particularly in connection to the energy islands project described in the agreement. It is essential that, in planning the further siting and development of specific technologies such as offshore wind, social acceptance costs are considered as part of the planning exercise (Hevia-Koch 2018; Hevia-Koch and Klinge Jacobsen 2019).

Comparison of and lessons learnt from scenario-planning and policy-making in China and Denmark

'Long-term energy scenarios provide crucial guidance on energy transition pathways. These projections analyse the socioeconomic and environmental benefits of sustainable energy policies and investments. They can play a central role in informing short-term COVID-19 crisis responses, designing mid-term green recovery policies, and promoting long-term resilience, energy security, justice, job creation, and sustainability in the energy sector. Strengthening the capacity within governments to develop and understand energy scenarios aligned with the Paris Agreement is essential for better decision making'. This is one of the main findings from the UN report on the sustainable development goals in the time of Covid-19 (United Nations 2020).

Looking at scenario-planning in China and Denmark, it is clear that comprehensive energy system scenarios exist in both countries, but also that their respective governments do not use scenario-planning as a key policy-making instrument. The comprehensive scenario analyses are often carried out by universities, think-tanks and organizations outside government and are often used to inform policy-makers about development pathways, but in the actual decision-making, simpler analyses and predictions are used as basis for the decisions. While in Denmark, high-quality scenarios are used as part of the government analysis for policy development (Danish Energy Agency 2019), the potential for expanding the horizon and scope of these scenarios, as well as their relevance in the policy-making toolkit, is vast and of great relevance due to the high levels of ambition regarding climate and energy.

China and Denmark both have clear, long-term visions for a deep-energy transition, and both countries could benefit from a more advanced use of energy scenarios to explore possible development pathways and also to analyse the anticipated pathways to fulfil the long-term visions. Especially when the solutions include new technologies and system configurations which are still in the development phase, it would be useful to give more attention to different pathways with different assumptions regarding the pace of technological innovation.

Looking at the overall energy-policy strategy, China and Denmark have several similarities. In both countries, a sustainable policy strategy would include strong energy-efficiency measures in the end-use sectors, as well as strong measures to promote the electrification of industry, buildings (heating) and transport energy consumption and to transform the power supply into a green, low-carbon system based on renewable energy. As medium- and long-term strategies, the development of storage technologies and conversion technologies in a system context will be vital for the deep decarbonization of the energy system. Both countries will rely on markets as a decisive tool for policy implementation, including a well-functioning power market with support to system flexibility and system security.

However, the two countries' implementation strategies would differ. Denmark is a small country within the EU, with excellent opportunities for power exchanges with neighbouring areas, while China's provinces are quite different regarding energy consumption and the availability of energy sources. A comparison between China and the EU would be more relevant regarding overall energy policy strategies, not only due to geography, but also with regard to the variety of resources and the different demographic profiles.

Close and long-term cooperation between China and Denmark in the field of energy policy and energy system analyses nevertheless provide an excellent platform for the further development and use of comprehensive energy system scenarios as a tool for policy-making, to the benefit for both countries.

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4 Mapping wind resources and extreme wind: Technical and social aspects

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Introduction

Over the past decade, renewable energy has become an important player in global energy and development policy, providing 62% of new power generating capacity (IRENA 2020). Wind energy grew from 13% to 24% of global renewable energy capacity from 2009 to 2018 (IRENA 2019). To ensure climate protection and sustainable development, the International Renewable Energy Agency (IRENA) calculates that renewables, including wind, must grow four times faster than this by 2030 (IRENA 2020).

Supporting political and economic decision-makers at all levels requires detailed data on the spatial and temporal resolution of wind resources and siting conditions. As well as the wind conditions themselves, the suitability of local environments for exploiting this resource needs to be considered. Against this background, this chapter presents an overview of methodologies for making assessments of wind resources and extreme winds respectively. This is accompanied by a general overview and a focus on studies applied to China, followed by a consideration of knowledge gaps and the outlook for the future. Then the non-technical aspects of assessing wind resources are presented, again presenting the state of the art and identifying gaps in knowledge. Finally, a brief summary and outlook for both the technical and non-technical aspects is provided.

Mapping wind resources

Development of methodologies and applications

In general

In the 1970s and 1980s, the development of wind energy was rather local and small in scale, mostly occurring in a few windy European countries, including Denmark. The methodologies for installing wind turbines were mainly linked to a number of civil-engineering functions, as in the case of buildings, bridges and air pollution etc. One essential methodology for assessing wind resources has been to use mast measurements in a particular area or site. The aim of the European Wind Atlas (EWA) was to establish the meteorological basis for assessing wind resources in Europe. Along with the publication of the EWA (e.g. Troen and Petersen 1989), the wind atlas method was developed as a microscale program for wind resource assessment, WAsP.[1] In making the atlas with the aid of this program, some two hundred meteorological stations were used all over Europe.

The wind-atlas method became a foundation for the further development of methodologies, which it still is. It helped set a standard for reasonable local measurements for planning new wind-farms. This requirement has accelerated the latest development of measuring techniques, such as remote sensing LIDAR[2] (e.g. Mann et al. 2017). At the same time, given the rapid expansion of the wind-energy industry, both farms and turbines are growing in rated capacity and physical size, so that it becomes more challenging and expensive to collect measurements in order to cover both the horizontal and high-altitude wind conditions. Accordingly, numerical modelling is assuming an increasingly important role in making wind-resource assessments. Most peer-reviewed methodologies use both measurements and modelling, their respective roles varying in different applications.

Methods with a high level of emphasis on the use of measurements also include those using satellite products (e.g. Badger et al. 2016; Hasager et al. 2020). The satellite data method is still challenged in some areas by sample size, resolution and quality at strong wind speeds.

In both onshore and offshore environments, the mainstream method is numerical modelling, assisted by measurements. Depending on its resolution,[3] numerical modelling can have grid spacing from hundreds to tens to a few km, down to 1 km scales. In line with the atlas method, the wind input required for high resolution modelling around the turbine site has been calculated from coarser modelled data. One such approach is the KAMM[4]/WAsP method (Frank et al. 2001, Badger et al. 2014). Wind distributions calculated as classes of speed, direction and stability are first prepared using long-term, coarse-resolution reanalysis data from global circulation models (GCM) with a resolution of 100 km. These classes of wind are downscaled to the mesoscale using KAMM, with a resolution of a few km,

1 www.wasp.dk

2 Light Detection and Ranging

3 Model grid spacing. A grid spacing of 1 km gives a grid size of 1 km x 1 km.

4 Karlsruhe Mesoscale Model, a static mesoscale model.

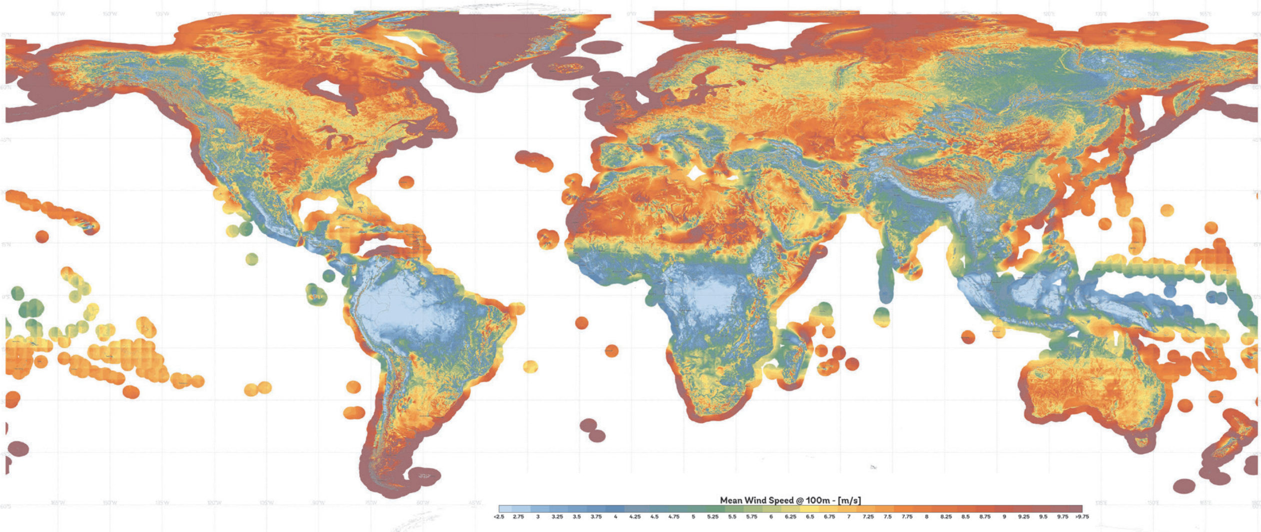

Figure 1 Map of mean wind speed at 100 m in m s-1 from the Global Wind Atlas III project. This map has been prepared by the Technical University of Denmark and Vortex FdC S.L. (VORTEX), under contract to the World Bank. The map can be obtained from https://globalwindatlas.info.

before they are further downscaled using microscale modelling of WAsP with a resolution of tens of meters. This method has been used to generate atlases of many regions and countries, including Europe, Egypt, Finland and part of China, as reported in, for example, Mortensen et al. (2006), Badger et al. (2010) and Tammelin et al. (2013). With larger and larger computation facilities becoming available, the dynamical downscaling of global circulation data to a few kilometres has become possible. In the New European Wind Atlas project, thirty years of weather data have been downscaled using the Weather Research and Forecasting (WRF) model down to a resolution of 3 km all over Europe (e.g. Hahmann et al. 2020). Wind climate generated from this dataset has been used in WAsP to obtain wind-resource estimates at resolutions of a few hundred meters.[5] Fig. 1 shows a map of mean wind speeds at 100 m over the globe from the Global Wind Atlas III project, which was derived from a chain of models, with winds from the ERA5[6] reanalysis data (approximately 30 km) being downscaled to 3 km through WRF modelling and further downscaled to 250 m using WAsP software.

Besides the atlas method, numerical modelling data have also been used together with measurements made in other ways. The WIND Toolkit from Draxl et al. (2015) combines seven-year high resolution (2 km, 5 min) WRF model output with site-appropriate turbine power curves to estimate the power produced at each of the turbine sites in the US. Using limited in-situ measurements to 'adjust' the modelled data constitutes a simplified form of site-modelling, with similar aims to microscale modelling, except that it is highly empirical. The philosophy is to combine the long-term statistics in the modelled data and the site-specific variability in the measurements. In Delle Monache et al. (2013), this concept was applied to assessments of wind resources. Measurements have also been used to assist in designing more cost-effective long-term simulations. For instance, in Fischereit and Larsén (2020), about 180 days of data were collected based on tens of sites of measurements over the southern North Sea that are able to represent thirty-year climatological statistics of wind and waves. Thus, the computation cost of performing high-resolution calculations is significantly reduced. The 'weather classification' method, as described below for wind resource studies in China, is another example of decades of data being condensed into a limited number of days.

In China

In the case of China, there are two aspects to assessing wind resources. One relates to planning, where maps of wind resources are used to draw up policies for the development of wind energy and make preliminary selections of sites for wind farms. The other aspect is the development of a coupling technology between mesoscale models and CFD[7] models in designing wind farms.

In mapping wind resources, the key technical issues are on the one hand how to improve the spatial and temporal resolution of the distribution of wind resources, and on the other hand how to calculate the long-term average wind-speed distribution over twenty to thirty years and related statistical parameters for wind resources cost-effectively. In order to do this, in 2010 the China Meteorological Administration developed the Wind Energy Resources Assessment System (Zhu et al.

5 https://globalwindatlas.info

6 The 5th generation of ECMWF's atmospheric reanalyses of the global climate.

7 Computational Fluid Dynamics Model.

Table 1 Standard assumptions for GIS analysis of available areas for wind development relating to Figure 2.

Slope (%)	Area available in category	Land Use	Area available in category
$\alpha \leq 3$	100%	Natural reserve	0%
$3 < \alpha \leq 6$	50%	Water	0%
$6 < \alpha \leq 30$	30%	Grassland	80%
>30	0%	Shrub	65%
		Forest	20%
		Distance to urban area≤3km	0%

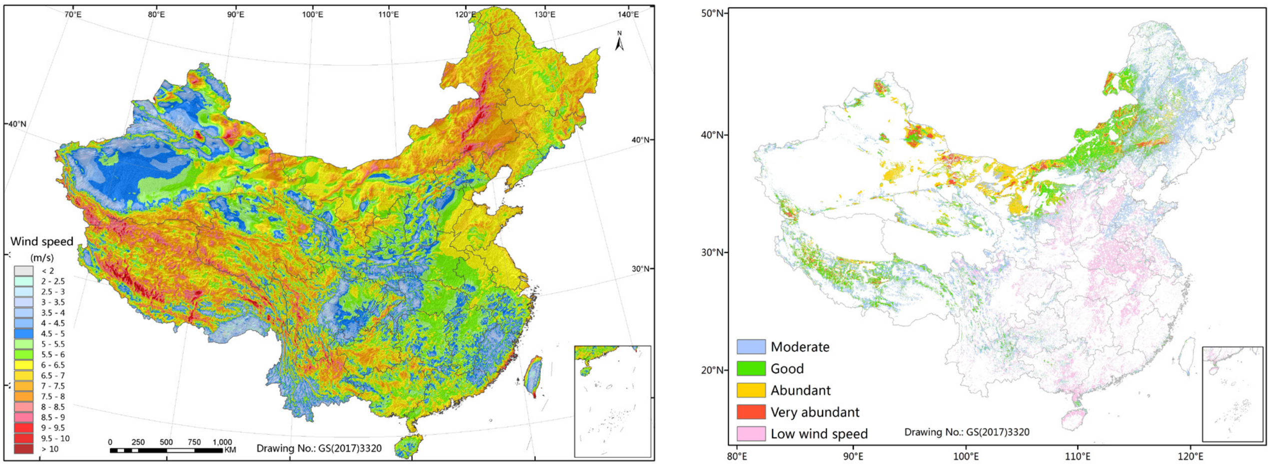

Figure 2 Spatial distribution of (a) annual mean wind speeds and (b) exploitable wind energy resources at 100 m above ground across China. .

2010, CMA 2014). A combination of a mesoscale model with microscale models is used to obtain a refined wind map showing climatic averages through the numerical simulation of a limited number of samples. The system is composed of three parts: weather classification, mesoscale and microscale numerical simulation, and Geographical Information System (GIS) analysis. In addition, a wind dataset with a resolution of 1 km was created that represents the long-term climate statistics of wind resources from 1979 to 2008. Figure 2 shows the spatial distribution of annual mean wind speeds and exploitable wind energy resources at 100 m all over China, with key analysis summarized in Table 1 (Zhu et al. 2020). According to the technical and economic conditions and policies, some areas, such as slopes greater than 30%, bodies of water, urban areas, national and state parks, and lands reserved for military use, should be excluded. Some areas cannot be used fully for wind development: for example, grass can be used up to 80%, shrub 65%, forest 20%, etc. In the figure of the distribution of exploitable wind resources, all the areas in colour are those that are available for wind farms, while the areas in white are not available. Wind distribution with a horizontal resolution of 50 m by 50 m or finer and a time resolution of 1 hour is favourable for resource assessments for a wind-farm design. To simulate the proposed wind farm, using high-fidelity numerical simulation methods coupled with a mesoscale model and CFD is the most effective and is focus of current technological developments. In China, a wind-forecasting method for wind farms has been developed (Ma et al. 2016).

Two wind-resource datasets are available for China: the long-term averaged high spatial resolution dataset, and the long-term series high spatial and temporal resolution data set. The former has a horizontal resolution of 1 km × 1 km, which represents the climatic average and statistical characteristics of wind resources in 1979-2008, and can be used to assess national or regional wind-energy potential and to provide a scientific basis for planning wind-power development. For example, the analysis results of this dataset of wind-energy resources has been approved by the National Development and Reform Commission and the International Energy Agency's '2050 China Wind Power Development Roadmap', the IPCC's[8] 'Renewable Energy and Mitigation of Climate Change Special Report', the Chinese Academy of Engineering and 'China Energy Medium and Long Term (2030, 2050) Development Strategy Research'. The

8 International Panel for Climate Change.

long-term series high spatial and temporal resolution dataset has a horizontal resolution of 3 km × 3 km and spatial resolution of 1 hour from 1995 to 2016. It can be used to start CFD modelling for wind-farm design and also to provide a database for wind energy enterprises and related technical advisory bodies. For example, enterprises such as the China State Shipbuilding Corporation Limited, the China Railway Rolling Stock Corporation, GoldWind and so on, have used these data to provide wind farm siting services to their customers.

Knowledge gaps and outlook

In all the approaches discussed above, efforts are made to resolve site-specific conditions. Downscaling to the microscale is both scientifically and technically challenging (e.g. Veers et al. 2019), despite which it represents a common, ongoing effort to bridge mesoscale flows with microscale flows. Another factor that is ceasing to be negligible is the wake effect from wind parks when estimating the available resources in an area, which, with normal spacing, can cause a power reduction of up to 10% in the neighbouring area. Currently, the most frequently applied and investigated method is the open-source WRF model, which has two primary parameterization schemes available: the Fitch scheme (Fitch et al. 2012) and the EWP scheme (Volker et al. 2015). Another ongoing research topic is how to merge the large-scale, farm-scale wake with the small-scale, turbine-scale wake (e.g. Porte-Agel et al. 2019), which is relevant for the more accurate modelling of wind resources.

Mapping extreme winds

Development of methodologies and applications

In general

With climate change, an increase has been observed in the intensity and frequency of some extreme weather conditions. Extreme weather causes a number of challenges in both the design and operation of wind turbines. Storms are often associated with strong winds, affecting the turbine's load and fatigue. The highly variable flow, with reference to the cut-out speed of, for example, 25 ms^{-1} (the speed at which the turbine is shut down), can cause large fluctuations in power production, which accordingly affects the power integration system. Here, extreme wind methodology development is analysed, for example, of fifty-year extreme wind at hub height, which is a design parameter specified in the IEC[9] standard 61400-1 (IEC 2007), as required for wind-farm planning. This parameter needs to be calculated to find suitable turbines for each farm in order to harvest the most wind energy while reducing the risk of damage from harsh wind conditions.

The earliest dataset of fifty-year wind was produced in line with general civil-engineering applications and was based on in-situ measurements, such as the European Wind Load Code (Eurocode 1995). In this code, many European countries made their own extreme-wind maps using different approaches (e.g. Miller 2003, Larsén and Mann 2009). As a result, there is significant discontinuity in extreme wind values at national borders.

The development of methodologies for estimating extreme wind can be sorted into the following categories: (a) statistical functions for region-specific extreme wind climates; (b) long-term measurements of pressure; and (c) numerical modelling approaches.

For category (a), one needs to determine how to combine samples from multiple extreme weather systems, given the existence of long-term measurements (e.g. Harris 2001, Kruger et al. 2010). Extreme wind events range from mid-latitude depression systems and channelling winds to thunderstorms and tropical cyclones.

In the case of category (b), since historically many more pressure data than wind measurements have been available, the geostrophic winds can easily be calculated from pressure data over the whole area, which will then be converted into Eurocode wind (Abild et al. 1992, Miller 2003). Efforts in category (b) have inspired the exploration of modelled pressure data in a similar manner, which is an attractive option for locations where measurements are not available (Frank 2001, Larsén and Mann 2009).

Unlike wind-resource assessments, estimating the fifty-year wind requires a significantly longer time series, which is often not available, causing significant uncertainties in making estimates (e.g. Larsén et al. 2015). Category (c) thus becomes a very attractive option. Long-term numerical model data have been made widely available, with spatial resolutions from several km to hundreds of km and temporal resolutions from 1 to 6 hours. However, these modelled data face a general problem: the numerical smoothing effect embedded in the simulation, which causes extreme wind to be systematically underestimated. Several approaches have been developed to confront this challenge. One is to increase the spatial and temporal resolutions to, for example, 2 km and 10 min, which are in the vicinity of mesoscale modelling and are associated with high computational costs, given that decades of simulation must be performed. Larsén et al. (2013) have developed a method to calculate extreme wind with a focus solely on severe storms over a long period, thus reducing the computation by 95%. The results of the extreme wind atlas are satisfactory in comparison with measurements. Another approach, the spectral correction method, aims to fix the missing wind variability in the coarse-resolution modelled data over certain frequencies and uses information from the limited measurements to fill in this missing variability through the spectral domain (Larsén et al. 2012). In the absence of measurements, a spectral model derived from measurements was applied. This method was

9 International Electrotechnical Commission.

used to create an extreme wind atlas for South Africa (Larsén and Kruger 2014) and has been implemented in WEng,[10] covering most parts of the globe.

While these methodologies are applicable to both onshore and offshore conditions, there are special challenges and advantages in the case of offshore conditions. The challenges are related to the fact that ocean waves are a function of wind and that it is difficult to model this dependence at storm wind conditions. Whereas the waves have a negligible effect on average wind structures, their effect is considerable during strong wind conditions. Wind and wave modelling are often coupled for storms and tropical cyclones (e.g. Liu et al. 2011, Wu et al. 2015). Larsén et al. (2019) used a wind-wave coupled system to draw up an extreme-wind atlas for the waters around Denmark. In general, there is still the challenge of too few measurements being available offshore, making it difficult to validate and improve modelling approaches. The advantage is that, over certain bodies of water, the best-track data for tropical cyclones are available. Ott (2006) used the Holland model and the best-track data to create a fifty-year wind atlas covering the western part of the North Pacific Ocean.

In China

Western Pacific typhoon activity in summer and autumn brings not only wind power to China's coastal wind farms, but also devastating disasters. Typhoon monitoring data for the past fifty years suggest that typhoons generated east of the Philippines and mainly affecting the southeast coast of China take three active paths: a westward path, a northwest path and a northward path. The distribution of maximum wind speeds once every fifty years along the Chinese coast, based on wind measurements from 205 wind towers taken during 198 typhoons from 2003 to 2010, shows that most of the islands and headlands in Zhejiang, Fujian and Guangdong provinces have a maximum wind speed once every fifty years of 50-55 ms^{-1}. Moreover, the ratio of the maximum wind speed once every fifty years to the annual mean wind speed exceeds the reference value of 5 times the IEC61400-1 standard and can reach 7-10 times on Hainan Island and the Xuwen coast of Guangdong. In addition, analysis of the turbulence characteristics of the coastal near-layer atmosphere under the influence of 44 tropical cyclones produces a number of samples near the typhoon's centre, with turbulence intensities exceeding the IEC61400-1 standard when the wind speed is less than 30 ms^{-1}. In order to produce typhoon-resistant wind turbines, China has organized research on typhoon wind characteristics and compiled a national standard for a 'wind turbine generator system under typhoon conditions'. The standard uses Western Pacific tropical cyclone data from 1949 to 2010 and observation data from 205 wind towers on the southeast coast of China from 2003 to 2010. By analysing the turbulence characteristics of the coastal near-surface atmosphere under the influence of 44 tropical cyclones, the design wind parameters of typhoon-type wind turbines in IEC61400-1 standard were adjusted.

10 WAsP Engineering.

Knowledge gap and outlook

The calculation of extreme wind is still challenged by our understanding of flow across multiple scales, particularly in the range of a few kilometres to meters, the so-called spectral gap region. This limitation is reflected particularly in complex terrains (e.g. mountainous area, coastal zones) and challenging weather conditions such as tropical cyclones and thunderstorms. Thus, it remains a problem to obtain reliable samples to assess the extreme wind climate and thereafter the distribution of these conditions when calculations cannot be achieved with high confidence. At the same time, whether assessing extreme wind directly or calibrating and verifying models, measurements are rare, since measurement systems often experience technical failures during extreme weather. Long-term, good-quality data are even more difficult to assess.

Non-technical aspects

The physical wind-power potential is defined by the resources analysed in the preceding sections, in particular the spatial and temporal distribution of (extreme) wind speeds and power. However, the physical potential of the power in the wind has certain geographical, technical, economic and social limitations. As far as possible, these aspects need to be considered in the context of resource assessments for onshore wind. Only then can they provide insights that are useful for relevant stakeholders such as researchers, policy-makers and investors with different levels of influence. This section briefly presents the state of the art in making resource assessments for onshore wind before summarizing the efforts to take the non-technical constraints into account and providing a brief summary of the knowledge gap.

State of the art

As outlined above, wind resource data and maps are only the first step in assessing the suitability of specific locations for wind-power plants. As well as the wind speed itself, several other factors influence the fraction of power in the wind that can realistically be utilized – these are summarized in Table 1 below. In order to inform scientific and policy discussions about the possible contribution and costs of onshore wind, detailed data on their spatial distribution are required. Many studies have analysed these potentials and costs based on a combination of detailed geospatial analysis (wind speeds and land cover), land-suitability criteria and techno-economic turbine characterizations (e.g. Dalla Longa et al. 2018; Bosch et al. 2017; McKenna et al. 2015). The results of these studies are typically employed by researchers to provide input to energy system models, which explore the economic viability of wind in competition with other energy technologies in the context of long-term energy scenarios (Zeyringer et al. 2018).

Attempts to consider non-technical constraints

The studies mentioned above have the limitation that they focus on the technical potential, thereby overlooking many non-technical constraints for onshore wind. Especially relevant is the issue of public acceptance, which includes concerns relating to the environmental impacts, noise, electromagnetic radiation and landscape impacts, the last of these having dominated the research literature on acceptance thus far. This literature shows, for example, that residents are more inclined to accept wind farms if they stand to benefit directly (e.g. as co-owners). Increasing the offset distance from a wind farm can also increase acceptance, as can involving local communities in the development process.

The value of the landscape to different stakeholders is difficult to measure, so data relating to this question are rare. Some studies in the field of regional and spatial planning have employed photographs of different landscapes, which are evaluated in terms of their aesthetic appeal (beauty of the landscape) by members of the public. These studies have provided a geospatial database of landscape beauty, which can be employed to estimate more realistic or feasible wind potentials. Examples include a study of the 'feasible' wind energy potential of the Baden-Württemberg region in Germany (Jäger et al. 2016) and more recently with so-called 'Scenic-or-Not' data for Britain (McKenna et al. 2020). In addition, Harper et al. (2019) present a multi-criteria decision analysis approach that takes into account the technological, legislative and social constraints in a British context, while Eichhorn et al. (2019) have developed a sustainability assessment framework for possible wind sites, including the environmental, social, technical and economic aspects, and applied it to Germany.

Although evaluations of landscapes provide a basis for evaluating the landscape, other data sources can be employed to evaluate the cost to the householder or other consumer of tolerating landscape modifications produced by onshore wind farms. Combining insights about actually paid compensation with preferences stated in surveys and preferences revealed by actual property prices allows aggregated 'acceptance costs' to be estimated for Denmark (Hevia-Koch and Jacobsen 2019). These acceptance costs can be added to previously determined generation costs to estimate the full cost of acceptance.

Other researchers have employed expert stakeholder workshops in order to arrive at more meaningful potential estimates for onshore wind. For example, Höltinger et al. (2016) present a participatory approach with key stakeholders to consider the effects of socio-political and market acceptance on the techno-economic potential for wind in Austria.

Knowledge gap and outlook

While progress has been made in accounting for these non-technical dimensions in making assessments of onshore wind resources, further developments are required. In particular, these should aim to increase the precision of these factors in the spatial modelling, as well as to improve the consistency and transferability of assumptions in the methods employed in different contexts.

Much of the research discussed above employs location-specific data on the actual or perceived 'value' of landscapes. However, financial evaluations of public acceptance are notoriously uncertain, as well as being person- and location-specific. At the very least, spatially disaggregated data relating to these preferences would be required to draw up a complete balance sheet. These data need to take into account the impact on communities living in the vicinity of new or existing wind farms, as well as calculate the economic value of beautiful landscapes. This would involve taking into account the number or frequency of 'sightings', as well as the actual value of each sighting as inferred from

Table 1 Overview of different potential definitions and their exemplary policy relevance (adapted from) McKenna et al. (2020).

Potential term	Defined as...	Affected by, e.g.	Energy policy relevance, e.g.
Theoretical potential	...the total energy content of wind globally.	Global climate, surface boundary layer etc.	Generally irrelevant
Geographical potential	...the amount of wind energy across the total area available for wind turbines	Terrain/topography, land use, slope, elevation, distance to coast etc.	Generally irrelevant
Technical potential	...the electricity that can be generated from wind turbines within the geographical potential with a given turbine technology (e.g. current, future).	Hub height, rotor diameter, power density (turbine spacing), specific rotor power, wake effects etc. Also planning constraints	Wind industry R&D, innovation and market dynamics
Economic potential	...a subset of the technical potential that can be realized economically.	Investment and O&M costs of turbines, subsidies	Energy-political frameworks
Feasible potential	...reflecting non-technical constraints.	Manufacturing capacity, public acceptance	Public acceptance, market barriers, inertia

its scenic beauty. Exploring the links between landscape beauty and other variables is another potentially promising research area. For example, there is a strong statistical correlation between the outcome of planning applications for onshore wind parks and the scenic qualities of the location (McKenna et al. 2020).

One starting point for extending these approaches to other contexts could be to identify similarities and differences between acceptance and planning procedures elsewhere (Suskevics et al. 2019). Either a set of images of the environment taken at eye-level is needed, or a relationship between scenic quality and land-use categories (Stadler et al. 2011) or other landscape metrics. For the former, scenic ratings of the images could then be crowd-sourced like for Scenic-Or-Not or estimated using computer vision approaches (Seresinhe et al. 2017). Further crowd-sourced ratings or deep-learning estimates would make it possible to increase data granularity above one photograph per 1 km^2. Ratings for further photographs would also help ensure that views in different directions were taken into account for each area. This framework could also be enhanced to take into account the size and type of turbine installed, introduce a setback distance to significantly increase acceptance (Betakova et al. 2015) or take into account the experience that local communities already have with wind energy (Van der Horst 2007). It could also include estimates of the potential impact of changes to landscape aesthetics on happiness and health, building on the modelling reported by Seresinhe et al. (2019) to help policy-makers understand the range of trade-offs at play.

Summary

This chapter has provided a review of both the technical and non-technical aspects of assessing wind resources and the technical aspects of estimating extreme wind. The overall development of methodologies and applications has been described, with a particular focus on China. Significant progress on these topics has been achieved in recent decades as a result of scientific discoveries, computational capacities, technical skills, market demand and international collaboration. Regarding the technical aspect, there are still limitations in our knowledge and challenges in our ability to calculate more accurately; the knowledge gap lies particularly in describing flow across scales, including improving the synoptic field through, for example, data assimilation and improving the downscaling from the mesoscale to the microscale, particularly for challenging terrain and surface conditions. In estimating extreme wind, continuous efforts are required to improve not only statistical approaches but also the physical aspects, such as modelling extreme weather, like tropical cyclones and thunderstorms. Much of the research discussed here accounting for the non-technical dimensions in making resource assessments for onshore wind employs location-specific data on the actual or perceived 'value' of landscapes. As a result, transferring these methods to other contexts relies on relevant spatially disaggregated data. These data need to reflect the impact of new or existing wind farms on communities living in their vicinity, as well as to consider the economic value of beautiful landscapes.

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5

Smart energy systems in China and Denmark

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Introduction

Energy plays an important role in the development of society. Before the industrial revolution, biomass (i.e., wood) was the world's main primary energy source. Since 1900, most primary energy came from wood and coal (Smil 2010), but with the advent of the automobile and airplanes in the early twentieth century, oil became the dominant fuel. In 2018, most of the world's energy was generated from fossil fuels (81%). The rest came from bioenergy, including traditional solid biomass (9.4%), nuclear (5%), hydro (2.5%) and other renewables, such as wind, solar, and geothermal (2.1%) (World Energy Outlook 2019). In recent years, with growing environmental concerns, especially over global climate change and local pollution, attention in international agreements to reducing greenhouse gas (GHG) emissions and cleaning air, with a consequential increase of renewable energy technologies, has increased. Therefore, many countries are making serious efforts to shift from fossil fuels such as oil and coal to renewable energy sources (RES). China as well as Denmark are interesting countries in this respect. Denmark has been a pioneer in implementing renewable energy, and the Danish energy system has undergone a transformational change, while China ranked first in the world in terms of cumulative and new installations of onshore wind power by 2018 (He et al. 2020).

Since major renewable sources like wind and solar can easily be turned into electricity, and electric power can easily be transmitted, transformed, and used, it is expected to become the dominant energy carrier in the future. In recent years, wind power and photovoltaic (PV) power have been growing rapidly in many counties. Fig. 1 shows China's cumulative installed wind-power capacity from 2004 to 2019, which reached about 236 GW in the latter year, accounting for almost 36% of total installed wind capacity worldwide (Global Wind Report 2019). It is estimated that over 25% of new offshore wind-power capacity will be added in China by 2030 (REVE 2020). In Denmark, cumulative wind power capacity was 6.13 GW in 2019, with onshore and offshore wind-turbine capacities reaching 4.43 GW and 1.70 GW respectively (Wind Europe 2019). In addition, wind-power production accounted for 47.2 % of Denmark's domestic electricity supply. Fig. 2 shows the proportion of onshore and offshore wind power, as well as the total wind-power share of electricity supply in Denmark between 2011 and 2019.

It should be noted that the power output of renewable technologies like wind and solar PV fluctuates due to rapidly changing meteorological conditions. Because they have a zero marginal cost, renewable power from wind and PV is replacing conventional thermal power plants, which conventionally have been responsible for providing many electrical power system services, such as reserves, voltage control, frequency control, stability services, and black start restoration (Hansen and Søndergaard 2015). The increasing penetration of these renewable power sources is therefore posing substantial challenges to the planning, secure and reliable operation, and control of power systems (Tang et al. 2017, Zhang et al. 2014). Hence, the requirements for the flexibility to accommodate large amounts of naturally fluctuating renewable energy (often referred to as VRE) are increasing.1

In several countries and regions, parts of the gas, heating, cooling and transportation systems have responded to these flexibility requirements by means of a deep coupling of multiple energy sectors. Indeed, due to the intrinsic storage capabilities of, for example, the thermal inertia of district heating pipes and buildings (Liu et al. 2019), the storage of electric vehicle batteries (Mathiesen et al. 2008) and various energy-conversion techniques (e.g., power to heat, power to gas, CHP units), the heating and gas sectors can provide extra flexibility to the electric power system (EPS). Different energy sectors are coupled at the production or demand side.

The integration of different energy sectors can solve some challenges to the stable and reliable operation of electric power systems with high penetrations of renewable energy (Pinson et al. 2017). This will not only facilitate the integration of renewable energy, it can also improve the cost efficiency of the whole energy system if done properly. In Denmark, Energinet is the transmission system operator (TSO) of the country's electricity and gas transmission grids (Hansen and Søndergaard 2015), which, by controlling both wholesale grid systems, basically demonstrates the integration of two different energy systems. In addition,

1 It is customary to refer to 'naturally fluctuating renewable energy sources' as VRE, or 'variable renewable energy'. However, when doing so, it should be clear that the VRE is not only (deterministically) variable, but that the variation is mostly stochastic and only partially predictable.

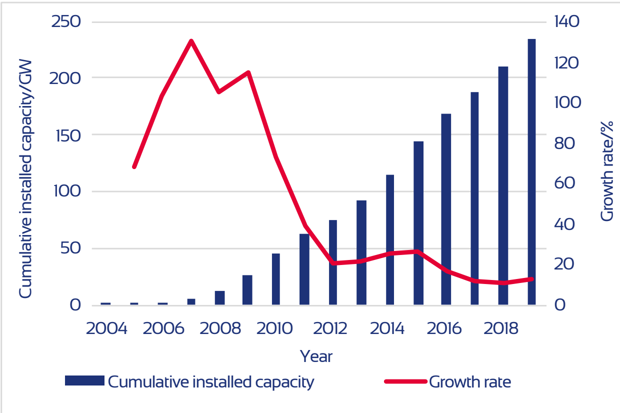

Figure 1 Cumulative installed wind power capacity in China (Source: He et al. 2020)

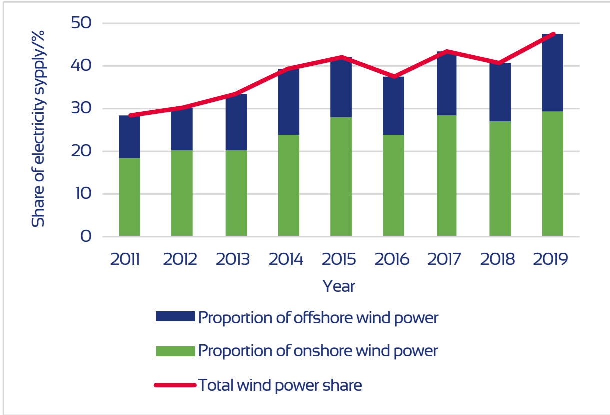

Figure 2 Proportion of onshore and offshore wind power and the total wind-power share of electricity supply in Denmark (Source: Energy Watch 2019)

the Danish Partnership Smart Energy Networks was established in 2014 to bring together Danish energy companies, industry and knowledge institutions within electricity, heating, cooling and gas. This promises to be an effective approach for achieving the ambitious Danish climate and energy goal of a fully 100% renewable-based energy system by 2050 (Partnership Smart Energy Networks 2015).

In addition to the integration of infrastructural technology, coordinated operation and control of an integrated energy system are necessary (Li et al. 2015, He et al. 2015). At present, in most countries, the regulation and management of different energy sectors are still separate both for historical reasons and due to the different sets of rules based on diverse principles. This lack of uniform standardization impedes the development of efficient integration and optimal solutions for the whole system. Well-functioning and efficient smart energy systems should be based on an integrated energy-system approach that incorporates novel digital solutions, including sensors and actuators embedded in the system, various internet technologies, platforms with service-based designs, and novel business models (Lund et al. 2017), but this can only work effectively if the cross-sector regulations are compatible.

During the last few decades, the concept of the Smart Grid has emerged. It involves new concepts and technologies in the EPS. The European Union Commission Task Force for Smart Grids (2010) defines the smart grid as 'an electricity network that can cost-efficiently integrate the behavior and actions of all users connected to it – generators, consumers and those that do both – in order to ensure an economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety'. The idea of the smart grid can be extended to smart energy, whereby information and communication technology also play an important role in enhancing the performance of the coordinated operation and control of all the coupled energy sectors (Yu et al. 2016).

Smart energy system

A 'smart energy system' is defined as a cost-effective, sustainable and secure energy system in which renewable energy production, infrastructure and consumption are integrated and coordinated through energy services, active users and enabling technologies (Partnership Smart Energy Networks 2015). Fig. 3 gives an overview of a Danish smart energy system providing flexibility for the cost-effective integration of renewable energies (DTU Sector Development Report 2020). The different characteristics of the coupled electricity, heating, and gas energy sectors in smart energy systems are listed in Table 1. An introductory semi-detailed introduction is provided below.

Electricity sector

There will be more naturally fluctuating power generation in the EPS, which can flow bi-directionally, from large-scale generators via the grid to the consumer, and be reinjected by prosumers into the grid. In addition, over time, small-scale distributed generation and fluctuating renewable generation will gradually replace the conventional central power plants. Since the traditional (large-scale) synchronous electricity generation units that provide inertia response are being replaced by non-synchronous renewable-energy technologies (effectively via power-electronics inverters), the total inertia in the system is being reduced, leading in turn to adverse impacts on the frequency security of the EPS (Teng et al. 2015). This considerably increases the requirement for flexibility, especially frequency control reserves (FCR), to maintain the system frequency security. To obtain additional flexibility to support the operation and control of the EPS, new energy-conversion techniques, demand response, and new power-generation scheduling strategies are being introduced into the electricity sector. The conversion techniques include the still conventional gas-fired electric power plants (gas-to-power) and cogeneration plants (gas-to-heat and electrical power), as well as heat pumps (electric power-to-heat) and future technologies that convert electrical energy into molecules such as hydrogen and methane (power-to-gas) (Guelpa et al. 2019). By promoting appropriate interaction between electric power generation and active consumers (including commercial, industry and residential), demand response can offer great benefits to operation of the system (Siano 2014). The electrical loads are controlled by intelligent management systems participating in the electricity markets. As an example, in the EU-supported project EcoGrid EU, flexibility on the consumer side is supposed to originate mainly from local heating systems in buildings (Zhang et al. 2019).

Heating and cooling sector

With the further development of low-energy buildings, residential and office energy consumption, including heating and cooling demand, will fall correspondingly. By developing more district heating and cooling systems where appropriate and justified, it is possible to move towards a more sustainable energy system based on renewable energy (Zong et al. 2019). In this regard, the concept of a 4th Generation District Heating System (4GDH) was proposed in Denmark (Lund et al. 2014), while the 5th Generation District Heating System (5GDH) was developed further, also known as Cold District Heating Networks (Wirtz et al. 2019). These systems are based on the idea of low-temperature and ultra-low-temperature district heating systems (DHS) respectively, which can reuse the waste heat from industry and buildings, as well as reduce heat loss. The heating networks in 4GDH are characterized by normal distribution temperatures of 50°C (supply pipe) and 20°C (return pipe) as annual averages, while the temperatures in pipes with 5GDH are around 5-30°C, which keeps heat loss to a minimum and reduces the need for extensive insulation. In 5GDH, electrical heat-boosters are usually installed at the building side for heating hot tap-water. In addition, heat storage is playing an increasingly important role in the heating sector, which can enhance the flexibility of CHP units and integrate fluctuating wind power better through the conversion of electrical energy into heat.

Natural gas sector

Due to the low cost of the energy carrier, low environmental emissions, and high efficiency of natural gas-based technologies, natural gas has become the second largest source of the world energy consumption (He et al. 2018). On the one hand, gas can easily be converted into electricity and heat by gas-fired power generation, such as combined cycle gas turbines (CCGTs), high-efficiency condensing boilers, and combined heat and power (CHP). CHP (or co-generation) intensifies the coupling between the natural gas and electricity power systems. On the other hand, with the hopefully successful future development of power to gas (P2G) technology, electric power can also be converted into gas (hydrogen and methane), and then the converted gas can be injected into the natural gas system together with biogas (Zeng et al. 2017). It should be noted, however, that although the overall efficiency of this process is quite low, it may nevertheless be a necessary building block in achieving the required system integration between sectors to ensure long-term storage. The P2G route can help decrease the curtailing of renewable energies and provide more flexibility for the EPS. Furthermore, the natural-gas system has large-scale storage capabilities due to the pressure flexibility and the large volumes in pipelines and caverns (Hansen and Søndergaard 2015).

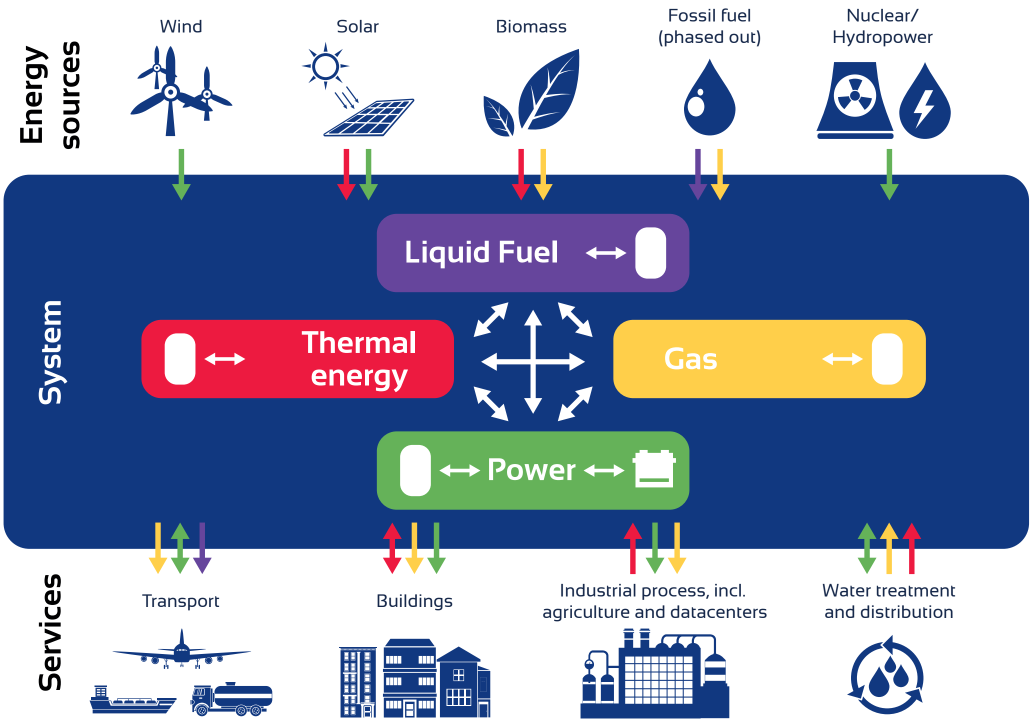

Figure 3 Overview of integrated energy system (Source: DTU Sector Development Report)

Transportation sector
The European Environmental Agency (EEA), which keeps track of worldwide final energy consumption, has found that the transport sector is responsible for about a third of overall final energy consumption (Shell International BV 2017). Thus, because of the accompanying CO2 emissions and local pollution, it is crucial that the transportation sector replaces fossil fuels with renewable-based energy carriers (Qian et al. 2020). The electrification of transportation through battery electric vehicles (BEVs) or fuel-cell hybrid electric vehicles (HEV) are promising technologies, since they can reduce fossil-fuel consumption, as well as enhancing the integration of naturally fluctuating renewable energies. For instance, BEVs can be charged and discharged at different times and locations. Thus, it is treated as a flexible load (G2V) and storage in the power system, which can change the load both in time and space (Knezović et al. 2017). Meanwhile, BEVs can discharge electric power to the power system like generation units through vehicle to grid (V2G) technology. With the proper design and control strategies, BEVs can provide multiple ancillary services to the power system, such as frequency response (Askjar et al. 2020).

Operation of smart energy systems
The optimal operation and smart control of smart energy systems can improve the sustainability, reliability, and cost efficiency of the whole system. Taking into account diverse energy-conversion technologies and the coordination of different energy sectors, the energy services required by customers or system operators can be provided in many different ways. With centralized control, the entire smart energy system is generally managed by a single operator, and overall the appropriate operation constitutes a large-scale centralized problem, which is more complicated than with an individual system. To improve computation efficiency and protect information privacy, distributed or decentralized solutions are desired to achieve independent yet coordinated operation (Tan et al. 2020). In addition, there will be quite a lot of local control via integrators and aggregators, which also requires distributed operation and control. Apart from the aforementioned technical aspects, a proper market design with the right incentives and clear (i.e. stimulating and no -mutually opposing) regulations will be required to ensure the effective operation of smart energy systems as well.

Current status of smart energy systems in China and Denmark

Current status of smart energy systems in China
During the period of the 12th Five-Year Plan (2011-2015), coal consumption in China fell by 5.2% and the consumption of non-fossil fuels increased by 2.6% (The development of energy in China 2018). Before 2006, electricity generation came mainly from conventional thermal power units and hydropower units. In order to reduce CO2 emissions, power generation from renewable sources of energy such as wind, solar and hydro has developed rapidly in China during the last decade. It is expected that carbon dioxide (CO2) emissions will peak at around 2030 and that the non-fossil-fuel share of primary energy will increase to 20% by the same year (International Energy Agency 2017). Moreover, the Chinese government has recently announced a target of achieving carbon neutrality by 2060. In addition, due to its higher conversion efficiency and lower environmental emissions, natural gas has attracted increasing attention, expecting to reach 15% of total fuel consumption in the whole energy sector by 2030. In northern China, the DHS is being adopted to supply heat to consumers. The combined heat and power (CHP) units and heat boilers cover 62.9% and 35.7% of heating production respectively, the rest mainly being supplied by industry waste heat and geothermal. However, the electric power and heat generation of CHP units depends on heat loads, which limits the operational region of the CHP units. CHP units must run when the heat is needed, leading to a high curtailment of wind power in the winter.

Since 2015, the National Energy Administration of China has issued several policies to support the de-

Table 1 Different characteristics of various energy sectors. Source: Hvidtfeldt et al. 2015.

Energy sectors	Properties	Intrinsic flexibility	Flexibility need
Electricity	Long-distance transport Low losses Easy to generate from renewable energy sources Easy conversion to other energy carriers	Very low (seconds)	High
Heating	Local/district Medium losses Difficult to convert to other energy carriers (if low temperature)	Medium (days)	Medium
Gas	Long-distance transport Low transmission losses Intrinsic losses during conversion at the point of use Easy to convert to heat and electricity	High (months)	Low

velopment of smart energy systems, including microgrids with high renewable penetration and an overall integrated energy system, referred to as the Energy Internet. The State Grid Tianjin Electricity Power Company is the first company to conduct demonstration projects of integrated energy systems, which would achieve coordinated management and control of the electricity, heating and cooling fluxes and flows. The integrated energy system, if done properly, improves the cost efficiency of the whole system and reduces CO2 emissions. The State Grid Jiangsu Electricity Power Company has completed a demonstration project of a district smart energy system with 70% penetration of renewables, which incorporates the electricity, heating, cooling, and transportation energy sectors. In addition, the China Southern Power Grid has investigated how to design and operate a smart energy system that includes the electricity, heating, gas, and transportation energy sectors. However, at present the EPS, DHS and gas systems are operated by different entities in China and are thus planned individually.

Current status of smart energy systems in Denmark

In 2018, electricity from renewables accounted for 60% of Denmark's domestic electricity supply, and wind power accounted for 40% (Danish Energy Agency 2018). In particular, the transition from fossil fuels to renewable energy for district heating is significant in Denmark. The percentage of renewables covered 60% of district heating production in 2018 (Danish Energy Agency 2018). Apart from securing adequate capacity through the connection with neighboring countries, the heating sector in Denmark plays a major role to provide flexibility for the EPS in integrating fluctuating wind power. The heating and electricity sectors are coupled through CHP plants, which generate around 70% of thermal energy in the Danish DHS. Since the electricity tax is being reduced gradually over time, electric boilers and heat pumps have attracted increasing attention. Combined with the electric boilers, heat pumps, and heat storage, CHP units can provide more flexibility to the EPS.

In order to facilitate the integration of wind power, Denmark has conducted quite a number of research projects on future smart energy systems. For example, the EnergyLab Nordhavn project is a demonstration project for a dense and integrated future energy system. It demonstrates how electricity and heating, energy-efficient buildings and electric transportation with the innovative use of data and analytics can be integrated into an intelligent, flexible and optimized energy system (A Smart City Energy Lab 2019). A low-temperature district-heating (LTDH) system incorporating smart energy network technologies, heat storage, energy-flexible buildings, decentralized supply options and fuel-shift solutions, has been developed. In the Copenhagen Nordhavn area, active participation by the occupants of the low-energy buildings acting as agile consumers and users, and therefore becoming active energy-flexible elements, has been investigated. Another project, 'Centre for IT-Intelligent Energy Systems (CITIES)', has developed methodologies and digital solutions for the analysis, operation and development of integrated urban energy systems, with the ultimately aim of achieving independence from fossil fuels by utilizing the flexibility of the energy system through intelligence, integration, and planning (Centre for IT-Intelligent Energy Systems in cities). The EnergyPlan tool has been developed by Aalborg University to design a 100% renewable-energy system that includes the electricity, heating, cooling, transportation and industrial sectors. It is investigating the modelling of all relevant energy-generation units, energy storage, and energy-conversion technologies (Lund 2010).

Recommendations for the further development of smart energy systems in China and Denmark

An efficient transition to a smart energy system requires intensive research and development efforts regarding the integration of various energy-conversion techniques, system operation frameworks, digitalization and communication systems etc. The following suggestions for further research into and development of smart energy systems are recommended for both China and Denmark:

1. Investigate new optimal operation frameworks and control strategies for multiple energy systems. Given the fact that various energy sectors are managed by different entities and that the coordination of different energy sectors is insufficient at present, research should be conducted to coordinate various energy sectors with different operational time scales and characteristics, while respecting the privacy of different entities. The development of smart energy systems should focus on providing secure and reliable energy services to end-users.

2. Design multi-energy carrier markets and develop new business model frameworks. In order to distribute smart energy system costs and benefits across energy sectors and services efficiently, new regulations and business models should be developed. A corresponding demonstration acting as operational platforms for new business models is needed. In addition, the incentives needed for energy consumers and building management to adopt flexible consumption should be explored.

3. Develop solutions for the more efficient integration of energy storage and advanced energy-conversion technologies to accommodate the growth in fluctuating renewable energy. The optimal operation and smart control of the various energy infrastructures should be investigated in depth, enabling additional flexibility across these infrastructures to efficiently balance and utilize renewable energy, mainly integrated into the power system.

4. Design and develop low-energy buildings for a green transition. Buildings play an important role as the main consumers in cities. Together with indoor climates and thermal inertia, the potential flexibility of buildings can be utilized. Advanced building energy management and control systems should be developed to interact with the (external) smart energy system and increase energy flexibility.

5. Develop integrated design and planning methods across energy sectors for smart energy systems. At present, there are no national policies and regulations regarding smart energy systems in either China or Denmark. The coordinated design and planning should evolve to remove the barriers between the different energy sectors and facilitate the deployment of smart energy solutions.

However, since China's current multi-energy system is not as developed as that in Denmark, there are additional challenges in China in developing smart energy systems:

1. The electric power system in China is undergoing market reform, and the regulations corresponding to the demand side have not yet been enforced. It is currently unclear how smart energy systems can participate in the market and make a profit by providing energy services.

2. For the time being, the 2nd generation of DHS supplies heating to consumers in China. These thermal network systems need to be upgraded to 4th- and 5th-generation DHS to improve energy efficiency and reduce environmental emissions, whereby the supply and return temperatures are reduced and more heat storage is included. Moreover, heating production should be generated increasingly from renewable and clean energies such as biomass.

Conclusion

Cross-sector smart energy systems will be developed in Denmark, China and the rest of the world. The integrated energy system will be the most efficient solution to the problem of increasing the energy efficiency of systems and reducing environmental emissions. This chapter has described the concept of the smart energy system, integrating the electricity, heating, cooling, gas, and transportation sectors with high renewable-energy penetration. The different timescales and characteristics of the different energy sectors create challenges for the coordinated operation of the different energy sectors.

Denmark and China are both dedicated to the development of smart energy systems in order to realize their commitment to mitigating climate change. Many projects have been conducted to demonstrate the economic and environmental benefits of smart energy systems. Compared to the extensive investigation of integrated energy systems and well-developed district-heating supply in Denmark, the development of smart energy systems in China is still at the beginning stage. Further research and development are required in both Denmark and China to deal with the challenges to the green transition towards a smart energy system, including advanced technologies, novel market designs and business models, as well as consistent national regulations to remove the barriers between the different energy sectors.

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6 Power electronics-based large-scale integration of renewables in power grids

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Introduction

In recent years renewable energy (RE)-generating technologies like photovoltaic (PV) cells and wind turbines have increasingly been connected to the electric power grid. According to (IEA 2019), the future electricity demand is expected to increase faster than overall energy demand and to be covered to a large extent by solar PV and wind power. Most wind-power and PV generation will be connected via power electronic (PE) converters, which are critical in converting DC from PV to AC of the grid, as well as being crucial building blocks for variable-speed wind turbines. Furthermore, PE converters can ensure better control and bring many new features to the power system. There has been significant growth in power-electronic interfaced power sources (PEIPss) with increasing power capacity. This gives rise to several technical challenges with special focus on the capabilities for managing the fast control and operation of the grid in case of failure so as to ensure reliability and security of the total electrical system. As examples, this could be due to low total system inertia, low short-circuit power and limited possibilities for dynamic voltage support (ENTSO-E Guidance 2017). To guarantee grid stability, the grid must always be operated in a balanced condition with power production matching power consumption. This will require more spinning reserves, which can take the form of rapid control of the power-generating units or of load changes to ensure the balance. Furthermore, the system should also create possibilities for harmonic injections to counteract resonances if several distributed energy resources (DER) with their converters are connected along a grid distribution radial (Lu et al. 2016). Consequently, manufacturers of renewable power generators, including PEIPS, will have to ensure that their generators and plants are adapted to the new grid codes.

As a consequence of the fluctuating and stochastic nature of RE power generation, it is difficult to guarantee rigorously planned and instantaneous power production and, depending on the market design, to avoid penalties for excessive deviations from the bids the RE operator has submitted before gate-time closure. Therefore, in recent years, investigations have been conducted into the possibility of introducing energy-storage systems to support wind-power and PV generation, whereby different storage options can be considered, that are applicable to both larger and smaller systems. The work by (Heide et al. 2011) examines Europe's storage and balancing needs for a fully renewable electric power system (i.e., 100% renewable electrical energy on an annual basis) which often has excess instantaneous wind and solar power generation. A method gaining more and more importance for dealing with the RES fluctuations and ensuring a supply/demand balance is to promote active demand response and cross-sector integration (Ponnaganti et al. 2018). However, Djørup et al. (2018) conclude that the current structure of the Danish electricity market cannot financially sustain a system with 100% renewable energy penetration (mainly from wind), even though the system modelled in that work utilizes a huge amount of cross-sector integration into other energy sectors. From a technical point of view, new grid codes are continuously being introduced by the transmission system operator (TSO) to ensure stability in the grid when integrating more wind or PV power. On the homepage of the Danish TSO Energinet (Energinet.dk 2020), several grid codes are available depending on the type of generation and size, new grid codes also being launched in order to integrate battery storage. These grid codes are based on the EU regulation Network Codes Requirements for Grid Connection of Generators (NC RfG as of 27 April 2019) and the Demand Connection Code (DCC as of 7 September 2019). (Reddy et al. 2017) compare different grid codes before setting up an appropriate wind-power management system for adaptation to the grid codes. (Mohseni and Islam 2012) review the different international grid codes related to wind power and suggest more global ideas and future trends before conducting a review of wind-generator technologies and their power electronic converters, which have to adapt to these codes. Among the issues related to the grid codes are fault ride-through capabilities (FRT) and power-gradient constraints and possibilities for spinning reserve provision controlled by the converters in the power-generating units. More questions about the provision of short-circuit power and concepts of voltage support are raised by (Jia et al. 2018) for adaptation to the grid codes.

To address the above issues in more detail, this chapter will be organized as follows: section 1 will describe the relevant grid codes and the main issues regarding con-

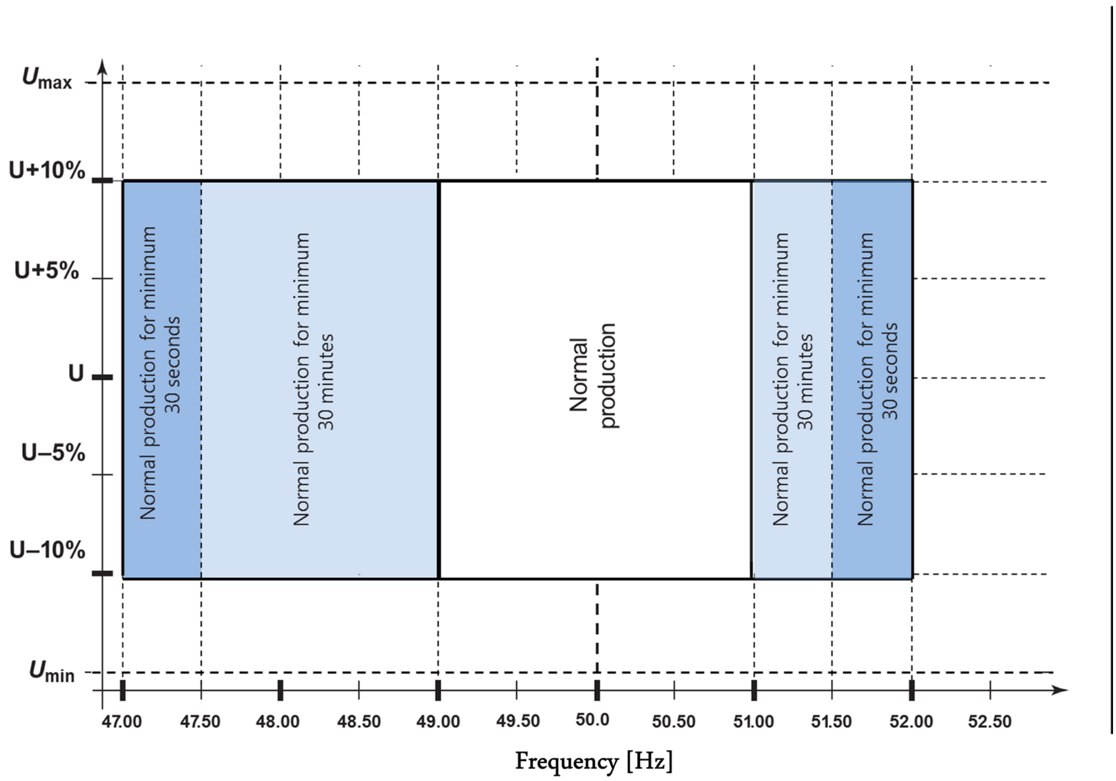

Figure 1 The required frequency/voltage operation range for wind-power plants with nameplate capacity ranging from 25 kW to 1.5 MW (Energinet 2016). U and 50Hz are the 'nominal' values.

trol and safety issues to which the PE interface must adapt. Section 2 will first review the balancing problem, including the power-gradient constraints and voltage-support issues, and then consider the application of storage and demand-response methods and how they can be applied together with the power electronic control of the RE power-generating units. Section 3 will address the problem of power quality by looking at harmonic injections and resonance issues in distribution systems with several parallel connected PE converters. Section 4 will include discussions and recommendations for the application of PE in relation to RE penetration. Finally, section 5 concludes the chapter.

Grid codes for power electronics-interfaced renewable power-generators

As already noted, large-scale renewable electrical energy (RE) technologies of the naturally fluctuating type, such as wind and PV generators, have steadily increased in installed capacity and will become a very significant part of the generating capacity of many different power systems, which consequently presents huge challenges to power system security. In general, modern RE generators use power electronic converters for connection to the grid and have very different features from the conventional synchronous generators. In order to ensure the stable, reliable and economic operation of power grids with a massive integration of RE power, grid operators must draw up regulations in the form of grid codes to secure reliable operation of the grid with the large-scale penetration of renewable power.

Grid codes for wind and PV generators specify the requirements that they must meet to operate in a power grid. The grid codes cover many different technical aspects usually including steady-state performances (frequency, voltage, active and reactive power, and power quality); dynamic performances (frequency gradients, start-stop, active power ramp rates, reactive power and voltage dynamic control, fault ride-through, inertia, overvoltage and protection); the communication and control interfaces; simulation models; certification and verification; and commissioning and performance verification (Chen 2018). In this section, some main aspects of the Danish grid codes (Energinet 2016) for wind turbines are used as illustrative examples.

The two very important grid operational parameters are frequency and voltage. A power-system operator needs to keep grid frequency and voltage within the specified ranges by assuring that suppliers balance the active and reactive power production with the active and reactive load consumption. With further increases in wind power, conventional coal-fired plants will be taken out of service, leading to reduced dispatchable capacity and a reduced ability to balance grid power as a consequence. Therefore, the grid code requires wind-turbine operators to take greater responsibility for balancing the power, for example, to operate outside the normal conditions for some specified time periods so that the system operator has the time to take the necessary actions to restore normal operations. The

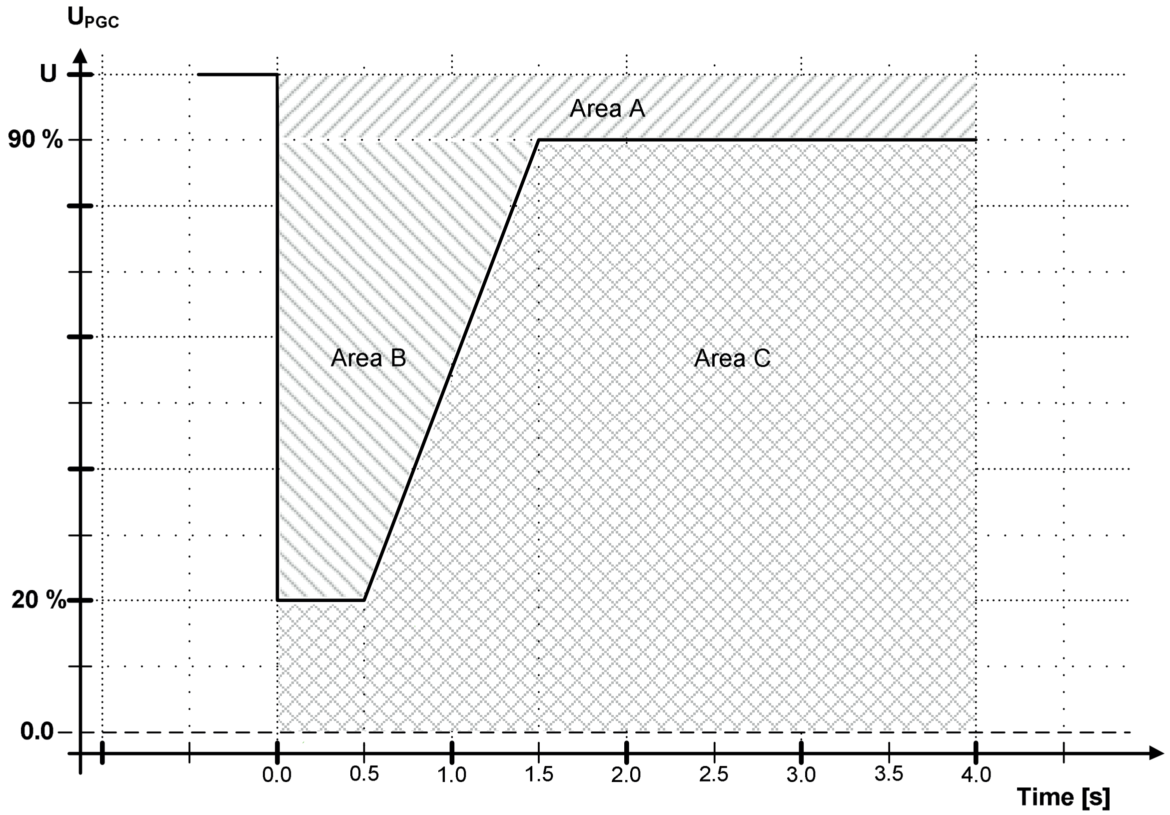

Figure 2 Requirement for tolerance of voltage drops, 'fault ride-through' (for wind turbine with an installed capacity > 1.5 MW) (Energinet 2016).

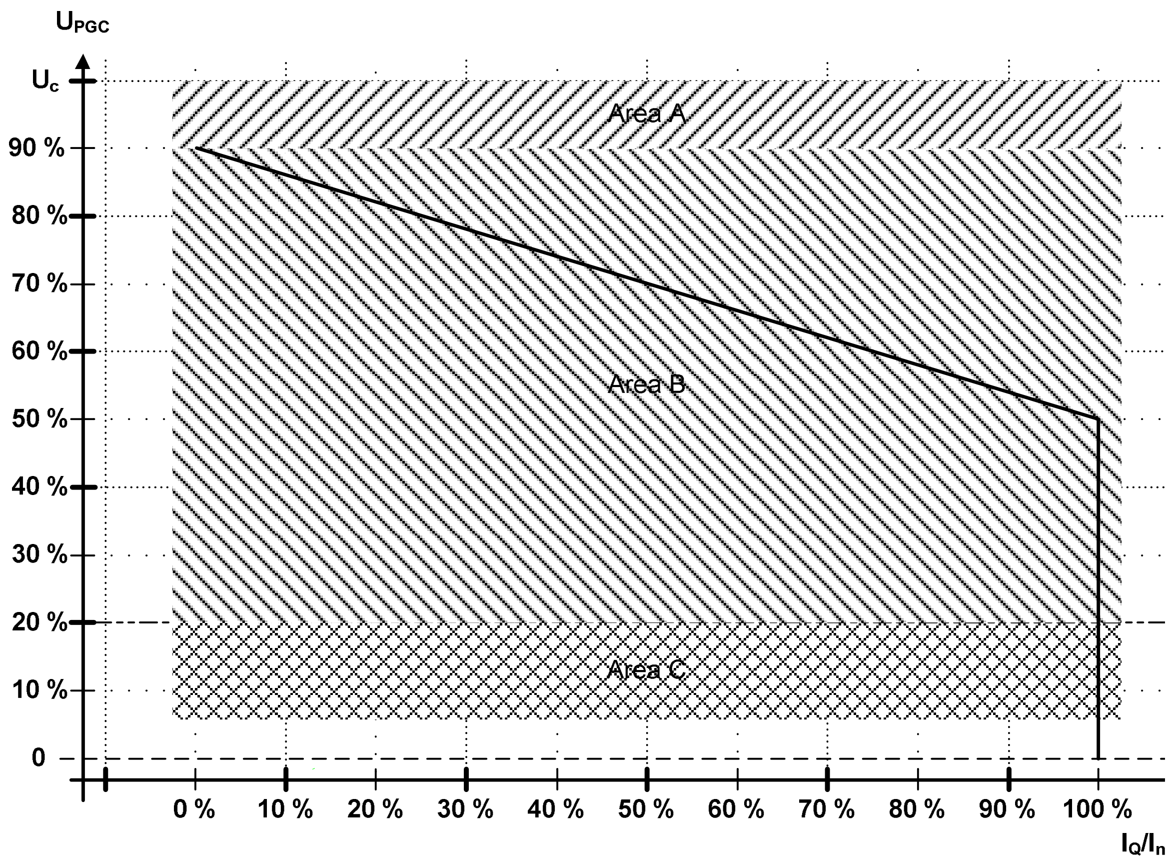

Figure 3 Requirement for reactive power supply during voltage drops (for wind turbine with an installed capacity > 1.5 MW) (Energinet 2016).

requirements will depend on the installed capacities of the wind-power plants. For example, Figure 1 shows the specified frequency/voltage operation range for wind turbines with nameplate capacity between 25 kW and 1.5 MW (Energinet 2016).

To contribute to the regulation of frequency, wind turbines are required to adjust their power output to frequency variation. A number of modes of operation should be available at every wind farm and be ready to be put into operation. They may include:

- **Balance control**: wind farm production can be adjusted up or down to specified levels.
- **Delta control**: the wind farm is operated with a certain constant reserve power band in relation to its available power production level; such reserves may be used for frequency/power control.
- **Power ramp rate limiter**: the speed at which the wind farm's power output can be adjusted.
- **Reactive power control**: the wind farm's reactive power output may be adjusted to a specified level.
- **Automatic voltage control**: the wind farm may automatically adjust its reactive power production in response to the voltage variation at the measuring point.

In an AC circuit, the product of voltage and current, VI, is expressed as volt-amperes (VA) or kilo volt-amperes (kVA) and is known as Apparent power. For an AC resistive circuit, such as heaters, irons, kettles etc., the current and voltage are in-phase, the dissipated power is real power and equal to the Apparent power. However, if the circuit contains reactive components, the voltage and current waveforms will be "out-of-phase", the Apparent power is not the active power any more. If the angle between the voltage and current is Φ, **Reactive Power** (sometimes referred to as imaginary power) is expressed by the equation: $VI\sin\Phi$ in a unit called "volt-amperes reactive", (VAr), symbol Q, while active power, P, is $VI\cos\Phi$. Reactive power is required by many types of electrical equipment that uses a magnetic field, such as motors, generators and transformers. It is also required to supply the reactive losses on overhead power transmission lines. In a high voltage system reactive power is closely related to system voltage, insufficient supply of reactive power would result in low voltage.

In order to provide the reactive power capability, reactive power compensation equipment, such as Static VAR Compensators (SVCs) and Static VAR Generators (SVGs; static synchronous compensators–STATCOMs), are often installed on wind farms to provide support in both normal and dynamic/transient conditions, while doubly-fed induction generators (DFIGs) and full-scale power electronic-interfaced wind-power generators can contribute to reactive power regulation with their power-electronic interface systems.

To help the power system recover after a fault, grid codes require wind turbines to have a 'fault ride-through' capability: that is, wind-turbine systems should remain connected to the electricity grid during a grid fault so that they can support the grid's recovery after the fault has been cleared. Otherwise, the disconnection of large numbers of wind turbines from the grid may result in a significant loss in generating capacity, which consequently may cause difficulties in restoring power-system operations after the fault. Figure 2 shows a 'fault ride-through' requirement, where Area A is the normal operational zone and Area B is the fault ride-through zone: that is, wind turbines should not be disconnected from the grid if the voltage is in Area B, while the wind turbine may be disconnected if the voltage is in Area C. To help recover system voltage, reactive power support is very important and is also specified in the grid codes, as illustrated in Figure 3, in which areas A, B and C correspond to areas A, B and C in Figure 2.

The grid code may specify other requirements, for example, that wind turbines should withstand more than one independent fault occurring at intervals of a few minutes. Also, wind turbines should provide good power quality and meet the limits of rapid voltage variations, flicker, harmonics and inter-harmonics. Monitoring and communication systems are also recommended.

The requirements of grid codes may vary from one country to another depending on the grid conditions. For instance, a weak or isolated power network would have more tightened fault ride-through requirements (lower voltage and longer duration of ride-through) than a strongly connected power system. The requirements may also change from one type of RE source to another, such as wind turbines and PV generators. However, the categories of the requirements, such as frequency and voltage range, active power regulation, reactive power operation range and operation under fault conditions, are quite similar.

The challenge of balancing with plenty of RE power-generating units

As mentioned in the grid codes, it is desirable for the connected large and medium-sized RE stations to have some ability to help regulate the output of active and reactive power in order to ensure the normal operation of the power system and further play a supporting role under abnormal grid conditions.

Taking wind power as an example, and starting from the power-generation side, industry and academia have launched a series of studies and attempts to reduce or even eliminate the impact of power fluctuations caused by large-scale wind power. Wind-turbine manufacturers such as GE and VESTAS add frequency control and active power-control modules to the wind-turbine controller to ensure that the renewable power output responds to changes of grid frequencies.

Further relevant research in academia is being undertaken to tap the potential of renewable power generation to provide frequency support through pre-assessment, controller and control parameter optimization and other methods. Kang et al. (2016) have evaluated the renewable technology support capacity for the design and optimization of a frequency controller at the RE station side. To improve the frequency response performance of RE and ensure its operational stability, Wilchess-Bernal et al. (2016) have studied an optimization method for controller parameters on the basis of an existing controller design, which can be applied to the adaptation of existing controllers. Starting from the wind farm itself, under the mode of maximum power capture of wind energy, an auxiliary power-regulation system is added to the side of wind farm to improve the impact of its wind power on the power grid.

The auxiliary power-regulation system also relies on energy-storage technology. Future advanced energy-storage technologies may include compressed-air energy storage, flywheel energy storage, battery energy storage, superconducting energy storage, super-capacitor energy storage, ice-cold and heat storage, hydrogen storage, P2G and other energy-storage technologies. In terms of physical form, this includes energy-storage equipment that can be used for the peak-shifting and auxiliary services in large power grids, as well as energy-storage modules for homes, buildings and parks. The energy-storage device can store and release energy in time to ensure the continuity and reliability of the power supply.

It is less economic to rely solely on the power-generation side to ensure the safe and stable operation of the system. Therefore, demand-side response (DR) is used to shape the electricity user's consumption behaviour. Demand response means that users respond to the price of electricity or other incentives by changing the way they consume electricity. The most commonly used price mechanisms based on demand-side response include time-of-use price mechanisms, critical peak-load price mechanisms and real-time price mechanisms, all in frequent use in Denmark and other countries. Through demand response, the load demand can be reduced quickly, and, more broadly, in principle in the future, at any moment, the load could be adjusted to achieve peak-load shifting. At least in principle, it is an accommodating way to generate large-scale RE and safely operate offline systems; however, regulatory and price-signal aspects have to be worked out properly to make it really effective.

In China, most of the areas connected to RE, such as wind and photovoltaic, are at the end of the grid. The demand for reactive power from the wind-power plants and the reactive power loss of the transmission lines increase when the installed wind-power capacity and the output power of the wind-power plant are both high. The voltage level and stability margin are reduced due to insufficient reactive power in the grid and the wind farm lacking reasonable reactive dynamic compensation. As a result, it is easy to produce the phenomenon of low voltage in peak-load period and high voltage in low-load period. In order to solve the above problems, reactive voltage control technology has been studied from the perspective of the wind farm. By controlling the power electronic devices of the grid-connected inverter, the wind farm can adjust its reactive power output in accordance with the local grid voltage and provide voltage support to the local grid, thereby increasing the utilization share of the wind power-connected grids.

Given the large-scale integration of wind power, photovoltaic and other renewable technologies, there are still quite a few issues that need to be studied. For example, the topology and control strategy of high-voltage and high-power DC/DC converters suitable for DC collection and transmission; the methods of dealing with the energy curtailments due to RE random fluctuations.

The problem of power quality in distribution systems

In recent years, increasing attention has been paid to the power-quality issue of grid-connected renewable power generation such as solar energy, wind energy and so on. Most renewable power needs to be converted into standard AC power through power-electronic devices before it can be incorporated into the system; so it is inevitable that harmonics are injected into the power grid, causing harm mainly reflected in: 1) causing additional loss of power lines; 2) affecting the normal operation of various pieces of equipment; 3) causing resonance in the system; and 4) causing automatic devices and relay protection to malfunction, resulting in measurement error.

Reasonable control of harmonics is of great significance not only to the power grid but also to users. Power Quality Harmonics of Public Power Grid (GB/T 14549-93), one of the power quality series standards issued by China in 1993, stipulates the limits of harmonic voltage at all levels (380V-220kV) of the public power grid. This has been the universal standard so far, as shown in Table 1. The International Electrotechnical Commission (IEC) has also successively published IEC61000 series electromagnetic compatibility standards and IEC 61400 wind-power standards. When RE is connected to the grid, the standard requirements mentioned above should be met to ensure the stable and economical operation of the system.

The methods for solving harmonic pollution can be divided into the following two categories. First starts

Table 1 Public grid harmonic voltage (phase voltage)

Grid nominal voltage kV	Total voltage harmonic distortion rate (%)	Each harmonic voltage contains rate (%) Odd	Even
0.38	5.0	4.0	2.0
6	4.0	3.2	1.6
10			
35	3.0	2.4	1.2
66			
110	2.0	1.6	0.8

from the harmonic source itself by controlling the power electronic converter so that it does not have the ability to produce harmonics or reduces the content of harmonics. The second is compensation control: if harmonics have been generated, compensation devices are installed in the power grid to compensate for the generated harmonics and reactive power.

Research shows that when RE technology is connected to the grid at the same access location, the larger the access capacity, the higher the harmonic distortion level in the distribution network. When the capacities of the connected units are the same, the closer the access location is to the end of the line, the higher the harmonic distortion level of the distribution network, while the maximum harmonic voltage distortion point will be the end node of the line. From the point of view of reducing the harmonic distortion rate, it is not appropriate to connect RE technologies near the end of the line, but rather to the middle node with heavy load.

RE feeds energy into the grid through grid-connected inverters, which are generally controlled using pulse-width modulation methods. These devices inject current with a large number of high-frequency components into the grid. In order to filter out high-frequency currents, filters can be added between the inverter and the grid. Guo et al. (2010) have proposed an LCL filter. Compared with the traditional L filter, the LCL filter provides a high-frequency bypass through the capacitor branch, which greatly attenuates the high-frequency current flowing into the grid and is widely used in high-power equipment. In addition, a source-active power filter or a hybrid filter can be added to inject a compensation current (equal in magnitude and directed opposite to the harmonic current) to the grid to suppress the harmonics.

A good control strategy can reduce the adverse impact of RE grid connection. PI control is the typical control strategy, the control algorithm is simple, and it is widely used in engineering. In addition, Proportional Rresonant (PR) control, repetitive control, fuzzy control, vector control and cross-coupling control etc. have also been applied.

Given the further development and deployment of RE technologies, other types of power supply will be connected to the distribution network; the different types of access to the power supply will affect the harmonics of the distribution network, and this needs further study. At the same time, the management of RE grid connections should be strengthened, and RE power installations should be scientifically and rationally planned to improve safe and stable operation of the grid after connection to it.

Discussion of some issues related to a power electronic-dominated electric power grid

In transmission systems, there are traditional thyristor-based current-type HVDC systems and the newly developed voltage source converter (VSC)-based HVDC systems. The latter are suitable for multi-terminal topologies, have fast power reserve capabilities and do not require a strong AC grid. Power electronics can also enhance the AC system by means of flexible alternating current transmission systems (FACTS), such as STATCOM for reactive power compensation and system voltage support. In distribution systems, power electronics are also used for reactive power compensation, and system voltage and power quality control, including active filters etc., as well as various types of energy-storage interfaces. On the consumer side, there will be more and more power electronic interfaced loads of various types, such as variable speed drives, heat pumps and electrical vehicles. It is clear that a power electronic-based power grid is emerging. Therefore, the conventional modelling and analysis methods, operation and control strategies have to be re-examined.

The stability of connected power electronic converters has also attracted a lot attention, with significant research efforts being made. For example, multi-loop-based active damping has been proposed to enhance stability by introducing an additional control loop, such as a capacitor-current feedback active damping loop. The controller parameters of an active damping loop may be tuned using a passivity-based method of analysis. However, the accurate parameters of the converter

LCL filter and controller may be difficult to obtain in practice. Thus, various assessment and identification methods of controller and filter parameters have been investigated, such as a grey-box impedance reshaping method, where the parameters of the converter LCL filter, the current control loop and the capacitor current feedback loop are identified by a vector-fitting (VF) algorithm (Zhou et al. 2019). If instability phenomena occur when the VSC is connected to a weak grid, then the parameters of the current control loop and the active damping loop are re-tuned to reshape the output impedance of the VSC, so that the undesired impedance interaction between the VSC and the weak grid can be avoided.

Large-scale power electronic interfaced RE generators that are integrated into the transmission network would change the power system's short-circuit power capacity, which presents a significant challenge to power-system protection systems. For example, a wind-power plant has different short-circuit features than a traditional synchronous power plant, as the short-circuit current will depend on the type of wind-power plant, its configuration and the power electronic design and control procedure. Normally, a power electronic converter would provide a much more reduced short-circuit current than a synchronous generator of the same capacity. This creates problems with some conventional protection relays. For example, distance protection, having been widely used to protect high-voltage transmission lines, is generally based on the principle of measuring the transition impedance, that is, the ratio of voltage to current. However, there are limitations to the application of conventional power frequency distance protection in PE-dominated power systems due to the fault characteristics associated with power electronic converters, such as a lower short-circuit current, frequency deviation of the fault current, high-order harmonics etc. Some efforts have been made to deal with the protection issue, one example being an improved time-domain distance-protection algorithm in which the fault location and transition resistance-related parameters are estimated directly using instantaneous sampling currents and voltages (Ma et al. 2019). The algorithm takes into account the tolerance for the transition impedance and the fast-response requirement to meet the demand for protection of transmission lines.

Summary

In this chapter, different issues related to the coordination of control strategies for power electronics applied in the network grid have been discussed. The focus has been especially on the large-scale integration of renewables into the grid at both the distribution and transmission levels. First of all, the grid codes for connecting renewables were addressed, with a particular focus on the requirements and limits of frequency and voltage control. Here, it was mainly the Danish grid codes that were used as an example. In the next section, the focus was on the problem of balancing when more renewables with fluctuating and non-predictable power production are integrated into the grid. This creates a need for more balancing reserves, which can also be obtained in the future from demand response of active loads and from the fast-reacting control methods used for the renewable technologies themselves. Therefore, the grid codes will have to be adapted to this situation. Many intelligent systems can be applied, as discussed in section 2. In sections 3 and 4 the focus was on power quality issues and on the power electronic influence on control and protection of the grid. Here the higher harmonic content generated by the power electronics converters applied to renewable technologies and future loads were discussed. Methods of mitigating the harmonics using different kinds of filters and intelligent control methods were addressed. However, as was also pointed out in the different sections, there are still many issues that remain to be solved in the future. One such issue concerns the power electronic interface and its control methods, which must become more intelligent if they are to ensure stability and reliability. Secondly, grid-balancing and voltage-stability issues at the network grid also have to be considered. This relates to how to achieve balancing with high penetration of renewables for larger areas, and how to ensure stable voltages on the distribution grid with fluctuating and non-predictable power generation from renewables. Even though many ideas and methods are already being simulated and discussed in the global research environment, they still have to be demonstrated in a real environment to prove their feasibility.

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7

Solar thermal energy

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Solar energy resources in Denmark and in China

Denmark, at a latitude of 55-57°, has a temperate climate, with humid, overcast, mild, windy winters and cool summers. Average annual global solar radiation in energy terms on a horizontal surface in Denmark is around 975–1150 kWh/m² (see Fig. 1). Although the differences are relatively small, six regions with different solar radiation resources were identified for Denmark, and Design Reference Year data have been created for use in calculating the respective performances of solar energy systems for the six regions (Dragsted and Furbo 2012).

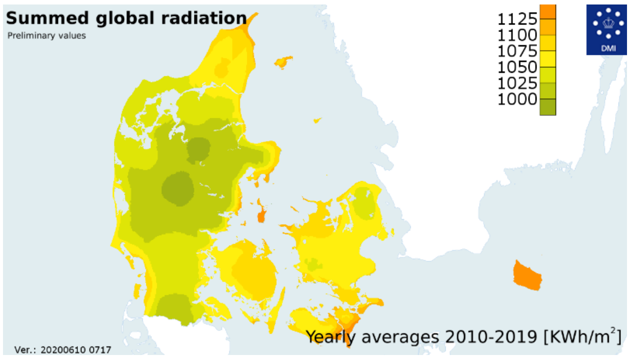

Figure 1 Global horizontal radiation of Denmark expressed as average annual energy density [kWh/m2] (Source: Michael Scharling DMI)

In contrast, China, which covers latitudes from 18 to 52°, has a vast territory with six very different climatic zones: tropical, subtropical, warm temperate, medium temperate, cold temperate and plateau. Consequently, China has annual global horizontal solar radiation varying from 930 to 2330 kWh/m². Global horizontal radiation is the total short-wave radiation that falls from the sky onto a horizontal surface on the ground. It includes both direct solar radiation and the diffuse radiation resulting from reflected or scattered sunlight.

Clearly, the climatic conditions and the availability of the solar energy resource have a significant influence on the design and operation of solar energy systems, including photovoltaic (PV) electricity generation and solar thermal. Huang and Fan have compared solar resources in Denmark and China and pointed out the great potential of solar district heating for China (Huang et al. 2019).

Measuring solar radiation

Typically, solar radiative power at the site of a solar heating plant is monitored and used as a control signal in operating the plant. For the solar pilot plant located in Tårs, 30 km north of Aalborg (DK), Tian et al. carried out measurements of solar radiation and the operating conditions (Tian et al. 2017). The detailed measurements include global horizontal radiation [W/m2], direct normal irradiation (DNI) [W/m²] and total radiation [W/m²] on the tilted collector plane of the flat-plate collector field. Direct normal irradiation (DNI), also called beam irradiation, is measured at the surface of the earth at a given location with a surface element perpendicular to the sun. Total radiation, also called global titled radiation, is measured on a surface with a defined tilt and azimuth. The distribution of diffuse solar irradiance from eight different parts of the sky was monitored closely at a climate station on the campus of the Technical University of Denmark – DTU (Andersen et al. 2015). The influence of clouds on global solar radiation was analysed. These investigations provide valuable input for the development of solar radiation models and the design and operation of solar heating systems.

Modelling solar radiation

Advanced solar resource modelling and forecasting are necessary for optimal solar energy utilization. The accuracy of seven empirical solar-radiation models, including one developed by DTU, were analysed by Tian et al. (2018). The results show that the DTU model could be used to calculate diffuse radiation, while the anisotropic models were more accurate for calculating the total radiation.

State of the art

Buildings consumed approximately 42% of the total final energy consumption of EU member states in 2017.[1] Solar energy could be an interesting and important renewable energy source for space-heating and domestic hot-water services in buildings. Typically, solar

1 https://www.eea.europa.eu/data-and-maps/indicators/final-energy-consumption-by-sector-10/assessment

thermal utilization for buildings can be categorized into solar domestic hot-water systems, solar combi systems, solar heating plants and solar air-dehumidification systems. These technologies will be touched upon in what follows.

Due to the fluctuating nature of solar radiative power, it is vital to integrate solar heat into advanced heat-storage systems and/or other renewable technologies. In 2010-2013, the Department of Civil Engineering, Technical University of Denmark – DTU Civil, carried out a project with the aim of integrating solar heating systems with so-called (electric) power-to-heat technologies (often abbreviated as P2H) based on forecasts of wind power (Furbo et al. 2013).

The application of solar heating systems to single family houses in Denmark is quite limited. However, there is increasing interest in solar district-heating plants because about 65% of all Danish buildings are connected to district heating. A 'large' central solar heating plant has many advantages compared to small-scale solar heating systems (Tian et al. 2019). Denmark is currently not only the country with the largest amount of total installed capacity and the greatest number of large solar district-heating plants, but also the first and only country with commercial, market-driven solar district-heating plants. At the end of 2019, about 1.6 million m2 (or 160 ha) of solar district-heating plants were in operation in Denmark. Furthermore, about 70% of the large solar district-heating plants worldwide are currently in operation in Denmark (Weiss and Spörk-Dür 2020). Although according to these statistics Denmark will be overtaken by other countries in the future, the country has still set out clear examples for other countries around the world to follow.

China is the largest country globally in respect of total installed solar energy-system capacity. About 70% of total solar collector capacity worldwide has been installed in China (Weiss and Spörk-Dür, 2020). The most popular form of solar thermal utilization in China is the solar water heater (SWH). Evacuated tubular collectors (70%) are currently the most commonly used type of collector, while electric heating elements are the most common auxiliary heat sources for SWH systems, followed by gas water-heaters and air-source heat pumps (Huang et al. 2019).

However, the manufacture of solar collectors in China declined significantly, from 64 million m^2 in 2012 to 37 million m2 in 2017, corresponding to a reduction of around 42% of the market in 2012 (Huang et al. 2019). More and more solar combi systems are entering the Chinese market. These are solar heating installations providing both space heating and domestic hot water in buildings. Investigations show that large-scale solar district-heating systems are technologically and economically feasible for China (Huang et al. 2019). Solar district heating (SDH) is expected to have a potential for broad application, particularly for areas with low but reasonable population densities, scarce resources, and strict environmental requirements, such as Tibet. Rural villages and small towns with better infrastructure, for example, district-heating networks, will be the best target market for SDH in the next five years.

Solar collector technologies

As the 'heart' of a solar heating system, a solar collector converts solar radiation into heat. The main solar collector technologies on the market are flat-plate solar collectors (Fig. 2), evacuated tubular collectors and concentrating solar collectors. Flat-plate solar collectors are the most popular version on the European market (approximately 90% of the market), while evacuated tubular collectors dominate the Chinese market (approximately 70% of the market). DTU has carried out ample

Figure 2 Flat-plate solar collectors used in Danish solar heating plants

investigation into developing flat-plate solar collectors by means of measurements and computational fluid dynamic simulations (Fan and Furbo 2008). These showed that from 2002 to 2007 the thermal performance of the solar collectors in Danish district-heating plants increased by 29%, 39%, 55% and 80% for a mean solar-collector fluid temperature of 40°C, 60°C, 80°C and 100°C respectively. The expected lifetime of the solar collectors used in Danish solar heating plants is greater than thirty years.

Differently designed evacuated tubular collectors were also tested side by side at DTU's test facility. The collector efficiency of a tracking compound parabolic collector was measured by Yuan et al. (Yuan et al. 2020).

As concentrating tracking solar collectors are more efficient at high operating temperatures, they should be used preferentially in solar heating plants operating at high temperatures. The long-term thermal performance of a hybrid solar collector field with flat-plate solar collectors and parabolic-trough collectors in series was measured and simulated using Trnsys (Tian et al. 2018). A quasi-dynamic model for the collector field was developed and validated by the measurements (Tian et al. 2018).

Heat storage

Heat storage is considered a vital component of solar heating systems. Types of heat storages can be divided into three categories: sensible heat storage, latent heat storage, and chemical heat storage.

The main forms of sensible heat storage are: hot water tanks, water pit heat storage, borehole heat storage, and aquifer heat storage.

Research on hot water tanks and water pit heat storage aims to achieve higher storage efficiency and thermal stratification in the storage unit. Fan and Furbo carried out experimental and numerical investigations on the heat loss of a hot-water tank and the influence of heat loss on thermal stratification in the tank (Fan and Furbo 2012a, 2012b). It was found that, due to heat loss from the side of the tank, relatively colder fluid moves to the bottom of the tank along the tank wall, while warmer fluid in the middle of the tank moves to the top of the tank. This natural convection helps create thermal stratification in the tank. The recent developments of types of water pit heat storage in connection with district heating in Denmark have attracted worldwide attention (Tian et al. 2019). Simulation models, developed through collaboration between Denmark and China, were validated against measurements of a 3000 m^3 water pit heat storage facility (Bai et al. 2020).

Latent forms of heat storage can make use of organic and inorganic phase change materials (PCM) as heat storage materials. The inorganic PCM has the advantage of having a high energy density, high heat-transfer rate and low cost, and is non-flammable. Salt hydrates, such as sodium acetate trihydrate (SAT), are the most frequently applied inorganic PCMs. SAT has the property of stable supercooling to a high degree, which can be used to store latent heat for a long time with minimal heat loss. Modularized heat-storage units utilizing stable supercooling[2] of SAT was developed and tested at DTU. Successful supercooling was achieved for certain heat-storage designs. With the support of the SDC PhD programme and the EU COMTES project, a complete heating system with developed heat-storage units was constructed and demonstrated on the DTU campus under real environment conditions (Englmair et al. 2020; see Fig. 3). The tests showed promising results. However, the flat heat-storage units were too expensive. Therefore, a tank-in-tank PCM heat-storage unit was developed with the aim of reducing the cost of storage by using mass-produced, standard hot-water tanks (Englmair et al. 2020).

Solar heating systems

Depending on user type, small or medium-size solar heating systems are available for single family houses or multiple-storey buildings and solar heating plants

2 Supercooling, also known as undercooling, is the process of lowering the temperature of a liquid or a gas below its freezing point without it becoming a solid.

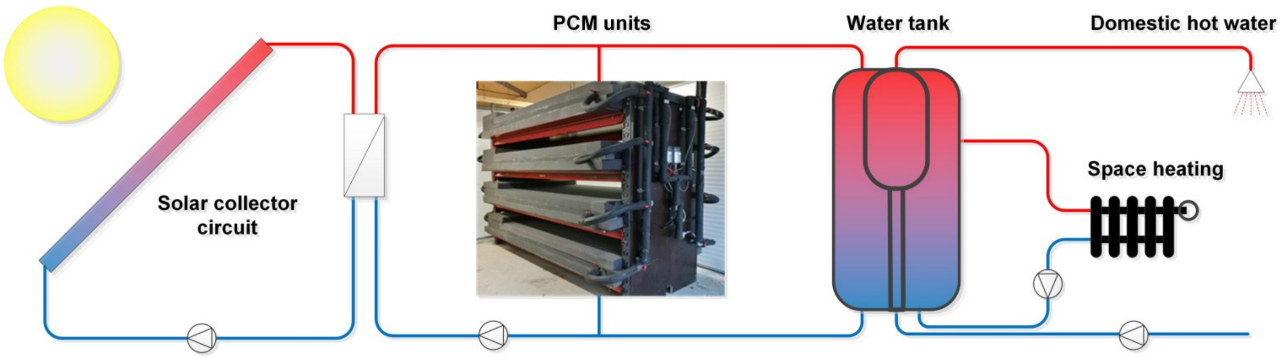

Figure 3 Demonstration of a solar combi system with heat-storage units utilizing stable supercooling of SAT (Englmair et al. 2019)

A Marstal plant (33,300 m²)

B Vojens plant (70,000 m²)

C Silkeborg plant (156,694 m²)

D Dronninglund plant (37,573 m²)

Figure 4 Danish solar heating plants (Source: Arcon-Sunmark, http://arcon-sunmark.com/)

for district heating. Differently designed solar combi systems for single family houses were investigated both experimentally and numerically (Andersen et al. 2014). The systems were based on highly stratified tanks with variable auxiliary heated volumes. They were also equipped with an intelligent control system that optimizes the operation of a heat pump/electric element combination based on forecasts of solar energy production, variable electricity prices and heating demand. The energy savings of solar heating systems in practice, compared to a traditional heating system fuelled by natural gas, was determined for single-family Danish houses (Furbo et al. 2011), being typically of the order of 500-800 kWhth per m² solar collector.

Figure 4 shows four Danish solar heating plants as examples. Numerous experimental campaigns and ample theoretical/numerical analyses and explorations exist of the thermal performance of solar heating plants. For example, a Trnsys model of the Marstal (DK) solar district-heating system was developed and validated by measurements (Fan et al. 2017), whereas Furbo et al. summarized the long-term measurements of 48 solar heating plants in Denmark with flat-plate solar collectors in the period 2012-2016. The measured yearly thermal performances per collector area varied between 313 kWhth/m² and 577 kWhth/m². Variable weather conditions and the location and temperature level of the plant are the major causes of the differences (Furbo et al. 2018). Also, Tian et al. investigated the annual thermal performance of a hybrid solar district-heating plant with flat-plate collectors and CSP collectors (Tian et al. 2017), leading to valuable inputs for the design of such hybrid solar heating plants, especially for areas with high solar radiation as a resource.

System integration of solar heating systems

One important topic is the integration of solar heating systems into overall energy systems. For example, single-family solar heating systems could be integrated with the electrical grid by means of smart solar tanks with variable auxiliary volumes (Perers et al. 2010). Through intelligent control of the system, it is possible to use the solar tanks as flexibility options for the electrical grid (Andersen et al. 2014). For example, booster heat pumps or resistor heating elements could be used. Huang and Fan investigated household solar heating systems in combination with different sources of auxiliary energy, for instance, air-source heat pumps, ground-source heat pumps, gas boilers, etc. The optimal solar collector area and the solar fraction were determined for the different combinations (Huang et al. 2019b). With applications of large forms of thermal energy storage in district-heating plants, it becomes feasible to integrate different renewable energy technologies (such as solar heat, wind power, and biomass) into the overall energy system. For centralized district-heating systems, Huang and Fan investigated the integration of air-source heat pumps, ground-source heat pumps, large-scale heat storage and gas boilers with solar heat (Huang et al. 2019a). The optimal solar fraction for an SDH with heat pumps was found to be 11-33%. The integration of solar heating with ground-source heat pumps was investigated for a village in the suburb of Beijing. It is essential to ensure the thermal balance of the ground optimal matching of the size of the ground heat storage, the collector area and the tank volume (Huang et al. 2020).

Economic analysis

The key success factor for solar heating is a good long-term economic balance (costs/benefits), while reducing greenhouse gas emissions as much as is reasonable or possible. In principle, one should distinguish between the overall cost/benefit picture for an investor in a solar heating system and the overall cost/benefit picture for society. The former should be clear; the latter includes the system integration aspects (e.g., thermal network, electricity grid, gas grid) for a whole region or country, as well as the external (environmental) costs. This last item is currently a subject of research worldwide, and only initial rough results (with ample simplifying hypotheses) are available in the scientific literature. In the following, we concentrate on the costs for the investor and operator of solar heating systems.

The 'levelized cost of heat' (LCOH) is widely used in economic analysis for a solar heating system; it can be defined as follows (Huang et al. 2019, 2019):

$$LCoH = \frac{I_0 - S_0 + \sum_{t=1}^{T} \frac{C_t(1-TR) - DEP_t \cdot TR}{(1+r)^t} - \frac{RV}{(1+r)^T}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}}$$

where the LCoH can be expressed in [DKK / kWh$_{th}$]; is the initial investment for the whole system, [DKK]; stands for subsidies and incentives [DKK]; refers to the operation and maintenance costs in year t [DKK]; is the tax rate [%/100]; is the asset depreciation in year t [DKK]; stands for the residual value of the system at the end of life [DKK]; is the total thermal energy demand in year t [kWh$_{th}$]; is the discount rate [%/100]; and is the overall lifetime of the system [year]. The *LCoH* is the fictitious average price for heat that the investor should receive (i.e., as revenue when selling the heat, or the avoided price for not having to buy heat) so that the investment and operational costs break even.

The LCoH enables solar heating systems using different technologies to be compared. In recent work, different types of solar heating system were applied to five European countries: Austria, Switzerland, Denmark, Germany and France. It was shown that without subsidies most solar heating systems have a higher LCoH than the reference conventional heating systems without solar, except for some solar domestic hot-water systems (Louvet et al. 2019). The reference systems without solar assistance are theoretical heating systems meeting the same useful heat demand as the solar-assisted heating systems. To make solar heating systems economically competitive in the market, supporting policies such as tax relief and subsidies are needed. The economics of solar heating systems were also investigated for single family houses in China (Huang et al. 2019b). There is an optimal solar fraction with the lowest system LCoH. Depending on the design of the system, the optimal solar fraction may vary significantly.

Thermo-economic analyses were also carried out for large solar heating plants. Tian et al. calculated the LCoH for a solar district-heating plant in Denmark with both flat-plate and parabolic-trough solar collectors (Tian et al. 2018). By design optimizations, the LCoH could reach 0.36 DKK/kWh$_{th}$, compared to a typical price for heat in Denmark of about 0.6 DKK/kWh$_{th}$ with tax. Huang and Fan investigated the potential of differently designed solar district-heating systems for China (Huang et al. 2019a). In combination with a PEST (policy, economics, social, and technology) analysis and a SWOT (strengths, weaknesses, opportunities, and threats) analysis, the LCoH was used to identify potential areas of development for solar heating plants in China (Huang et al. 2019). It is believed that SDH has a broad potential for application in China, especially in the west and north-west of the country, where there are abundant solar/land resources and favourable policies.

Conclusions

Based on the information available in the scientific and technical literature on solar heating applications, the following conclusions can be drawn:

1. Since solar energy-based technologies have a significant influence on system performance, detailed measurements and accurate prediction models of solar irradiance are necessary.

2. Denmark is the world front-runner in the field of solar district heating, while China has the world's largest solar thermal market, with a share of approximately 70% of the world's total capacity. The research collaboration on solar district heating between China and Denmark will therefore be beneficial for the development of solar heating technologies.

3. Thermal energy storage is an important component of any solar heating system. Research is still necessary in order to develop more efficient forms of heat storage with a high degree of thermal stratification and minimal heat loss.

4. In order to develop solar heating systems that are economically competitive in the heat market, support policies, such as tax relief and subsidies, will still be needed until investment costs come down.

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District heating for China's energy transition: Lessons from Sino-Danish collaboration

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Introduction

Cities are important role models for achieving sustainable green urban development. More than half the world's population now lives in cities, which are responsible for over 70% of global energy use. Energy use in the urban areas of municipal corporations accounts for 40 to 50% of GHG emissions worldwide, compared to rural areas outside cities (Gielen 2019). In 2013, the United Nations Environment Programme (UNEP) initiated research on and surveyed low-carbon cities worldwide to identify the key factors underlying their success in scaling up energy efficiency and renewable energy, as well as in attaining targets for low or zero greenhouse gas (GHG) emissions (UNEP 2015).

District energy provision, including centralized heating and/or cooling at the regional level, is a proven energy solution; indeed, in many locations with the appropriate circumstances, it has been deployed for many years in a growing number of cities worldwide (Dhar 2013) District energy systems have three main components: energy production as suppliers, distribution systems as thermal networks, and end-users as consumers (see Figure 1). They represent a diversity of technologies to develop synergies between the production and supply of heat, cooling, domestic hot water and electricity. However, there is no fixed term for 'district energy system' (DES) in use worldwide. For district heating (DH) or district cooling (DC), such systems are defined as distributing thermal energy in the form of steam, hot water or chilled liquids from a central production source through a thermal network to multiple buildings or sites for space or process heating or cooling (EU 2010).

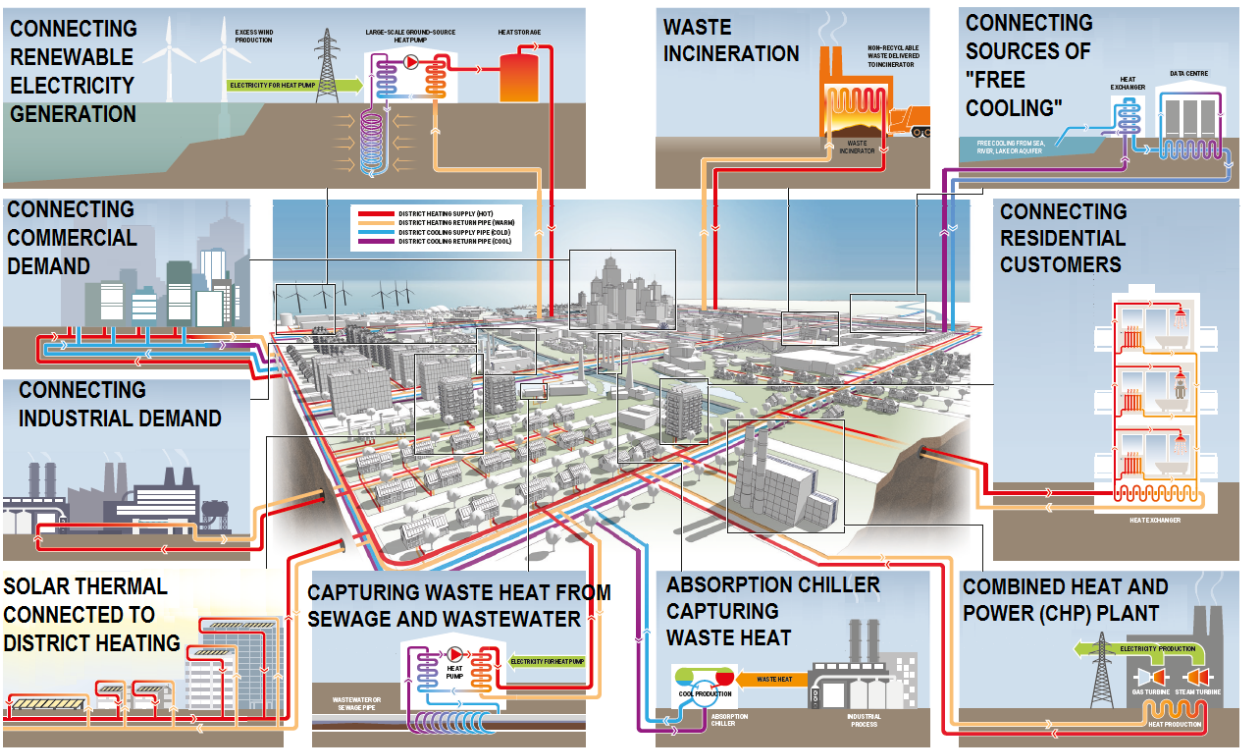

Figure 1 Illustration of a typical district energy system (UNEP 2015)

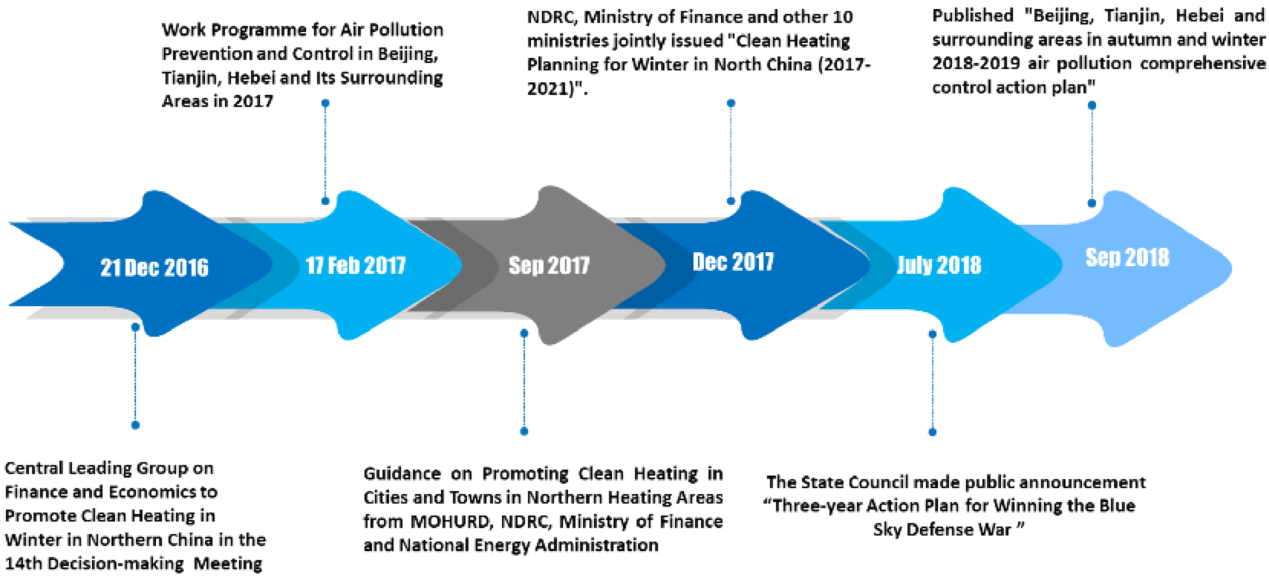

Figure 2 Clean DH developing in China from 2016 to 2018

Cities with sustainable development goals are adopting district energy systems to achieve what they regard as important benefits. DES can contribute to affordable energy provision; higher overall system efficiency, with reduced reliance on energy imports and fossil fuels; community economic development and community control of energy supply; local improvements to air quality; CO2 emission reductions; and an increased share of renewables in the energy mix. All these elements, which are seen as attributes of 'clean' or 'green' district energy systems, can be regarded as making major contributions to the UN's Sustainable Development Goals (SDGs), including SDG-7 (Affordable and clean energy), 9 (Industry, innovation and infrastructure), 11 (Sustainable cities and communities) and 13 (Climate change).

Given the motivations driven by the ambitions just mentioned, cities around the world are taking real actions to impose ambitious sustainability targets on projects on the ground. The city of Copenhagen has gone one step further by using the SDGs as an opportunity to raise the bar and expand both new and existing sustainability initiatives beyond the thermal field to include the spatial planning of buildings and vegetation, and transportation. These efforts, including the climate plan's goal of a CO2-neutral Copenhagen by 2025, are made in dialogue with citizens, companies and civil-society organizations through activities at the city level (Department of Finance 2018). In another example, the city of Bristol, UK, has mapped SDG targets on to its One City Plan objectives, to be achieved by 2030 (University of Bristol 2019). Many other cities in the world with similar ambitions for sustainability are learning about successful experiences and best practice from both cities through city networks or partnerships like C40 (C40 Cities 2020) and Eurocities (Eurocities 2020). The aim of such partnerships is to find ways to make the world's metropolises more sustainable.

In line with the experience of Denmark, achieving the goal of having 100% renewable energy by 2050 requires not only a long-term national policy to set the general direction and policy framework – it also requires active and creative cooperation at the regional and local levels by cities and citizens to implement the policy. Last but not least, it will involve developing and testing concrete new green solutions to create better and more liveable urban environments (State of Green 2019).

Based on the experience and observations of Sino-Danish and international collaboration projects in the DH sector, this chapter aims to summarize the lessons learnt and provide recommendations for a green transition so that Chinese cities can prepare their clean DH action plans and integrate them into the upcoming national 14th five-year plan.

China's national clean district-heating strategy

Due to China's rapid urbanization, the total building area in the country will exceed 60,000 km2 in 2020 (National Bureau of Statistics of China 2012). This urban development is generating high levels of energy consumption for building operations (including space-heating), which has reached 963 million tons of standard coal equivalent (or about 27 PJ). This type of use accounts for 21% of China's total final energy consumption (Building Energy Conservation Research Center 2019). Due to the lower availability of natural gas, Chinese DH systems are still dominated by coal, with coal boilers and large coal-fired electricity-generating plants often operating in CHP mode supplying 32% and 45% respectively of the DH heating area in northern China. Approximately half China's annual consumption of heating coal takes place at low efficiencies of 10%-15%, as with small district boilers and household coal stoves (Zhang et al. 2020).

To alleviate environmental problems and reduce the pollution from heating, the Chinese government has drawn up a "Clean Heating Plan in the Northern Region (2017-2021)", officially making clean heating a national strategy. The target is to reduce the overall use of coal boilers in rural and urban areas to less than 30% of total installations as heat sources in the Northern Region and to reduce the primary energy consumption for DH to 8 kgce/m2 (234 MJ/m2). To reach this target, cleaner heating processes with higher efficiencies, lower primary energy consumption and lower emissions of pollution were promoted by the Chinese government to replace low-efficiency coal boilers (Clean heating plan in Northern region 2017). The road map of clean DH development in North China from 2016 to 2018 is shown in Figure 2.

Denmark's target for becoming carbon neutral by 2050

Denmark has a long tradition of setting ambitious national energy targets. In 2030, renewables should cover at least half the country's total final energy consumption. By 2050, Denmark aims to be a low-carbon society independent of fossil fuels. The country is moving convincingly to meeting these world-leading targets (IEA 2017). Denmark has successfully decoupled its economic growth from its greenhouse gas emissions, thanks to a combination of improvements in energy efficiency and fuel-switching to renewables. The Danish Energy Model has shown that it is possible to sustain significant economic growth, a high standard of living and a high level of security of energy supply while reducing fossil-fuel dependency and mitigating its climate change footprint. This situation can be achieved by means of a persistent, active and cost-effective energy policy with ambitious renewable energy goals, enhanced energy efficiency and support for technical innovation and industrial development (DEA 2016).

Electricity generation in Denmark has changed fundamentally over the past two decades. Coal generation has deliberately been vastly reduced, and the bulk of power generation now comes from wind and bioenergy (DEA 2018). Supported by a flexible domestic power system and a high level of interconnection with neighbouring countries, Denmark is now widely recognized as a global leader in integrating variable renewable energy while at the same time maintaining a highly reliable and secure electrical power grid (DEA 2016).

The heating sector is also critical for Denmark's low-carbon ambitions. Denmark's large-scale use of combined heat and power plants with heat storage capacity and its increasing deployment of wind power, which connects electricity from renewable energy to the thermal energy of heating, offers great potential for the efficient integration of heat and electricity systems. In 2015, total DH supply in Denmark amounted to 128 PJ, and 67.4% of all DH was produced in cogeneration with electricity (CHP). Heat and power generated using CHP reflects the significantly greater efficiency of overall energy systems than heat and power generated separately. Typically in Denmark, a heat-only boiler has an efficiency of around 90-95%, while a condensing power plant generating electricity alone has an efficiency of only 40-50%. A CHP plant may have an overall energy-system efficiency of 85-93% (here for convenience simply defined as the sum of thermal and electrical efficiencies), resulting in an overall fuel saving of approximately 30% compared to the separate production of heating and electricity compared to the typical systems (DEA 2017).

Demonstration projects in the DH sector as part of Sino-Danish and international collaboration

For quite some time, there has been considerable collaboration in providing technical support to assist the green energy transition in China. Significant attention has been given to building local capacity in China in order to spread knowledge about energy planning by teaching local decision-makers and technical staff in relevant government agencies and local communities. In recent years, the demonstration projects in Tongchua and another five pilot cities are examples of this kind of collaboration. Danish experience has played an important role in these projects.

DH planning project in Tongchua

Sino-Danish collaboration to demonstrate Danish heat planning in China was recently concluded in the city of Tongchua in Shaanxi province and its surrounding area. The area has a population of around a million people and is located just north of Xi'an. Danish heat planning was used to analyse the situation in the area, with the invaluable help of the local government.

Danish heat planning is about finding the best space-heating solutions for a selected area, taking into account the heat-technical aspects, as represented by heat demand densities, sources of low-cost waste heat, and the economic and environmental impacts. This methodology often results in local district-heating solutions being introduced in urban areas, along with a more efficient and flexible energy system, compared to individual heating choices being made by consumers.

The Tongchua DH planning project showed that DH can be beneficial in large urban areas with available excess heat from power plants and/or industry. The same is true in smaller towns where residual resources are available cost-effectively, as well as in small rural villages with high building densities, when small-scale biomass boilers, heat pumps or renewable sources are available and the price of electric power is sufficiently low.

Danish experience shows that DH and DC can be the key to creating an energy-efficient society. DH systems in particular contribute substantially to the development of low-emission urban societies. However, this must be carefully planned and designed to secure low or reasonable heat prices.

The Tongchua analysis revealed that the inherent heat-storage benefits of a DH system assist in avoiding emissions and expensive peak-load heat-production capacity investments. Additionally, heat storage and solar collectors were shown to be a possible solution for the transition of small rural villages from coal to clean heating. However, this transition would need to be financially supported in a demonstration period until supplier competition has emerged and technology prices are reduced.

In order to take full advantage of these synergies when doing heat planning, it may be advantageous to include the electricity sector in the planning process, thus opening the door to more efficient and flexible systems. However, some information about the electricity situation is required. Normally, data on the electricity system are not available for heat supply areas, which are typically different from electricity planning areas. In China, some electricity planning is carried out in the provinces, meaning that the required data on electricity systems may be aggregated data from the provincial level.

Demonstration projects in five pilot cities under GEF-6

Under the auspices and with the support of the Global Environment Facility (GEF-6), the National Development and Reform Committee (NDRC) and local municipalities in China, since 2016 UNEP has been conducting demonstration projects to implement modern DES in five pilot cities (Jinan, Xi'an Chanba, Baotou, Yinchuan and Qianxi). The objectives of this project are to:

- increase knowledge of the multiple benefits of DH
- provide technical assistance to identify potential pilot projects, undertake pre-feasibility studies, design business models, support the tendering process and develop local long-term DH strategies
- scale-up locally, through the establishment of local multi-stakeholder coordination units, and nationally, through a National Delivery Unit and the development of a regulatory framework
- unlock investments by means of suitable financial mechanisms to address financial barriers and support the initial projects in new markets.

Using rapid assessment methods, the potential of different DH technologies, policies and environmental benefits in these pilot cities were evaluated. The region of Chanba in Xi'an was selected for an extended, deep-dive assessment, including a city-level GIS-based energy mapping and planning exercise, pre-feasibility studies of two potential clean DH projects with initial design of business models, a financial support mechanism and preparation for public tendering. At the same time, applicable methodologies and tools for technical, environmental and cost-effective DH evaluations are being developed.

The Chanba deep-dive analysis reveals that the municipality has a strong interest in capacity-building to develop a clean DH action plan and a suitable business model. This requires a degree of coordination among different authorities inside the municipality to implement the energy planning results and to incentivize policies and the involvement of relevant stakeholders. The region has great potential to develop multiple clean heating sources, but it cannot combine them into a single DH network due to complications over ownership. The metering strategies need to be re-evaluated and integrated with digital technologies to optimize the control and operation of both the heating sources and the DH network.

Recommendations for the 14th five-year plan for clean DH in cities based on Sino-Danish collaboration

Denmark has gone and is going through a path from energy savings in buildings and the low-carbon development of cities and regions towards making the whole country carbon-neutral by 2050. Even though the size of the population and the economic and energy requirements are totally different in Denmark and China, Chinese cities can still learn from Denmark and its cities. Indeed, much can be learnt by treating the road map as an overall experiment with policies, technologies and business models with a view to addressing the kinds of roles cities can play in achieving a green transition. The medium- to long-term targets of carbon neutralization at different administrative levels in Denmark, such as cities, regions and communities, and their climate-change action plans have provided China with good examples in launching on the path towards clean DH development. According to the national 14th five-year plan, at present under consultation, cities and municipalities can and should adapt the national plan and develop their own action plans for the coming five years in respect of GHG emissions reductions, air pollution mitigation and energy savings. The cities and municipalities are recommended to break down their medium- and long-term targets in these actions plans so as to determine how to implement clean DH and to what level the clean DH can contribute.

Based on the experiences and observations in this Sino-Danish collaboration, several recommendations can be made for Chinese cities to consider in developing their own action plans for clean DH and thus fulfilling the national 14th five-year plan.

The role of municipalities in coordinating stakeholders
Municipalities should play a key role as planners and regulators, facilitators, providers, consumers, coordinators and advocators (UNEP 2015) in introducing clean DH. Although the national government can still impose high-level requirements and set targets in the 14th five-year national plan, Chinese cities should try and adapt these targets on the basis of the current development level. In order to achieve this, they should not only publish local incentivizing energy policies and carry out energy mapping and planning, but also facilitate the market for clean DH and regulate municipal utilities' interconnections with resources and networks.

The implementation of clean DH requires huge amounts of cross-sectional coordination. Municipalities are recommended to set up a DH authority or appoint a focal point to coordinate with different authorities inside the government, including construction, energy provision, urban planning, environment protection and financing, to implement clean DH action plans. Energy mapping and planning should be integrated into the master plan within the same document. The energy planning should not only cover DH, but also achieving energy efficiencies, introducing green-building certification requirements and stimulating renewable energy so as to take into account the overall contributions to reducing energy consumption from different sectors in the region.

The municipalities should also take the lead in publishing guidelines for the design, implementation, operation and pricing structure of clean DH so that different stakeholders can also work out their roles or ways of participating in or benefiting from the transition to clean DH.

Finally, attention should be paid to avoiding counterproductive administrative procedures or mechanisms and instruments that discourage potential participants and investors. The future DH market in China can only be successful if smooth and consistent system-friendly regulations and market designs are put in place.

Cutting-edge technologies from planning to implementation of clean DH
As just noted, energy mapping and planning should be integrated into urban planning as one of the documents in the overall master plan, but they should be updated or revised whenever necessary. Advanced technologies, including digitalization in energy systems, a Geographic Information System (GIS), big-data analysis of predictions of end-user energy demand and the Internet of things (IoT) or 'Internet+' for optimisation in DH and DC operation should be used in the process and considered not only in planning, designing and implementing, but also in operating and optimizing. Chapter 9 of this report has detailed descriptions of these digitisation technologies and their impacts and contributions to overall energy efficiency.

Meanwhile, some criteria which differ from those frequently used at the building level to evaluate energy efficiency, including primary energy efficiency and peak electric power load shifting etc., should be used to measure the energy efficiency of cities and even regions.

In Denmark's experience, one of the most promising advanced technologies for achieving clean DH is the 4th generation of district energy systems (4GDH) (Lund et a. 2014). This system is operated at low temperatures and includes the integration of excess waste heat, renewable energy, booster heat pumps, advanced control or metering strategies and the energy efficiency of buildings. 4GDH are district heating systems running at low temperatures that match the lower energy requirements of more efficient buildings. Lowering supply temperatures reduces losses in heat distribution and enables suppliers to use the additional heat sources available at those temperatures, notably excess industrial heat, and solar and geothermal energy. Developing 4GDH requires new infrastructure in heat production, distribution and consumption. Some applications of 4GDH in Denmark have also enabled buildings such as data centres, supermarkets and industries to sell excess heat to the DH network, which in turn increases the region's primary energy efficiency.

Another often used concept in Denmark is sector coupling between heat and electricity systems, especially because of the large share of wind energy (and the large peaks of instantaneous power generation). Well-integrated DH systems with co-generation of electricity and heat, power-to-heat production in large-scale heat pumps or thermal energy storage can help to balance the grid by producing or consuming more electricity in a specific period of time, representing effectively some sort of virtual electricity storage (DBDH 2019). Even though some types of co-generation systems have been applied to some of China's DH systems in recent years, the greatest share of electricity still comes from coal-fired or other types of fossil fuel-driven power plants, thus reducing the sustainability of energy systems overall.

Business models for clean DH
A new type of business model in the DH sector in China is heating as a service. The roles of DH suppliers should change from regular energy suppliers to whole-chain service providers. Decarbonizing heat, is difficult, as the energy sector needs to combine building renovations with network upgrades in different ways to deliver high-quality low-carbon heating services. Other sectors have already discovered how to marshal complex supply chains to deliver heating services that consumers want to pay for. They have done this by developing processes to reveal what consumers are willing to pay and how well their offers perform.

Best practice regarding successful business models for engaging energy service companies (ESCOs) and private sectors as partners in public-private partnerships should be shared. Clean DH projects in China should move from depending mainly on financial support from governments to self-sufficient commercialized ones. More activities to build local capacity are needed in order to make good use of energy planning as a tool for long-term DH business planning.

Developing and applying suitable and maybe innovative business models in clean DH has the potential to unlock investments from the private sector. As a result, the transition to green energy in the DH sector can be accelerated.

Ownership of DH suppliers

One of the key drivers of efficient and green district-heating systems is the prevalence of consumer-owned district-heating companies. In broad terms, these fall into three types:

- Directly owned systems where consumers finance, build and operate their own district heating system
- Consumer-owned systems held through housing cooperatives
- Municipally owned systems, where the company is run on behalf of the consumers

In all three types, though more directly in the first two, consumers hold the power in the company through an executive board. This structure ensures that long-term operational and investment decisions are geared towards lowering consumer costs, as each consumer pays based on his or her consumption, and economically viable non-profit legislation keeps extra revenue in the company.

The majority of district-heating companies in Denmark have favourable consumer prices compared to alternative heat supplies from natural gas, oil, electric heating etc. They also have well-functioning boards, which continuously invest in new cost-effective and energy-efficient and/or green solutions.

A clear recommendation for China's 14th five-year plan, based on Danish experience, would therefore be to close the revenue loop around district-heating companies and give consumers a direct stake in the system. This would ensure that revenue resulting from efficiency gains would directly benefit the district-heating system, and that consumers are incentivised to manage their consumption better. This combination, when paired with consumption-based heat bills, would undoubtedly improve efficiency and open the door to cleaner heating initiatives.

In order to ensure that the district-heating companies are as efficient as possible, the regulator should compare the costs and tariffs of all companies and publish the results. This helps to correct the information imbalance that would otherwise exist and makes it possible for the consumers to demand better management if their company has high costs.

In conclusion, while the publicly owned heating companies in China provide a good service to its citizens, their incentives to make efficiency improvements are weak. A change to ownership rules that closes the revenue loop and hands more power to consumers would ensure strong long-term incentives to achieve efficiency gains.

Conclusion

This chapter has focused on the lessons learnt from Sino-Danish collaboration to develop modern district-heating systems (DH). It has summarized the recommendations for Chinese cities to implement clean DH as part of their green transition and to develop relevant action plans based on the requirements of the upcoming 14th five-year national plan. In general, there are recommendations in four key fields for cities to take into account in integrating clean DH into local energy systems for a green energy transition: enhancing stakeholder coordination, employing cutting-edge technologies in planning, developing suitable business models, and improving definitions of DH supplier ownerships.

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9

Digitalisation for energy efficiency and flexibility

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Introduction and scope

An initial distinction must be made in this chapter between the terms 'digitisation' and 'digitalisation', for which the definitions given in (Bloomberg 2018) will be used from this point on. Digitisation implies a transformation of operations and exchanges of information from an analogue to a digital process. While this requires new digital skills and infrastructure, it does not fundamentally change the business model or operating procedure of the actors involved. On the other hand, digitalisation draws on the infrastructure built up by digitisation to implement a new 'digital economy', with new actors and business models putting forward innovations.

'Big Data', machine-learning and the Internet of Things (IoT) are just a few examples of thriving new fields of research and industrial and commercial applications brought about by digitalisation. While digitisation appears to be a prerequisite for digitalisation, successful digitalisation will also lead to further waves of digitisation, in a cyclical process. Physically, the digital world relies on electricity to gather, transfer and process information, making electrification of the energy sector highly compatible with the trend towards digitalisation.

Digitalisation in the energy field can be seen as lying at the crossroads between upstream electrification trends and downstream data-based economies that rely on artificial intelligence (AI). While energy use has always generated data, before digitalisation these data for the most part went unrecorded, or at least were left at too low a resolution to be useful. In return, this lack of data has long favoured analytical over empirical models when it comes to understanding the underlying properties and dynamics of systems. Given the access to large-scale high-resolution data provided by digitisation and subsequently digitalisation, new insights have emerged regarding our physical and societal dynamics. Digitalisation should therefore be understood as the catalyser between the physical and the modelled (or cyber) space, bringing with it new business opportunities and action levers to change the energy sector. The remaining questions are which changes seem the most promising, how these changes will impact on the energy sector in the years to come, and what stakeholders in the field should prepare for.

Although digitalisation will affect most parts of the energy sector, this chapter will focus on energy efficiency and flexibility viewed from the consumption side, while also showing that the boundaries between production and consumption become blurred with digitalisation, which increases the transfer of information in both directions. Energy efficiency focuses on reducing overall energy consumption and is traditionally associated with process optimisation problems, as it is closely linked to economic returns. On the other hand, flexibility concerns the optimal way of dispatching a given quantity of energy, mainly through load time-shifts and fuel-shifts. Compared to energy efficiency, energy flexibility has only received attention much more recently, largely because of the paradigm shift brought about by demand adapting to variable and uncontrollable supply, instead of dispatchable generation traditionally adjusting itself to variable loads. Many digitalisation processes will affect efficiency and flexibility simultaneously, whether in a complementary or conflictual way.

The remainder of this chapter is structured as follows. First, the overall digital maturity of Denmark and China are assessed. Following this, an analysis is performed by end-use sector for both countries. The consumption-side digitalisation potential of each country is then summarized in a Strengths-Weaknesses-Opportunities-Threats (SWOT) table. Finally, current investments in energy digitalisation for both countries are presented, before the chapter ends with a discussion and conclusion on each country's position regarding energy digitalisation and points towards future research directions and possibilities for collaboration.

Digital maturity of Denmark and China

Denmark

Denmark has a world-leading position in respect of the digitalisation of public systems and businesses, as well as in its ICT-specialist skills (Lindberg et al. 2019). However, compared to other OECD members, the country is lagging behind with regard to the second wave of digitalisation, particularly in respect of Big Data, the diffusion of AI technology and the appropriate regulations that come with them (Lindberg et al. 2019). Many Danish companies have identified the lack of a qualified workforce in STEM-related subjects relevant to AI as a major barrier to AI adoption (Lindberg et al. 2019). Nonetheless, research in new technologies is being prioritised by the government, which has recently allocated DKK 50 million to new initiatives in digital technologies at universities (Erhvervsministeriet 2018).

From a physical infrastructure perspective, Denmark has the second highest number of IoT devices per capita in the world after South Korea, according to the OECD's *Digital Economy Outlook* 2015 (OECD 2015) .

China

The digital economy plays a significant role in China: in 2017, it accounted for 22.1% of total employment and experienced a growth rate of 20.3% (Zhu et al. 2020).

In recent years China has imposed itself as a leader in AI, with eleven of the top fifteen AI university programs and more than half of AI start-ups in the world being Chinese (Lindberg et al. 2019). China also has four times the cumulative number of patent applications in the field compared to Europe (Lindberg et al. 2019). China is also emerging as a leader in 5G technology, which it is currently rolling out. By the end of 2019 5G was available in fifty Chinese cities, making it one of the world's largest 5G deployments (BBC, 2019). The increase in speed, stability and coverage of 5G is considered particularly important for the development of the energy sector, partly due to the increase in data traffic from IoT systems, the push for real-time information (for technical and market operations) and the shift to OPEX 'everything-as-a-service' driven business models (Leligou et al. 2018).

However, China still has several technological, market and policy barriers to overcome in its development of smart grids before it will be able to implement solutions based on digitalisation (see Chapter 5 of this report, on the challenges to smart grid development), as shown by its dependence on imported power electronics to develop its grid (Shell and DRC 2020). Smart grid R&D efforts in China in recent years have mainly focused on system-wide issues such as the integration of renewables or grid congestion, while being less oriented towards demand response (Xu et al. 2014).

China is also aiming to push forward its electricity market liberalization with the help of digital solutions. For example, the down-regulation ancillary-services market on the production side in north-east China uses fifteen minute-based settlements, which means automated metering and communication at high resolution (DEA and EPPEI 2018).

Digitalisation for energy end-use sectors

So far, across end-use sectors, IT has made energy use more convenient, but current efforts are also aiming to make it greener and more intelligent (Shell and DRC 2020). The predicted increase in cross-sector electrification to achieve carbon neutrality and improve system efficiency and flexibility (Van Nuffel et al. 2018) will make the problem at hand significantly more complex, rendering the insights provided by digitalisation very valuable. As digitalisation goes hand in hand with system electrification, it depends on technological innovations in a variety of sectors.

Industry

In the industrial sector, IT has traditionally been used to improve energy efficiency through energy-management information systems (Shell and DRC 2020). For example, ABB mentions the use of smart sensor solutions which could reduce downtime, increase lifespan and optimize the operation of electric motors, thereby reducing their consumption by up to 10% (ABB 2017). However, this silo approach does not take the grid's overall needs into account when optimizing each industry's consumption.

In Denmark in 2017, the industrial sector (manufacturing, agriculture and construction) represented 20% of final energy consumption (DEA 2018). From 1990 to 2013, final energy consumption declined by 20% in the sector, while the gross added value increased by 25% (CNREC and DEA 2015). However, without new initiatives, industrial efficiency is predicted to stagnate from 2020 onwards (DEA 2018). Certain schemes such as the Manufacturing Academy of Denmark (MADE) promote digital innovation and industry 4.0 through initiatives such as MADE Digital (MADE, n.d.). An example of research innovation in this field is the testing of evolutionary algorithms for greenhouse climate control (Sørensen et al., 2016).

In China, industries represent 67% of the country's overall electricity consumption (Dong et al. 2017), thereby providing huge efficiency and flexibility potential in the power grid. The efficiency of Chinese industry can be greatly improved, as productivity (and therefore partly energy efficiency) remain less than a tenth of productivity in Europe, Japan or the USA (ABB 2017). However, there is believed to be limited potential for further electrification of the industrial sector (Shell and DRC 2020), due to the high-grade heat requirements of processes.

Chinese industrialists' belief in the impact of digitalisation on their sector is nonetheless very high: according to (Beier et al. 2018), 85% of the study's survey respondents whose companies had a sustainability strategy believed that digitalisation will have a major impact on this strategy, compared to only 53% for a similar survey in Germany. Yet only 14.7% are aware of the energy consumption of the machines they operate (Beier et al. 2018).

Residential and services

'Smart homes' embody the digitalisation of the residential sector: smart heating, cooling, lighting and appliances can optimize and schedule household energy consumption through sensor and actuator feedback, user preferences and learning planning algorithms. For households worldwide in 2040, it is predicted that more than 50% of electrical appliances will be network-enabled (IEA 2017a).

For households in Denmark, building energy consumption has declined by 45% per square metre since 1975, largely without digitalisation, but mainly through better insulation and renovation measures (CNREC and DEA 2015). In general, heating and cooling still have the greatest potential for energy flexibility in buildings in Denmark, particularly through flexibility in district heating (Skytte et al. 2019). As already mentioned in Chapter 8 in this report, digitalisation can play an important role in increasing district-heating efficiency and flexibility by optimising usage dynamics. One example is Leanheat, a subsidiary of Danfoss. Leanheat's software allows heating consumption at the building or district-heating level to be optimized by combining IoT sensors with AI learning processes using weather, usage pattern and ventilation data inputs (Danfoss 2019). However, such initiatives are also confronted with the behavioural aspect of energy consumption. This implies increased efforts in providing consumer information, for which smart meters can be used to obtain data on real-time energy consumption. The mandatory roll-out of smart meters in all households in Denmark by summer 2020 will improve the completeness of consumption data (Kitzing et al. 2016), useful, for example, in forecasting consumption.

While overall final energy consumption in Denmark is only expected to rise by 6% between 2017 and 2030, the service or tertiary sector is predicted to experience a 44% increase in consumption, mainly due to the addition of data centres, which are predicted to represent 15% of total electricity consumption by 2030 (DMCEU 2019). Ironically, this consequence of digitalisation can be improved using digitalisation: in 2016, Google's DeepMind reduced the energy used to cool Google's data centres (one of the primary sources of energy use for data centres) by 40% using neural networks (Evans and Gao 2016). The potential benefits of AI-optimized cooling relate not only to energy efficiency, but also to energy flexibility, as thermal processes can be shifted more easily in time.

The electricity consumption of buildings in China currently represents only around 15% of the country's overall electricity consumption (Baležentis and Štreimikiene 2019), but this is bound to change as the economy shifts from high-energy consuming industries to services (Shell and DRC, 2020). Air-conditioning use, which has increased by 13% per year since 2000, reached around 16% of peak electricity load in 2017 (IEA 2019b). While this represents a challenge to the power system, it also provides greater flexibility to the system due to the thermal inertia of cooling loads. To date, very limited data are available on demand-response schemes involving private households (Stern 2015). This can also be explained by the particularly low electricity prices for private consumers in China (IEA 2019a), which create very few incentives to introduce efficiency and flexibility schemes.

Transport

According to the IEA (IEA 2017a), the impact of digitalisation on the transport sector is the most uncertain. This is partly because it relies heavily on electrification of the car fleet as a prerequisite. However, the potentials are large: connected vehicles could coordinate charging schedules by sharing information to avoid consumption peaks, vehicle-sharing through digital platforms (apps) could increase transport efficiencies (more passengers per vehicle) and usage rates, and mobility-as-a-Service (MaaS) could simplify energy flexibility operations, as the service-providers play the natural role of aggregator for their car fleets. However, there are concerns whether this increase in convenience will reduce private car ownership or simply attract customers who previously used public transport (Noussan et al. 2020). Another uncertainty in ride-sharing schemes is the potential conflict between efficiency and flexibility with higher usage rates, as higher usage rates improve efficiency but reduce the available charging times, thereby reducing flexibility (Brown et al. 2019). Such behavioural factors should be considered along with adequate regulatory and economic incentives or disincentives.

Denmark is lagging behind other Nordic countries in respect of the electrification of passenger vehicles, partly due to policy shifts in 2016 (IEA et al.). This makes the testing of digitalisation solutions such as optimal battery-charging, vehicle-to-grid or aggregated fleet-ancillary services difficult due to the lack of data and real-life scenarios. However, a few commercial applications such as the CLEVER metering system (CLEVER, n.d.) have emerged with the help of digital-user interfaces. Although CLEVER smart meters are not yet actively engaged in charging optimization for increased flexibility, they do provide a physical infrastructure to which 'smart charging' algorithms could be added in later steps.

As mentioned in the introduction, while electrification increases the potential for digitalisation, it is not a sufficient condition. In 2018, China accounted for 45% of the world's electric passenger car fleet, and it is one of only five countries with electric car shares above 1% (IEA 2019c). However, quantitative research on smart-charging potential and economics remains insufficient in China (Jian et al. 2018).

Conversely, digitalisation has played a key role in the impressive uptake of bike-sharing services in China over the last few years through user-friendly mobile apps which reached 130 million users in 2017 (Ibold and Nedopil 2018). 62.9% of users used bike-sharing services for the 'last mile' (Ibold and Nedopil 2018), typically as a connection between public transport and their workplace, which shows the importance of digitalisation in transport interconnection and coordination.

SWOT analysis of end-use sectors' digitalisation in Denmark and China

The competitiveness of Denmark and China with regard to the digitalisation of their energy consumption is summarized in Table 2 using a Strength-Weakness-Opportunity-Threat (SWOT) analysis. This table shows that in several respects Denmark's and China's

Table 2 SWOT comparison of energy consumption sector digitalisation in Denmark and China

	Denmark	China
Strengths	• Smart meter installation for all consumers • Centralized data collection system DataHub • High sector-coupling experience with CHP and district heating • High market liberalization allows financial incentives for flexibility and efficiency	• World-leading AI R&D • High share of EV pool with standardized charging system (Shell and DRC 2020) • Some of the worldwide largest ICT-based companies by market capitalization: Tencent, Alibaba, China Mobile, Huawei (Johnston 2018)
Weaknesses	• Unclear/limited role of aggregators • Lack of AI research centres (Lindberg et al. 2019) • Lack of STEM-educated workforce (Erhvervsministeriet 2018) • Industry structured around SMEs is lagging behind in AI adoption (Lindberg et al. 2019) • Low share of EVs • -demand response so far limited to industry and other large consumers	• Lack of consumption data • Lack of smart-grid standards • Dependence on imports for key smart-grid technologies (DC, power electronics, renewable energies) (Shell and DRC 2020) • Monopoly market structure • Low incentives for consumer involvement due to very low residential electricity tariffs set by the government (Guo et al. 2017)
Opportunities	• Highly digitalised society in 'first-wave' technologies (Lindberg et al. 2019) • High acceptance of digitalisation in society (Lindberg et al. 2019) • Many collaboration opportunities between researchers and industries through living labs	• Large potential in centralized energy-intensive industries (Shell and DRC 2020) • Strong governmental push for DER (Distributed Energy Resources), which need smart grids to be integrated, and energy efficiency, through 13th (and 14th ?) FYP and Made in China 2025 initiative
Threats	• Data privacy regulation • Slow innovation rate in risk-averse energy sector; need for human-verifiable results in potentially life-threatening activities • Cyber security restrictions • Increase in socio-economic inequalities for 'digitally illiterate' populations	• Digitalisation and electrification of economy could reduce flexibility from processes with high thermal inertia • Consumption switch from centralized energy-intensive industries to services and households could make the grid considerably more complex.

characteristics complement each other well, demonstrating the potential for fruitful collaboration projects.

Existing projects and main funding directions

Denmark and China are both making large-scale investments to achieve flexibility and efficiency improvements in their energy sector, but their funding priorities and mechanisms differ based on their specific socio-economic contexts. While Denmark focuses more on consumer-centric solutions with implementation being tested out with private companies, China continues to invest more in supply-side efficiency and flexibility on a national scale, and mainly focuses on industries for demand-side projects, as mentioned in this section. However, both countries seem to rely on small-scale testbeds to test solutions before implementing them on a larger scale.

National-scale funding

Denmark

In Denmark, energy technology research projects are mainly funded by Innovationsfonden, EUDP (Energy Technology Development and Demonstration) and ELFORSK. Among the different project categories, those relevant to this chapter are 'Smart grids and systems' and 'Energy efficiency'. In general these two categories represent a significant proportion of the funds allocated to energy-technology research projects, benefiting respectively from DKK 880 and 777 million[1], which combined represent 42% of the total funds invested in currently ongoing energy-technology projects (Lindholm et al. 2019). Projects range from individual heat-pump control optimization to municipal school or industrial heat process-scheduling, but remain largely at the demonstration level, as will be shown below.

China

By contrast, China's funding focus in energy technologies is still much more directed towards the supply side, as the country is still undergoing a net increase in energy consumption. In 2016, the National Energy Administration (NEA) released its Energy Innovation Action Plan (2016-2030), identifying the key sectors for technological innovation in the energy area. Of these

1 Financial values are left in the local currency units. However, as this report is being written, values between Danish Krones and Chinese Renminbi (Yuan) are directly comparable, since based on the exchange rates of 18/06/2020, 1 DKK = 0.13 Euro and 1 RMB = 0.13 Euro.

fifteen areas, eleven focus on generation-side technologies (or the handling of their consequences, such as nuclear waste treatment), while the remaining four points are divided between energy storage, grid improvement, 'energy internet' technologies and energy efficiency technologies (CNESA 2016).

Research projects and living labs

Denmark

In Denmark, in 2018 CenterDenmark was set up as an independent research centre promoting research, development, testing and demonstration of projects focusing on digitally integrated energy systems. One of the largest of these projects is Flexible Energy Denmark (FED), which gathers universities, municipalities, utilities, grid-operators and service-providers together to work on improving consumption flexibility across all sectors through digitalisation. The Centre for IT-Intelligent Energy Systems (CITIES) is another project which focuses on methodologies and ICT solutions to harness the flexibility in the energy system (CenterDenmark, n.d.). In both projects, solutions are tested out in living labs spread throughout the country, providing large and detailed data sets fed into developed models and data analysis tools. The outputs of these projects are forecasting, planning and operations tools and methods for commercial and scientific purposes. Other projects such as the Digital Energy Lab at DTU focus simply on making consumption data available to the research community, thus providing a fertile breeding ground for data-driven solutions to be developed.

In addition, or as part of these research projects, many solutions are tested in Living Labs, where technologies are integrated into everyday life on a small scale, and their effectiveness is monitored. A few involved in demand-side flexibility and efficiency through digitalisation are GreenLabsDK, DOLL Living Lab, GreenLab Skive and, until recently, Energylab Nordhavn (Lindholm et al. 2019).

China

In China, the testing of smart grid solutions (and energy technologies relying on digitalisation in general) follows a similar approach to its ongoing electricity market liberalization: test beds are limited to a certain number of cities and are still very limited in scope.

Since 2013 four demand-side management (DSM) tests have been carried out in the cities of Suzhou, Beijing, Foshan and Tangshan (Stern 2015). Most of these projects were based on implicit demand response with time-dependent tariffs, real-time prices or peak-load pricing, and focused mainly on industries, along with a few municipal facilities, which were monitored through an online real-time DSM service platform (Stern 2015). One further step was taken in Shanghai, where China's first demand response program was launched in 2014. In this case, over 100 MW of load capacity distributed among industrial and commercial users was centrally controlled through a DR management platform, with financial compensation schemes for load interruptions or displacements (Stern 2015).

In none of these cases are individual consumers or aggregators actively involved in DSM. This can be attributed to the lack of appropriate electricity markets, which 'as they stand, [...] are unable to support full adoption of demand response markets.' (CNESA 2017). The ICT technology deployed in these pilot projects so far mainly has monitoring and informational functions, with very little personalised or data-based strategy optimization. Participation remains compensation-based, and in the case of Beijing, was covered to 93% by industrial consumers (CNESA 2017). Examples such as the Beijing pilot project which used fifteen-minute interval readings show that high-quality data are available, creating the potential for data analytics and the implementation of accurate market mechanisms (CNESA 2017). However, such innovations also require data access for third-party actors to develop and implement these tools, which is still very limited, given that most smart-meter users do not have access to their own usage data (Guo et al. 2017).

In the case of China, the digitalisation technologies that have been described throughout this report therefore have great potential but can only be used effectively if the appropriate market and policy mechanisms are put in place to support active consumer involvement. The development of data-driven demand-response schemes will therefore closely follow the advances in market unbundling and liberalization. Moreover, as mentioned above, further investments in data-gathering infrastructure (smart controls, sensors, wireless networks) and processes (data-sharing platforms, data access procedures, etc.) must be made a prerequisite for the implementation of demand-side data-driven solutions. Finally, open-access data sources would facilitate the development and implementation of policy, planning, control and forecasting tools for demand response, using China's expertise in AI and other advanced data-analysis methods.

Discussion

Ambitious goals

Denmark, as a pioneer in renewable-energy technologies, and China, as the largest market for renewable technologies (IEA 2019a), are both relying on renewables to achieve ambitious carbon-reduction goals, as shown in Chapter 3. However, the nature of VRE (Variable Renewable Energies) power requires a more flexible, interconnected, transparent and efficient energy system to fit demand to the variable supply. This considerable complexification of energy networks can only be achieved through the automation and digitalisation of processes. Both countries are therefore exploring options to integrate innovative digital technologies into the energy sector.

Complementary properties

Denmark's and China's strengths in the field of digitalisation are quite complementary, which partly explains their strong collaboration in the field of technical-science R&D described in Chapter 2. Denmark performs well on the data-collection side, with a national rollout of residential smart meters and high IoT shares per capita. Data connectivity is also high due to the high rates of 'first-wave' digitalisation, with online services, country-wide Internet access and high smartphone usage rates. The high penetration rate of renewables and the liberalized electricity market provide a good physical, financial and regulatory testbed for innovative data-driven solutions, as is shown by the multitude of 'living labs' spread throughout the country. This decentralized structure also explains the focus of many research projects on consumer-side applications such as transportation and residential loads, which are the two sectors in the country that consume the most energy (IEA, 2017b). Such decentralized projects are supported by Denmark's extensive data-collection and pooling efforts. Energinet's DataHub is an example of data availability being increased through digitalisation. However, several reports have underlined Denmark's weakness in terms of data analytics, with a lack of machine-learning or Big Data tools being taken up by industry. This is partly explained by the lack of a workforce specifically trained in this 'second wave' of digitalisation.

This is where China's strong position in artificial intelligence and its leading universities in the field offer opportunities for collaboration. China's research output in smart grids, the energy internet and machine-learning applied to the energy sector is substantial. But the lack of DERs and the monopoly-based electricity market prevent interconnected consumer-centric solutions based on these machine-learning algorithms from being implemented. Denmark's living labs could provide the appropriate conditions to test these solutions. For its part, Denmark's experience in integrating renewable energy is highly valuable for China, where the reduction in the curtailment rates of installed and future VREs is one of the main drivers for smart-grid developments. On the consumption side, residential and private consumer loads have been investigated less in China, where there is a high focus on industrial consumers. This could partly be due to the high potential in energy efficiency and improvements in flexibility in the manufacturing sector, and partly due to the easier control of larger industrial loads from a centralized grid-management perspective. China will therefore first have to make physical investments in its grid and IoT infrastructure before it can exploit its great potential for flexibility and efficiency improvements with internally developed optimization tools.

Challenges and opportunities

Although both countries will inevitably go through digitalisation of their energy sector, the economic benefits to them both will depend on the capacity of existing players in the energy industry to innovate. (Brown et al., 2019) stress that the energy-utility industry has traditionally been more conservative than other industries. Yet digitalisation is marked by the try fast/fail fast/learn fast approach embodied by GAFAM (Google, Amazon, Facebook, Apple, Microsoft). These companies have already started to get involved in the energy sector through power purchase agreements with VRE generators and could move down the chain to the retail sector, particularly if digitalisation is extensive. This would force utility companies to retreat from the retail sector and focus on their generation and storage assets (Brown et al. 2019), thus decoupling the retail sector completely from physical production.

This risk is higher for Denmark than for China, as several Chinese companies occupy world-leading roles in the digital economy, from smartphone production, 5G installation and mobile network services to large conglomerate forms of influence such as Tencent and Alibaba, which are involved in almost every aspect of the Chinese economy's digitalisation. While China still needs to catch up in some sectors in order to digitalise its energy system, the importance of its digital economy and the government's support to this sector provide it with great momentum for change. The country's main challenge remains the liberalization of its energy market to provide the necessary conditions for this change to happen.

Denmark must take advantage of its rich energy-consumption databases to push its digitalisation of energy further. The integration of consumption aggregators into energy ecosystems has been identified as a crucial step in the development of demand response (Energinet 2017). However, aggregators face major uncertainties and barriers to market entry, which could partly be solved by improving consumption forecasts, developing insights into market behaviour, increasing flexibility availability times and increasing aggregation pools. Such solutions can typically be implemented with the help of machine-learning tools. Data platforms such as EnergyDataDK, obtained from the EnergyLab Nordhavn project, provide an opportunity to develop, train and test machine-learning methods on real-life applications and assess the impact on the energy system.

Conclusion

The changes brought about by digitalisation in the energy sector are moving from 'back-office' digitalisation, where the same services as before are being offered, but with greater efficiency and convenience, to 'transformative' digitalisation, which enables new operational and business models (Brown et al. 2019).

The digitalisation of the energy sector becomes increasingly advantageous the more complex the system becomes, driven by the increase in decentralized and variable renewable energies. New digital solutions depend on the availability of data, which requires the installation of connected sensors and actuators, combined with a digital connectivity infrastructure as a backbone, such as 5G, cloud computing and common access databases. With this infrastructure in place, energy flexibility and efficiency can be improved using data analytics, with, for example, machine-learning algorithms.

Of course, the application to real-life projects will not follow a linear path from data collection to analysis, as data infrastructure will be added to support flexibility and efficiency solutions in an iterative way. This is where testbeds such as those in Denmark and China provide valuable learning experience. However, while most of these live tests report positive results, their influence on the overall energy system is negligible. Future steps will have to analyse the impact of these digital solutions on the energy system once their application becomes widespread.

The complementary properties of Denmark and China are interesting with regard to progress made in different end-use sectors. Denmark's widely decentralized energy sources and liberalized energy market allow digitally enabled prosumer and aggregator participation in decentralised markets to be tested, particularly in the residential sector. Although Denmark's digital infrastructure is also adapted to the integration of electric vehicles, the slow uptake of the EV industry is preventing large-scale implementation. China, on the other hand, has succeeded in developing a strong EV industry, but lags behind in industry efficiency, in which Denmark has many years' experience.

Finally, apart from ensuring the complementarity of their end-use sectors, Denmark and China also complement each other well in terms of expertise in digitalisation. While Denmark is at the forefront of collecting energy consumption data and making it available on platforms such as DataHub, China's acquired expertise in artificial intelligence can provide interesting insights into the data thus obtained.

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Part III
Transforming the energy system through policy and innovation

10

Catching up through green windows of opportunity

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Renewable energy and sustainable development

There is worldwide attention on environmental innovation as concepts and political agendas focus on challenges related to green growth, low-carbon technology development and sustainability transition. Central to meeting these challenges is the need to address the tensions between the environment and the current (unsustainable) economic regime. However, achieving the political goal of building green economies requires a holistic perspective that links economic policy with controlled carbon emissions and enhanced energy and resource efficiency. A reorientation of investments to greener industries and businesses relies largely on green technological innovation and the creation of new sectors, with both elements driven by policy initiatives (Schot and Steinmueller 2018; Geels et al. 2017; Borel-Saladin and Turok 2013).

Conceptually, the transition to sustainability consists of "long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption" (Markard et al. 2012: 956). Given its relative immaturity, this transition often relies on the scaling up of innovative 'niches' in green technologies (Geels 2007). Research focused on advanced economies has shown that the rolling out of green technologies typically requires protected experimental and learning spaces for the nurturing and empowering of innovation. These spaces have nurtured the development of renewable energy technologies in many countries, promoted by domestic environmental policies that seek to promote sustainable solutions for the incumbent fossil fuel-based energy system (Sachs et al. 2019; Hayashi et al. 2016).

Recently, scholars have analysed how the green transformation influences latecomer development in emerging economies. Green windows of oppOrtunity (GWOs) refer to favorable but time-bounded conditions for catching up, arising from changes in institutions, markets, or technologies, associated with the green transformation (Lema et al. 2020). They are specific specific windows of opportunity (Perez and Soete 1988; Lee and Malerba 2017) that emerge in the context of global challenges of climate change and the response from governments and companies indicate that some of these green windows of opportunity are linked directly to sustainable transition. Windows of opportunity can result from domestic policy and institutional windows, demand (Landini et al. 2020) and major shifts in technology (Dai et al. 2020). In general, open windows allow companies to catch up by pursuing one of three paths: Following the developments of other industrial actors; skipping stages in industrial evolution; or creating new technological paths for the global industry (Lema et al. 2020). In China, a unique environment for renewable energy industries has been driven by windows of opportunity related to government policy, access to technology and company responses (Urban 2020 and Zhou; Lema et al. 2020; Dai et al. 2020).

This chapter addresses the transition to sustainable energy sources and innovative solutions in China. It shows how the Chinese response to the sustainability challenge is dependent on both technological and institutional innovation. The cornerstone of the country's transition of its energy system towards green energy sources is founded on diffusion, combination and adaptation of renewable energy technologies. While diffusion is an innovative process in its own right, combination facilitates the development of green energy technology. Meanwhile, adaptation of this technology relates to the dynamic capabilities of the industry. All three elements are processes dependent on technological and institutional innovation. Indeed, combining technological and institutional innovation has been key in the transformation towards sustainable energy production and consumption in China (CNREC 2018; Lewis 2012).

In some of the technological areas related to renewable energy presented in this chapter, the catch-up of China has been supported by Sino-Danish research collaboration. This is the case for wind power (see Chapter 4, 5 and 6), solar thermal energy (see Chapter 7) and district heating (see Chapter 8).

This chapter is organized as follows. Section 2 looks at the bigger picture, outlining the environmental challenges and the policy responses initiated by central, provincial and urban governments in China. Sections 3 to 7 focus on renewable energy and offer insights from the trajectories of key renewable energy technologies. Finally, Section 8 discusses the wider global implica-

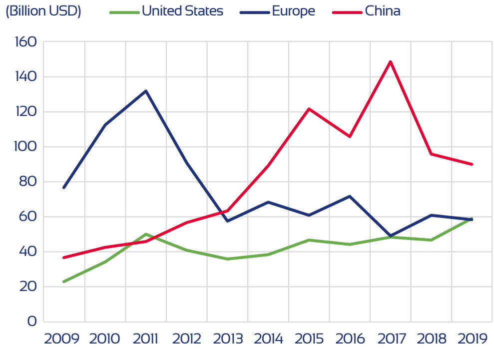

Figure 1 New renewable energy investments in the United States, Europe and China (2009 to 2019) (Source: Renewables 2020 Global Status Report)

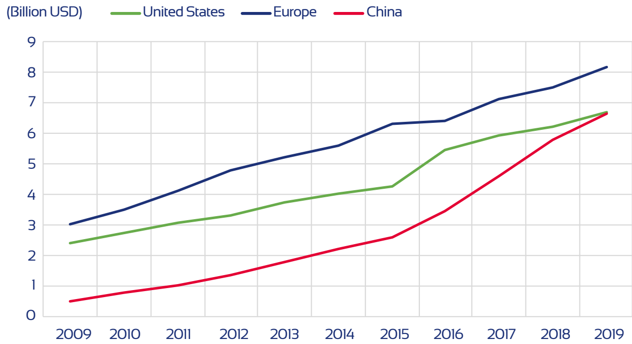

Figure 2 Renewable energy consumption in power generation (excluding hydro power) of the United States, Europe and China (2009 to 2019) (source: BP 2020)

tions of China's growing innovation capacity in green technologies, both in terms of global competition and collaboration in renewables.

The significance of China in renewables

The intense pressure to green China's economy has led to a host of ambitious initiatives. Whereas the prior section sought to shed light on the motivation driving these initiatives, this section aims to show how this is translated into renewable energy diffusion on the ground. We start by providing an overview, before moving onto specific sectors of renewable energy technology.

China has made remarkable strides in both consumption and production of renewable energies and the country aims to become a global technology leader, particularly after the United States announced its decision to withdraw from climate change initiatives. International organizations, such as the International Energy Agency (IEA), predict that China will continue to lead the world in renewable energy development (IEEFA 2017a). Among the 30 leading global science and engineering hubs in 2020, seven are in China, the centre of gravity for patents and publications within biotech, pharma, food and climate tech (ATV, 2020). Denmark is not on this list.

Influential policy initiatives have seen financial resources channelled to the industry. As shown in Figure 1, since 2013 new renewable energy investments in China have exceeded both the United States and Europe. Despite a significant drop in 2016, China still leads in global renewable energy investment, acounting for 29.84% of new investment in 2019 (REN21 2020). Meanwhile, China is also positioning itself as a global leader in overseas clean energy investment, operating alongside the country's Belt and Road Initiative (IEEFA 2017b).

China dominates global growth in renewables. Central milestones in its industrial development - stimulated by institutional windows of opportunity - were the local content requirements introduced in 2003 and the Renewable Energy Law implemented from 2006. The Renewable Energy Law set long-term targets and prioritized renewable energy in the national grid system, leading to unprecedented growth of the domestic market and industrial catch-up. In 2016, China surpassed the United States to become the largest producer of renewable power. Total renewable installed capacity reached 570 GW, with hydro power providing 332 GW, wind 149 GW, Solar PV 77 GW and bioenergy 12 GW (NEA 2017b). In 2016, the total global renewable capacity addition amounted to 165 GW of which 68 GW was installed in China (IEEFA 2017a; see also Zhou et al. 2020).

Figure 2 shows power consumption in China, the USA and Europe between 2009 and 2019 from renewable sources such as wind, geothermal, solar, biomass and waste. China has made significant progress in its use of renewable energies, rising from only 0.52 exajoules[1] in 2009 to 6.63 exajoules in 2019 (BP 2020). China's share in global consumption increased from 6.31% in 2009 to 22.88% in 2019.´

China is increasingly taking a leading role in renewables. Rapid expansion of the renewable energy sector is not only a result of sizable government financial support and extensive regulatory measures, but also relies on China's increasing innovation capacity in many renewable technologies, such as solar PV and wind. Since 2000, a substantial amount of science and technology funding in China has been allocated to the renewable energy sector (Huang et al. 2012). A growing number of clean energy research centres are being established, and more funding is being provided for the R&D of early-stage and high-risk new energy technologies. Building on the country's political agenda to support transformative and indigenous innovation, technological innovation capacity is seen as key in increasing China's global competitiveness and securing its leading role in the renewable energy technology sector. Indeed, as this capacity has been generated in only two decades, it represents a remarkable catch-up by the renewable energy industry.

1 1 exajoule = 10^{18} joules, approx. 23.9 mtoe

Table 1 China's share of patents of selected renewable energies (2005-2016, cumulative).
Source: IRENA INSPIRE based on data from EPO PATSTAT. The EPO Climate Change Mitigation Technology classification was also used.

Technology	Percentage (%)	
	2005-2010	2011-2016
Solar Thermal	32.78	40.75
Solar PV	10.95	19.19
Wind Energy	15.94	25.05
Biofuels	14.54	19.12

With strong governmental support for technological innovation, the past decade has seen the rise of innovation capacities across multiple green sectors in China. Consequently, the sector has transformed itself from a follower to a world leader in certain technologies. This is illustrated in Table 1 which shows China's share of patents for four renewable energy technologies. Before 2006, China possessed relatively weak innovation capacities within these four technology sectors, while from 2006 to 2010, patent applications significantly increased. In 2011, China became the country with most patents in solar thermal, wind energy and biofuels (Helm et al. 2014). Taking biofuel as an example, before 2001 there were less than ten biofuel inventions in China annually, but by 2011 this number had shot up to 931 (Albers et al. 2016).

Wind energy

Since 2009, China has been the largest market for wind power in the world. Over ten years, China has maintained its leadership position in new installations. Figure 3 shows the new and cumulative installed capacity of wind energy in China from 2006 to 2018. In 2018, China installed an additional capacity of 21.1 gigawatts of wind energy and maintains its position as the world's wind power leader, with a total wind capacity of 210 gigawatts (CWEA). Figure 4 illustrates the trend of electricity generation from wind energy in China, in which a significant and steady increase can be observed.

To understand the reasons behind this success in wind, it helps to examine how China was able to increase its share of the global market. Historically, the sector mainly focused on on-shore technologies and relatively small turbines. More recently, wind turbine manufacturers have developed partnerships for offshore technology and digital solutions for system integration (Dai et al., 2020). We can identify four interrelated sources of wind energy competitiveness that have created the windows of opportunity for the domestic industry to develop (Schmitz and Lema 2015; Haakonsson 2020).

The first is the strength of the home market. The Chinese government, understandably concerned with energy security, has fostered the production of renewable energy. The 2005 Renewable Energy Law was the institutional disruption that opened different windows of opportunity across new energy industries (Lema et al 2020). It translated sustainability-induced pressures into legislation that has since been implemented and incorporated into sector specific political plans across Chinese ministries. Along with other complementary policies, the Renewable Energy Law initiated the rapid development and expansion of a domestic market for wind turbines. Foreign enterprises were not directly prevented from competing in this market, but Chinese enterprises were favoured, as they received government support through various means, some visible (e.g. local content requirements

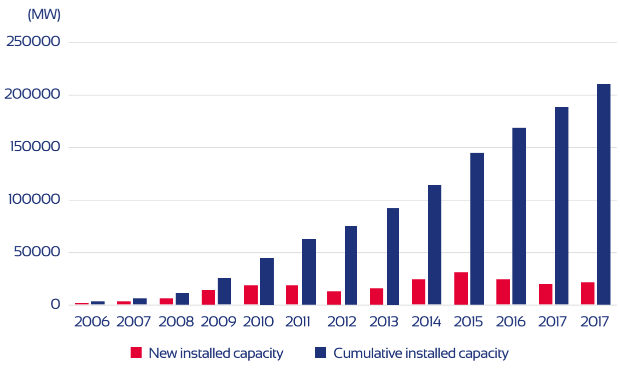

Figure 3 New and cumulative installed capacity of wind energy in China (2006-2018) (source: Chinese Wind Energy Association)

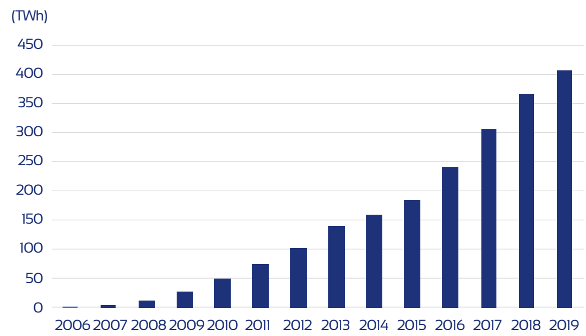

Figure 4 Electricity generation from wind energy in China (2006-2016) (source: National Energy Administration statistics, 2009-2019)

in place between 2005-2009), others less visible (e.g. the difficulty experienced by foreign enterprises in winning competitive bidding for state-funded projects). Since the Chinese market was large and growing rapidly, success in this market had a major impact on global market shares at the company level (Lema, Sagar and Zhou 2016).

The second source of Chinese competitiveness is producer power and capacity. The size and rapid growth of the domestic market enabled Chinese wind turbine manufacturers to adopt a model of industrial organisation geared towards economies of scale. A turbine is a complex product typically comprising more than 10,000 parts. While leading European firms - such as Vestas of Denmark and particularly Enercon of Germany - produced many of these parts in-house (seeking to constantly improve design and quality), their Chinese counterparts to a much greater extent relied on buying components from suppliers who also supplied other turbine makers and were thus able to achieve economies of scale and reduce costs. This was possible as many of the European component suppliers were developing spin-offs of their specialised components by designing plug-in solutions that would function as modules for highly specialised parts, such as control systems and blades. Simultaneously, international standards and certification agencies were evolving (Haakonsson et al. 2020).

The third source of competitiveness is financing power. This is as yet little explored in the literature but is of increasing importance. Crucially, Chinese firms can offer supplier credit, while this is much more difficult for Western firms. This is hugely significant for their customers since investment requirements for wind farms are high and time frames are long. Project finance is particularly important for competing in export markets. Compared with their Western counterparts, Chinese companies have deep financial pockets. Sinovel, for example, which is no longer among the leading firms, had a 6.5 billion USD line of credit from government-owned banks (Schmitz and Lema 2015), while China Exim Bank has injected capital into Goldwind and Ming Yang to support foreign expansion. This type of support facilitates an export model that has not been directly exploited by European companies – the pulling together of wind farm project finance and turbine exports, a full package solution integrated in industrial policy. Many new projects undertaken abroad by Chinese turbine firms have been implemented with tag-along finance.

The fourth pillar of competitiveness is the strength of innovation. The extent of China's development of innovation capabilities in wind energy is contested and difficult to accurately specify. Some analysts question China's ability to achieve high utilisation efficiency from their turbines (Physics World 2018) and critics point out that key innovations, such as Goldwind's permanent magnet Direct-Drive (PMDD) technology, was in fact invented in Goldwind's German subsidiary, Vensys.

Although it is clear from patent analysis that Chinese turbine firms have less advanced innovation profiles than their European and North American counterparts (Zhou et al. 2016), it is clear that the pace of learning is unprecedented, with significant advances from production to innovation capabilities within a ten-year time span (Hansen and Lema 2018; Dai et al. 2020).

Solar photovoltaics

Development in the solar-photovoltaic (Solar-PV) industry has been very different from the wind energy industry, as the domestic Chinese market only became a significant factor very recently. The Solar-PV industry started out as an export-oriented industry catering almost exclusively to the international market. Through 'learning from exporting'strategies, Chinese manufacturers have upgraded their position in the value chain in a short time-span, moving from supplying components to building complete solar panels under their own brands. Rapidly, we witnessed Chinese Solar-PV companies undercutting European and American manufacturers, leading to major job losses and prompting a trade war (Fischer 2012).

Chinese companies, backed by the government, caused a major disruption in the market and drove down costs in the solar panel industry. These dynamics were markedly different from how the wind sector evolved from the domestic market. In Solar-PV, Chinese companies managed to build up manufacturing potency by catering to the world market, while the domestic market – and policies for reducing greenhouse gas emissions domestically – played a minor role, if any. Solar-PV production was driven by exports during its 'take-off' phase. Exports from Chinese companies enabled China to replace the EU as the leader in the production of Solar-PV equipment (Fischer 2012; Lema and Lema 2016). Indeed, in contrast to the wind sector, in which Chinese manufacturers still produce predominantly for the Chinese market, the Chinese Solar-PV sector has partially emerged on the basis of policy support for solar-energy deployment schemes outside China, mainly in Europe. This sector has relied on demand-led and institutional windows of opportunity abroad.

The development of China's Solar-PV sector originated from the production of PV cells and modules. By focusing on these elements, enterprises concentrated on the steps in the Solar-PV value chain in which they enjoyed a competitive advantage due to low labour costs, economies of scale and comparatively weak environmental standards applied to production processes. The development of the Chinese Solar-PV sector and exports to key markets have also been facilitated by modularization and comparatively low transportation costs.

Although the industry has been growing since the turn of the century, securing a share of the domestic market share was not a priority until around 2010 when the industry faced restrictions in international markets due

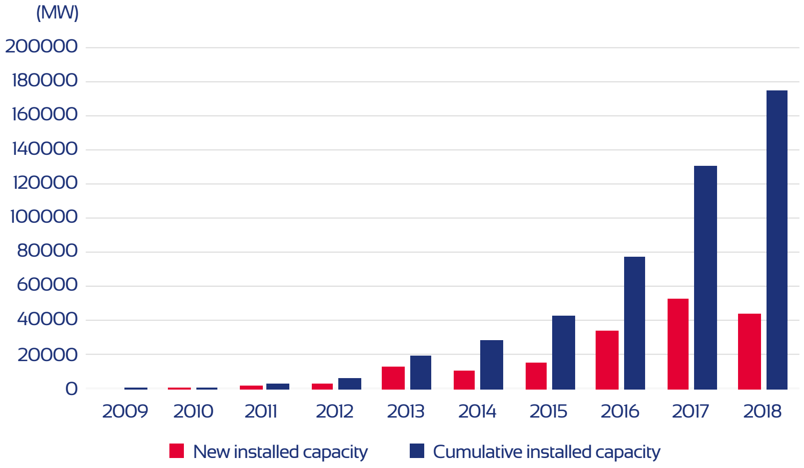

Figure 5 New and cumulative installed capacity of solar PV in China (2009-2018)
(source: European Photovoltaic Industry Association, National Energy Administration of China)

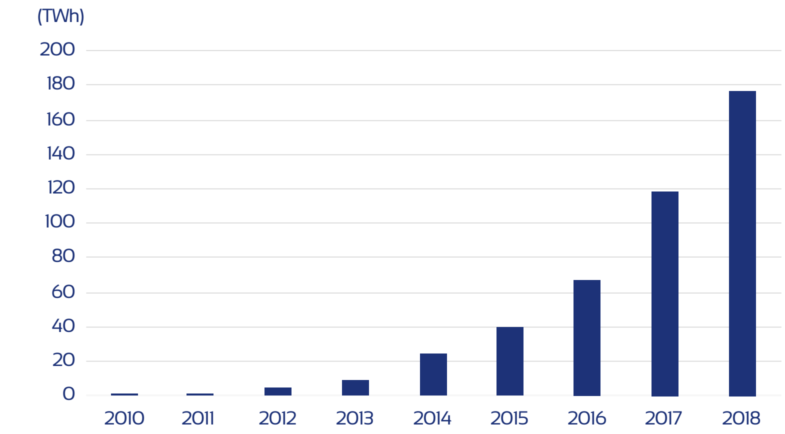

Figure 6 Electricity generation from solar PV in China (2010-2016)
(source: China Electricity Council statistics from 2011 to 2019)

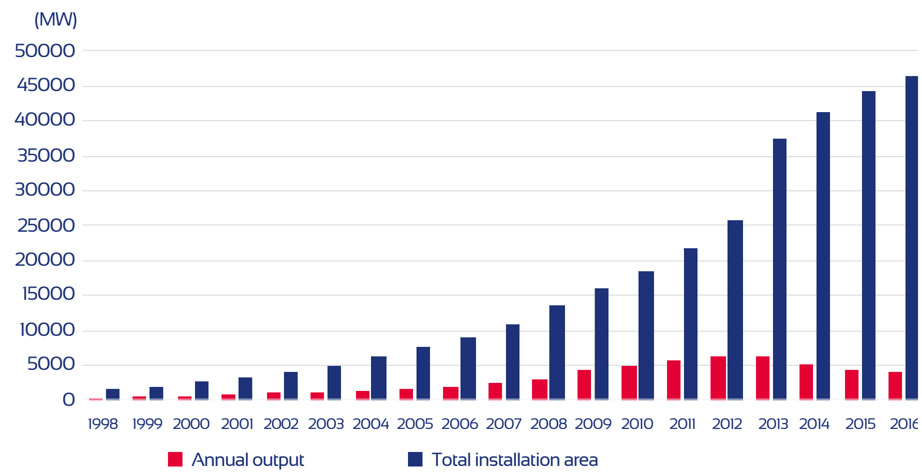

Figure 7 Annual output and total installation area of solar water heaters in China (1998 to 2016)
(source: Solar Vision)

to the financial crisis and anti-dumping measures. In China, government support for the industry was driven by local economic considerations and by the backing given by local government to other export-oriented industries (Iizuka 2015). Hence, a domestic market developed on the back of support schemes initiated to foster the use and deployment of PV energy technology in China, precisely when export-oriented manufacturers of Solar-PV cells and modules faced falling external orders, particularly in Germany. In essence, when central government started to support PV energy use within China in 2009, the Chinese PV industry was already a highly capable manufacturer and a strong competitor in global markets. Figures 5 and 6 show the increase of solar PV energy applications in China since around 2009.

Solar thermal energy

China is leading the global solar thermal market (Islam et al., 2013). At the Copenhagen Conference in 2009, Premier Wen Jiabao referred to China as leading the world in the application of solar water heaters. In 2019, China accounted for 69% of total global installed capacity, followed by the United States, Germany and Turkey (REN21, 2020). Figure 7 shows the annual output and total installation area of solar water heaters in China from 1998 to 2016.

Though the drivers behind China's dominance in the global solar thermal market are multiple, three factors stand out.

First, during the early stage of creating a pathway, key indigenous innovations made large-scale industrial production of solar water heaters possible. Together with huge domestic demand for hot water use, a niche market was successfully opened up. In 1984, Professor Zhiqiang Yin at Tsinghua University patented evacuated glass tubes, marking the start of large-scale industrial production of water-in-glass evacuated tube solar water heaters in China. Since then, the market has steadily grown.

Second, leading enterprises in solar water heaters placed technology innovation at the centre of their development strategy, dedicating substantial financial and human resources to R&D activities. In addition to R&D capacity building within enterprises, cooperation with research institutes and universities was another important mechanism for the establishment of innovation capacity. For instance, in 2007, a research centre was jointly established by Linuo Paradigma, a leading solar thermal enterprise in China, and Tsinghua University. Later in 2010, another solar research institute was formed by Linuo Paradigma, together with Shanghai Jiao Tong University. Cooperation between enterprises and universities advanced R&D in solar thermal technologies. It is estimated that Chinese enterprises have patented more than 95% of global solar water heater technologies (Chinadialogue 2014).

Third, government support played a significant role in further deployment of solar water heaters in both rural and urban China, generating demand and windows of opportunity for the industry to grow. In 2009, solar water heaters were included in the national *Home Appliances to the Countryside (HATC)* scheme, which sought to exploit the unexplored rural market to offset the impacts of the 2008 global financial crisis by providing rural residents with government-subsidized home appliances. The HATC scheme prompted the opening up of the large rural market. Simultaneously, from 2005 mandatory policies for the installation of solar water heaters in buildings have been enforced in many Chinese cities. Initially implemented in low- or multi-storey buildings, the mandatory policy was later extended to high-rise buildings, which created a new market segment for solar water heaters, the 'construction project market' (Huang et al., 2018b). Contracts are often signed directly between real estate developers and manufacturers to install solar thermal products for an entirely new-built neighbourhood. This mandatory policy has boosted market expansion in urban areas, though a number of problems emerged. For instance, in order to meet government requirements and at the same time control construction costs, many real estate developers chose to purchase low-cost, low-quality solar water heater products, resulting in poor user experiences and thus jeopardizing the development of the industry as a whole (Yu and Gibbs 2018).

Bioenergy

Bioenergy refers to energy generated from the conversion of solid, liquid and gaseous products derived from biomass. Biomass is organic matter available on a renewable basis, such as feedstock derived from animals or plants, and organic waste from municipal and industrial sources (source: IEA). In China, the use of biomass resources was officially encouraged by the 2005 Renewable Energy Law. Bioenergy has been used in a number of sectors including electricity generation, transportation and heating. While the biomass power and liquid biofuel (mainly bioethanol and biodiesel) industries have reached a significant scale, other biofuel industries, such as biomass briquettes, are still in the early stages of development.

China has a long history of biofuel innovation and utilization. As early as the 8th Five-Year period (1991-1995), some research institutes started to conduct experiments in biodiesel (Yuan et al. 2009). Later, during the 10th Five-Year period (2001-2005), biodiesel technology was included in the National High Technology R&D Program of China (863 Program), funded by the Ministry of Science and Technology (MOST). In 2006, the National Development Reform Commission (NDRC) established approximately 30 demonstration projects for bioenergy technology nationwide. In the *12th Five-Year Development Plan for Biology Technology* and the *13th Five-Year Special Plan for Biology Technology Innovation*, published by MOST, bioenergy technology was included as a key strategic area. The focus was placed on supporting and promoting R&D in key bioenergy technologies, such as non-grain fuel ethanol, biodiesel, biogas and specialized equipment for production processes of bioenergy products (Chen et al. 2016). Two national R&D centres, the National Energy R&D Centre for Liquid Biofuel and the National Energy R&D Centre for Non-food Biomass, were established in 2010 and 2011 respectively.

In October 2016, the National Energy Commission (NEA) announced the *13th Five-Year Plan for Bioenergy Development*. Specific targets were set for the development of different biofuels up to 2020 (Table 3). For instance, the total installed capacity of biomass power was expected to reach 15 GW, and the annual production of liquid biofuel 6 million tons.

To promote the application of bioenergy, the Chinese government has deployed a number of policy instruments, including subsidies and tax reductions. For instance, since 2010, new agricultural and forestry biomass power generation projects have been able to benefit from a feed-in tariff of 0.75 RMB/kWh. Similarly, subsidies have been provided for bioethanol production. In 2012, subsidies for grain ethanol and non-grain ethanol were 500 RMB/ton and 750 RMB/ton, respectively. Government support has significantly driven the diffusion of bioenergy technology and the expansion of the biofuel industry. However, a number of challenges remain, such as low levels of specialization, marketization for biomass briquette and biogas technology, and a lack of comprehensive standards, including testing and certification standards.

Emerging renewable energy sectors

In addition to conventional renewable energy sources, such as wind and solar, China is also exploring other new energy technologies.

A must-mention technology is the new energy vehicle (NEV). According to the State Council of China, NEVs include plug-in hybrid electric vehicles, battery electric vehicles and fuel cell vehicles. As early as the *8th Five-Year Plan* (1991-1995), central government started to support the development of NEVs in China. Ever since, the significance of the NEV industry has been articulated in multiple national plans and strategies. Targets have been set for each phase of technology development from basic and applied R&D to demonstration and commercialization. After nearly three decades, China has established a relatively comprehensive technological system, with more than 3000 patents and 30 energy-saving and NEV-technology innovation platforms (MOST 2012). The rise of leading NEV enterprises, such as BYD, demonstrate China's growing technology capacity. NEVs produced by BYD are now operating in more than 200 cities across 48 countries, including Japan, the USA and the UK (IEEFA 2017b).

China has also made significant progress in smart grid development. In China's *13th Five-Year Plan for Power Sector Development* (2016-2020), accelerating the development of the smart grid is specified as a main task. The smart grid is also listed as one of the major projects in *Science and Technological Innovation Report 2030*. The period between 2011 and 2015 saw the widespread construction of smart grids (H3C 2010), led by major power grid corporations. By the end of 2014, the State Grid Corporation of China (SGCC) had initiated a total of 358 smart grid projects, of which 305 were complete (State Grid 2017). In the next stage, China aims to further enhance the smart grid system, a process that will involve the development of smart power transmission and transformation technology, and the improvement of grid connection and integration technology for large-scale renewable energy resources (Han et al. 2017).

The building sector is another focal area. In the *12th Five-Year Plan for Economic and Social Development*, the introduction of green buildings was formally proposed (Zhang et al. 2018). In 2017, the *13th Five-Year Plan for Building Energy Efficiency and Green Building Development* was published, including the requirement that by 2020 50% of all new urban buildings would be certified green buildings. China has paid special attention to the improvement of innovation capacity in green building and the government has supported a number of scientific projects on green buildings. The technology behind energy saving buildings is also a major focus of the *13th Five-Year Plan on Scientific and Technological Innovation*. This development is being driven by a combination of innovations – a bricolage of technological solutions that together have the potential to develop houses that generate more energy than they use (WinDoor City). Partnerships have been formed with European and US companies that employ more advanced technologies in this area (MHURD 2017). These partnerships are re-

Table 2 Targets of bioenergy development in China by 2020

Bioenergy	2020 Target	2015 Level
Biomass power installed capacity (GW)	15	10.3
Biomass briquette annual consumption (million tons)	30	8
Bioethanol annual production (million tons)	4	2.1
Biodiesel annual production (million tons)	2	0.8

markable in the sense that many of these companies would not have collaborated in their home markets, in which competition is fierce.

Compared to other technologies, the development of concentrated solar power (CSP) is relatively new in China. CSP denotes technologies that 'use mirrors to focus and concentrate sunlight onto a receiver, from which a heat transfer fluid carries the intense thermal energy to a power block to generate electricity' (U.S. Department of Energy, 2014: p. 34). Although CSP was listed as a key technology in both the *Summary of National Mid & Long-Term Science and Technology Development Plan (2006–2020)* and the *Mid & Long-Term Development Plan for Renewable Energy*, China is still in the early stages of CSP commercialization. By the end of 2012, only six demonstration CSP stations had been constructed, three were under construction, and 14 other projects were in the preparation stage (SGERI 2013).

In September 2016, the NEA published the *Notice on the Construction of Solar Thermal Power Demonstration Projects*. This marked the beginning of large-scale demonstration CSP projects in China, under which a first round of 20 projects were selected as national demonstration projects. However, the implementation of these projects did not run smoothly, and four were eventually terminated (Economic Daily 2018). To address the situation, in May 2018, the NEA released the *Notice on Promoting the Construction of Solar Thermal Power Demonstration Projects*, extending the deadline for completion of demonstration projects from the end of 2018 to the end of 2020, and establishing, in th mean time, a clawback mechanism for subsidized electricity prices. Overall, the development of CSP is still at an early stage in China. The success of national demonstration projects will be key for the commercialization of this technology and the channelling of private financial resources.

Conclusions: Upgrading renewables in China

Over a remarkably short time span of only two decades, Chinese researchers and companies have not only been able to catch up, but also take a leading position in renewable energy industries. A number of green windows of opportunity facilitated industries to move from path-following towards market or technological take-over. This paper has shown how Chinese industries have caught up in wind turbines, Solar-PV, thermal solar power and biomass. This industrial 'catch-up' can be directly linked to green windows of opportunity, rooted in national policy, the development of technological capabilities, and the creation of domestic and international markets. These windows were both domestic and international, and in the case of the latter were linked to changes in foreign markets (e.g. solar-PV in Europe) or to opening up new networks and alliances with foreign actors, such as lead companies and universities (e.g. wind turbine industry). Chinese companies have demonstrated high levels of adaptability and creativity in devising solutions to issues of up-scaling and mass production. These solutions are based on a combination of three core elements that are opening new green windows of opportunity - access to technological solutions, domestic markets and, not least, the support of domestic policies. Chinese actors are playing an important role in further developing renewable energy.

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11

Sustainability-driven innovation in China: The case of Windoor

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Introduction

1978 marked the start of a new era in China's history - a period of new reforms and opening up with significant implications for both China and the world. In the past three decades, the country has experienced tremendous economic growth and transformation which was initially driven by manufacturing and China becoming the 'factory of the world' and the largest exporter of manufactured goods. However, China's ascendancy in global manufacturing is now coming under increased pressure. The array of drivers behind this drop-off is extensive and includes a domestic rise in labour costs, a deceleration in economic growth and an improvement in the supply base in low cost South East Asia economies and elsewhere. Furthermore, Chinese government policy incentives centred on innovation, competitiveness and strengthening of domestic brands have encouraged many Chinese companies to look at the opportunities that innovation offer. The vision of the Chinese Government is encapsulated in the words of president Xi Jinping, delivered at the 18th Meeting of the Academicians of the Chinese Academy of Sciences: 'Seeking innovation-driven development is a natural choice if we are to adopt to changing developmental conditions... We must seize the time, because wait-and-see produces nothing and imitation gets us nowhere...' (Xi 2017).

What are the distinctive strategies that Chinese companies pursue when exploring innovation in general and in sectors where energy and sustainability issues particularly loom large? What are the implications of their efforts? How well are we equipped theoretically to understand and explain these processes? These are some of the questions that this chapter tackles.

The study employs an in-depth single case study of Orient Sundar Group, a manufacturing company from Gaobeidian in China's Hebei province. The company, whose current activities are predicated on the slogan "Making building more energy efficient, making life better!", is at the centre of the Gaobeidian Passive House project. This project is one of the largest Passive House initiatives in the world. The project brings together technology and expertise from a range of best-in-class specialized suppliers from all over the world and helps to advance our understanding of how to scale energy efficient building. Our study chronicles the transition of the company from a low-cost manufacturer to an advanced Passive House system integrator and reveals new paths to innovation that are supported by the unique context of China's ecological modernization (Stubbs and Cocklin 2008; Bohnsack 2018).

Drawing on a multidisciplinary approach and borrowing perspectives from business model innovation (Chesbrough 2010; Zott et al. 2011), global innovation networks (Dicken et al. 2001; Mudambi 2008; Haakonsson and Kirkegaard 2016) and sustainable development (Hart and Milstein 1999; Bansal and Roth 2000; Kirin et al. 2013; Yang and Jiang 2019), we investigate a case of local sustainability-driven innovation. This drive to innovate emerged in response to Chinese government policies for developing sustainable buildings and features business model innovation based on network orchestration capabilities. This chapter heeds the calls for new conceptual perspectives as well as more empirical cases on business models for sustainability (e.g. Schaltegger et al. 2016).

The chapter comprises three main parts. First, the theoretical background section introduces the conceptual basis of the paper. Second, we examine empirical insights into the case study. Finally, we present an analysis and discussion, and conclude with the key lessons and implications for future research.

Study context and theoretical basis

Ecological modernization

Dealing with sustainability-related challenges is a pressing necessity worldwide. In recent decades, China has attracted wide attention due to, on the one hand, the severity of its environmental challenges and, on the other, its distinctive set of effective strategies to tackle these challenges. McKinsey Global Institute (Woetzel et al. 2019) estimated that China has been the world's largest source of carbon emissions since 2006. Indeed, in 2019 China accounted for 28 percent of annual global carbon emissions. At the same time, China has been striving to counteract potential negative environmental impacts of rapid industrialization. In 2017, the country invested around USD 127 billion or 45 percent of the global total in these efforts. That is three times more than the combined investment of the USA and Europe (Woetzel et al. 2019).

Sustainable development has been high on the agenda of the Chinese government for quite some time (World

Bank 2013; Yang and Jiang 2019). Recently it was given particular prominence in the country's 13th Five-Year plan. For example, the plan stated the objective of doubling GDP between 2011 and 2020 without doubling energy usage. Further, the long-term focus on achieving environmental targets is reflected by the formation of a new unit of central government, the Ministry of Ecology and Environment.

These ambitious sustainable development targets are dependent on continuous industrial upgrading and the emergence of an innovation ecosystem that enables independent business actors to identify common ground for cooperation and innovation that can foster the harmonious co-existence of business, societal and environmental sustainability, i.e. delivering on all dimensions of the Triple Bottom Line. The notion of the Triple Bottom Line has been around since the 1990s, and is underpinned by the idea that a company's success not only depends on its financial performance, but also on the environmental and social contributions it makes.

Stubbs and Cocklin (2008) conceptualize a sustainability business model as one where sustainability becomes the key driving force of the company and determines its decision making. In this conceptualization the dominant neoclassical model of the company is transformed so that economic performance goals become subordinate to the primary goals of environmental and social performance. The sustainability business model is informed by an ecological modernization perspective, i.e. a paradigm of decoupling economic growth from environmental degradation through environmental policies, innovation and new technologies (Stubbs and Cocklin 2008). In this regard, China offers a particularly rich context for advancing our understanding of sustainability-driven innovation beyond the usual approach to sustainable development based on philanthropy, corporate social responsibility and product innovation.

Emerging business models for sustainability in China

As the Chinese ecosystem for innovation in sustainable technologies is still not sufficiently mature to drive radical innovation, it at least in part relies on links with global innovation networks (Haakonsson and Slepniov 2018). Chinese industrial actors are developing strategies to tap into knowledge and technology globally through strategic alliances, joint ventures and acquisitions. Planning entirely new cities from scratch, actors in the construction industry can combine and test new technologies, and more importantly, they are able to combine old technologies in new ways, over time creating a new path for radical innovation. This emerging business model reflects unique industry- and system-level attributes and highlights a new value creation logic, and potentially new governance forms, that contribute to knowledge and ideas that transcend boundaries between value co-creating actors.

This pathway is facilitated by policies supporting strategic industries, which has seen Chinese companies evolve from being followers towards becoming global market leaders, and in some cases technology leaders. This evolution is not necessarily based on internal resources and capabilities. Rather, it is due to the ability to connect the dots of global capabilities in innovation and integrating them into new solutions relevant to the local context (Haakonsson and Kirkegaard 2016). This approach is at the core of the case study we examine in this chapter.

Global targets for carbon dioxide emissions, the visible increase in air pollution in Chinese cities, a still growing economy and, not least, a growing demand for energy, has put China in a position where following is no longer an option and existent technology packages do not suffice. To achieve the sustainable transition required, a gradual accumulation of capabilities and simply catching up is no longer a viable strategy. Indeed, China needs to develop radical solutions for which the technological and innovation capabilities do not yet fully exist, even in advanced economies.

In sustainable housing, incumbent companies from the Global North are highly specialised in specific technological segments, such as windows, doors, roofs, insulation and energy optimisation. An array of technologically specialized companies compete against each other in their home markets, where most houses are old and are being slowly renovated to reduce carbon dioxide emissions. These companies compete in their niches when introducing 'green' or 'sustainable' solutions to the market for green renovation, striving to convince their customers to invest in one specific technology over another. Due to this competitive model, incumbent lead-companies do not have a history of collaboration and they are not organized in networks, as is the case in other sustainable industries, such as the wind turbine industry. Sustainable housing companies are internationalized to some degree, but mostly in terms of their market, through exploitation strategies.

The Chinese context is characterized by a completely different dynamics. Chinese cities are growing and national, regional and local governments have given leading companies the mandate to develop, test and build sustainable houses and entire cities from scratch. In the planning of new suburban areas around the larger cities, the directive is clear: houses should produce the same amount or more energy than they consume. This housing type is termed 'passive houses' or 'zero-energy houses'. The overall plan is to construct entirely new suburban sustainable towns along railways around large Chinese metropoles. The ultimate goal is to achieve a comprehensive sustainable solution that, over time, has the potential to contribute to urban development beyond China. This is a unique opportunity to 'build from scratch', to develop urban solutions to sustainability issues without having to take into account existing infrastructure. Rather, sustainable designs can be introduced from the very start of the planning phase. Let us take a closer look at one of these initiatives in China and the company behind it.

Methodology and case study

Case study strategy of inquiry

As mentioned above, we conducted our research in the form of a single case study design (e.g. Eisenhard 1989; Yin 2018). The study applies this investigative method with the aim of providing in-depth insights into a contemporary phenomenon in its real-life context. By using a qualitative approach we also seek to contribute to a growing body of qualitative research coming out of China. Interest in the case study research method in East Asian contexts has been on the rise recently, but is still lagging behind quantitative approaches (Tsou 2012; Shi and Au-Yeung 2015).

The authors have followed the company since August 2017 and the case study has been developed by drawing on multiple sources including interviews, archival records, site visits and meeting notes.

Case study

How it all began

Orient Sundar Group - the company behind Windoor - is a Chinese private construction company founded in 1988 by Shouqiang Ni in Gaobeidian, Hebei Province. Mr. Ni's venture started as a carpentry company with initial capital of RMB 4800 and eight employees. At the start, the business focused on manufacturing windows for the local market. A decade after its establishment, the company had 310 employees and was registered under the name Orient Sundar Window & Door Co., Ltd.

By the 1990s, China was rapidly establishing itself as the largest manufacturer and consumer of architectural doors and windows. There are more than 30,000 players in the Chinese doors and windows construction industry. The industry is highly fragmented and none of the players, including Windoor, can boast occupying a noticeable market share of the domestic market. The company's founding family quickly realized that in order to survive and stand out in a very competitive industry, innovation and bringing new value to the market were key. Since its own R&D capacity could only partially support the strategic ambitions that the management set out to achieve, the decision was made to focus on external sources of knowledge and learning through international collaborations.

Rapid internationalization

2004 marks the next important chapter in the company's history. Orient Sundar formed its first joint venture with a privately owned German company, Moser GmbH. In 2005, Orient Sundar established another joint venture with Raico Technik GmbH, and in 2009 initiated international collaboration with M. Meesenburg KG from Germany. These close international partnerships signified the start of the internationalization and transformation journey that the company has been following ever since.

International collaborations were an excellent means to upgrade its status and capabilities. In 2012, the Ministry of Science and Technology (MOST) granted Orient Sundar the title of 'National Scientific and Technological Cooperation Base'. In terms of physical space, the company significantly expanded. In 2013, the production facilities site and its surrounding areas were awarded the status of a 'National Construction and Green Technology Innovative International Zone'. The company fully embraced this opportunity, investing heavily in its own Window and Door technology R&D centre as well as opening an on-site Experimental and Testing division. In 2016, the company established collaboration with the Passive House Institute in Germany and further expanded its international network to include new strategic partnerships in Austria and Italy.

Production and R&D, however, were not the only focal points that the company was eager to advance, as activities directed towards the market and customer experience received increasing attention. For example, to enhance customer experience and brand awareness, the company opened the China Windows and Doors Museum on its premises. Furthermore, it also built China's first Passive House demonstration building to promote the concept of zero-energy building and highlight its possibilities for users and customers as well as collaboration opportunities for domestic and international partners. Over the years, the company managed to develop into a competent integrator and partner for foreign companies seeking access to the dynamic and challenging construction industry in China.

From internationalization to innovation

Since the early 2000s, the company has been developing its international cooperation with European companies. The joint ventures mentioned above provided a solid foundation for its internationalization strategy and the continuous expansion of its global network.

In 2016, during the Eighth German-Chinese Forum for Economic and Technological Cooperation, the Orient Sundar Window Group signed the Sino-German Enterprises cooperation agreement with the European Building Hardware Association. The company also participated in activities conducted under agreements between the German Rosenheim Research Centre and China Academy of Building Research.

In 2012, on its premises in Gaobeidian, the company started organizing international trade fairs for windows and doors related industries, attracting more than 600,000 attendees representing business partners, government officials, academic institutions from China and more than 20 foreign countries.

All these efforts earned the Orient Sundar Group a reputation as a dynamic international partner capable not only of attracting investment for its windows manufacturing operation, but also of bringing together best-in-class actors from the global construction industry. Over the years, the company's premises in Gaobeidian have significantly expanded into Windoor City, a permanent exhibition which hosts 112 foreign companies and more than 300 domestic companies, creating a physical space to collaborate and gain access to Chinese market knowledge and product development platforms.

Organising international sustainability-driven innovation
Only a small fraction of China's buildings are built in an energy efficient way, which presented a significant opportunity for the Orient Sundar Group and its partners clustered in the Windoor City Innovation Park. The company divided the park into three bases (Energy-saving Windows Base, Ultra-low Energy Consumption Building Base, China-EU Building Energy Saving Base) and four centres (Window and Accessories Exhibition Centre, Quality Test Centre, Warehouse and Logistics Centre and National Green Intelligent Building Science-Technology Experience Centre). The park also hosts ten professional exhibition halls displaying the latest technology for energy-saving windows and doors systems, energy-saving materials, building heat preservation systems and energy-saving ventilation equipment.

In 2013, the company constructed its first Passive House demonstration building on its premises. In 2015, apartments were constructed using multiple technologies from the Passive House project. In 2016, the company was recognized as both a 'Chinese passive ultra-low power green building industry demonstration base' and a "Hebei province building energy-saving new technology and new product demonstration base'.

In 2018, the company's in-house R&D department had 170 employees and by 2019 this number had risen to 220, accounting for approximately ten percent of its total workforce Over the years, the company has registered more than 300 patents and received multiple certificates, including the German Passive House Research Institute (PHI) certification, the Energy Star certification and the Chinese Energy-saving identity authentication.

Changing role of manufacturing
Manufacturing capabilities were crucially important for the company from its inception. In recent years, the Orient Sundar Group reorganized its manufacturing base with clear divisions between different levels of demand groups. The high volume lower market end windows were produced at the largest production site in Windoor city, while the Sino-German joint venture, Shunda Moser Doors and Windows, manufactures for the mid- and high-end markets. Both sites closely collaborate with the company's R&D operations and have access to its international partners' base at Windoor City. In 2017, new lines were added with a focus on energy-efficiency, and niche and complementary products, such as ventilation systems, glazing, heat insulation and sun shading systems.

Discussion and contribution

Windoor represents an example of sustainability-driven innovation built on bringing together technology from a range of locations and specialized suppliers into a larger system, the Passive House. Several lessons can be distilled from Windoor's journey.

China's unique conditions and urgency for environmental modernisation created conditions conducive for new innovation and business models. The Gaobeidian project alone comprises 330,000 square meters of certified Passive House buildings, including high rises, multifamily buildings, villas, offices and retail space. The scale is impressive and rivals anything outside China. Perhaps it is less domestic technological prowess, and more speed, scale and ability to collaborate that led to rapid change in the industrial structure, and in the longer run is likely to create new areas of dynamic comparative advantage.

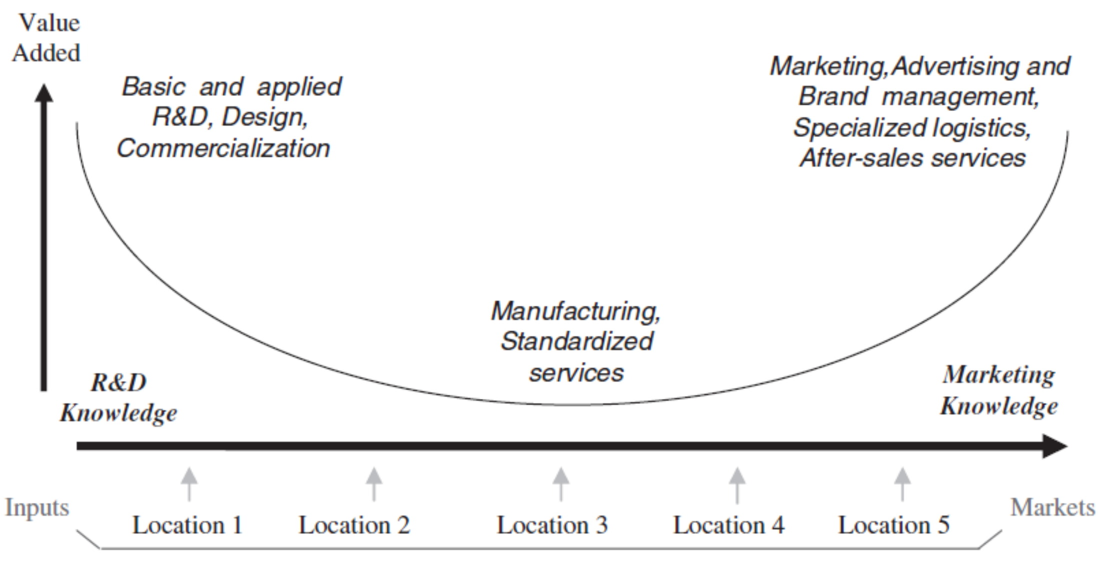

Figure 1 Value chain disaggregation (Mudambi 2008)

The company actively prepared to respond to a window of opportunity provided by government policies and national standards for climate-robust green buildings and urban design to avoid locking in existing carbon footprints. This case not only presented commercial opportunities for the companies involved but might also provide valuable lessons for policy makers in other provinces of China and abroad.

The case also highlights the importance of emerging market actors in sustainability-oriented business models and the new roles they play. Understanding the development of emerging market actors has traditionally drawn on international business approaches that seek to understand topics such as the position of a company in global value chains and production networks, how to increase exports by linking up with global buyers and how to attract foreign direct investment to specific industrial sectors. Hence, we can assess the progress of companies and industries by examining to what extent they have upgraded to increase their participation in the value chain.

Innovation management literature related to emerging markets mainly analyses the dynamic and innovation capabilities of companies, while exploring how the institutional framework for innovation has played a role in the catching up process of domestic corporations. The literature argues that these innovation capabilities and frameworks have resulted from from transfers of technology and linking up with global buyers and suppliers. Figure 1, based on Mudambi (2008), illustrates how one study assessed the value chain of a specific product or company.

Windoor's development trajectory reveals a more nuanced journey in the company's rise from the bottom of the value curve. While Windoors R&D output remained relatively limited compared to its European partners, the company still managed to establish itself as the leading player in the chain. The case demonstrates China's rise, and current industrial and leadership changes, as more value chains are becoming integrated the further downstream companies move, and there is a realization that radical innovation and new value creation may involve integration of different products and technologies not previously combined.

In order to become an industry leader, a company may not necessarily be dependent on cutting-edge technological expertise. Rather, leadership can also come about from taking on a coordinating role – building a new business model linking different types of (fragmented) technology into a systems solution. In other words, establishing global innovation networks that can be driven not only by companies from the developed North, but by emerging orchestrators from the developing South.

Technology transfer has become just one of several sources of innovation capability, with companies integrating diverse technologies into new products. Moreover, innovation may result from integrating technologies across value chains. In this case, focused on the complex production of sustainable buildings, the passive house, technologies taken from a range of value chains are braided into an assembly line of specialised technologies. As the literature states, moving downstream in a value chain increases the value added. Emerging market actors can take a lead through moving further down the wider value chain, beyond the confines of their own, specific value chain. In the case of Windoor, the company reached a point where products from different value chains complement each other and together provide system solutions, radical innovation and new approaches to environmental modernisation.

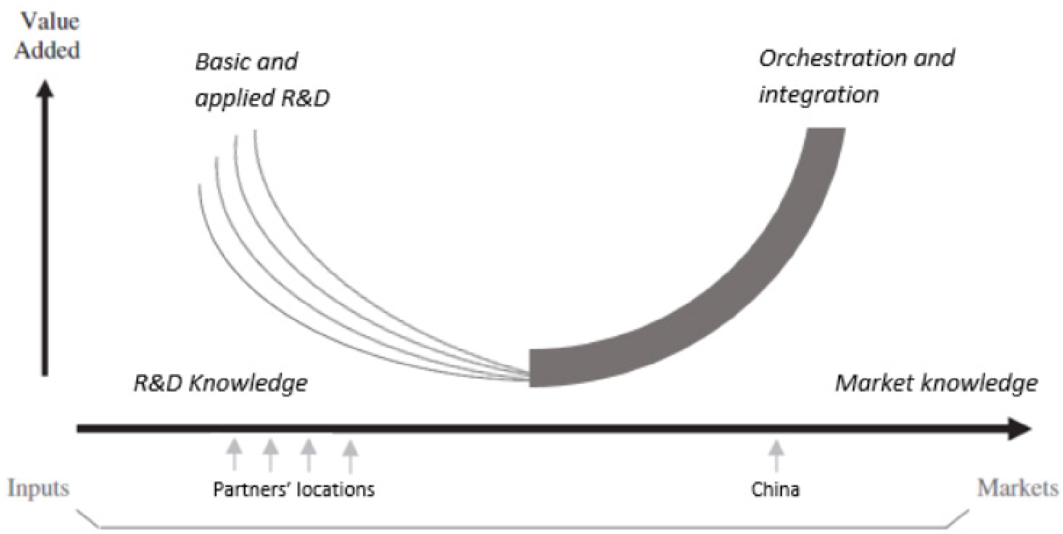

Figure 2 Windoor vlue chain disaggregation (author's creation)

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12 Energy transitions in urban China: Drivers, developments and challenges

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Introduction

The past few decades have witnessed unprecedented industrialization and urbanization in China. By the end of 2019, more than 60% of the population were living in urban areas, as compared to only 17.92% in 1978 (National Bureau of Statistics 2020). However, rapid urbanization is giving rise to mounting pressures related to energy security, resource scarcity and environmental degradation in contemporary China. As a response, the Chinese government has highlighted green development as one of its main national development strategies, supported in more detail by a series of sectoral and technological guidelines for the transition and upgrading towards a green and low-carbon economy.

It is widely agreed that China is making substantial inroads in sustainable energy production and consumption (Zhou et al. 2020). Cities are major contributors to climate change, consuming over two-thirds of the world's energy, and producing more than 70% of all carbon dioxide emissions (C40 Cities Climate Leadership Group 2020). The energy-related CO2 emissions and energy consumption of China's cities accounts for 58% (Stockholm Environment Institute 2020) and 75% respectively of the country's totals (Cheng et al. 2019). Cities are therefore at the frontier of forging low-carbon transitions, and they possess tremendous potential as 'innovation hubs' for sustainability (Castán Broto and Bulkeley 2013).

As one of the largest countries in the world in terms of its population and geographical size, and increasingly its GDP, China provides a large experimental field for energy transitions. In Chinese cities, numerous projects have proliferated in different sectors experimenting with new solutions for the deep decarbonization of the existing energy production, distribution and consumption system. Focusing on energy transitions in urban China, this chapter presents a brief overview of the rationales for a transition, transition practices and the challenges faced by Chinese cities in the transition.

Drivers of energy decarbonization in China

In recent years, Chinese cities have made substantial achievements in the decarbonizing urban systems. This 'green' turn is a response to several challenges that have become increasingly evident and acute after three decades of rapid economic growth and urbanization.

The cultivation of an 'ecological civilization'

Since its economic reform of the late 1970s, China's top national priority has been economic development and poverty alleviation, environmental issues being considered less important. Due to long-term and large-scale applications of less environmentally friendly technologies in industry, environmental problems are becoming so severe that they can no longer be ignored. For instance, the well-known heavy smog in Beijing and many other mega-cities represents serious air pollution. In 2016, the air quality of 78.4% of China's cities were not up to standard (State Council 2016). Therefore, recent years have seen environmental protection assume increasing importance in public and political narratives in China. In March 2018, for the first time, 'ecological civilization' was written into the Chinese Constitution. Notably, controlling air and water pollution, promoting energy transformation and developing renewable energy are key tasks assigned to this national strategy. For instance, in China's 13th Five-Year Plan it was specified that emissions of sulphur dioxide (SO2) and nitrogen oxides (NOx) must be reduced by 15 percent by 2020, and PM2.5 by 25 percent (State Council 2016).

Building green innovation capacity

China has also made remarkable achievements in the development of several new and renewable energy sectors, such as wind power and solar energy. China views these sectors as promising arenas in which it can take the lead not only in respect of manufacturing capacity but, more importantly, innovation capability as well. This ambition can be seen in policy initiatives launched by the central government in recent years. Starting with the period of the 12th Five-Year Plan (2011-2015), a special focus has been placed on the building of national innovation capacities. In 2013, the *12th Five-Year National Independent Innovation Capacity Building Plan* was published, which is China's first national plan and guiding document for the systematic enhancement of independent innovation capacity. The main objectives were to build and deepen innovation capabilities related to infrastructure, by building new partnerships, cultivating innovative talent and improving the overall innovation environment. This strategic policy emphasis on innovative capacity-building is further strengthened in the *13th Five-Year Plan for National Scientific and Technological Innovation*. Specifically, for green innovation in the energy sector, two important documents were promulgated: the *Energy Technology Revolution Innovation Action Plan (2016–2030)* released in March 2016, and the *13th Five-Year Plan for Energy Technology Innovation* released later, in December 2016. These two documents put forward specific aims, measures and initiatives for advancing technological innovation in the energy sector. The main goal is to establish a comprehensive energy technological innovation system and to make breakthroughs in key technological areas such as renewable energy, smart grids and energy storage.

Energy security in changing geopolitical circumstances
Rapid and large-scale urbanization and industrialization have placed significant pressures on domestic energy supplies. Domestic energy resources are far from sufficient to meet the country's huge energy demand, and energy supplies are highly dependent on foreign imports. In 2017, China's dependence on foreign oil and natural gas reached 67.4% and 39% respectively (CNPC 2017). This poses serious questions for the stability of the country's energy supply and energy security. This situation, combined with changing geopolitical circumstances and the 'energy concern', is increasingly being taken into account in the geopolitical and geoeconomic calculations surrounding China's international relations. Energy-based international relations have become a core part of Beijing's national interest and its foreign-policy priority. For example, China's investment in renewable energy is increasing under the Belt and Road Initiative (*PV Magazine* 2019); China's energy ties with Russia are developing more strongly in terms of both the newly opened Russian gas pipeline to China and their joint ventures in energy exploration in the Arctic region; one of the aims of China's proactive defence policy in the South China Sea is to secure access to the region's energy reserves; and Chinese trade and investment in energy are becoming a pivotal part of China's economic relations with Africa and Latin America (*The Economist* 2016).

Energy transition initiatives in urban China

The Chinese government has assigned high importance to the mission to achieve the energy transition, in which respect cities are considered a critical arena. Accomplishing an urban energy transition involves non-trivial processes of infrastructural reconfiguration through which new governance arrangements (such as urban laboratories and urban experimentation) are fitted to the actual landscape of intervention (Castán Broto 2015). It covers a wide range of sectors in the urban system such as manufacturing, electricity, transportation and construction. This section reviews three national-level initiatives in China that aim to promote low-carbon development in cities.

The Low-carbon City Initiative
In 2010, the National Development and Reform Commission (NDRC) initiated the *Low-Carbon Province and City pilot program*. Cities participating in this program are required to develop long-term plans for low-carbon development, design specific measures to reduce carbon emissions, and establish carbon emissions accounting and management systems (Lo 2014). Till now, three batches of designation have been announced successively in 2010, 2012 and 2017, covering a total of 71 cities (Table 1).

The Low-carbon City Initiative has a long history, having been a consistent and continuous low-carbon effort in China for the past decade. It takes many years to pilot new ideas and experiments, so while the latest batch of cities were designated in 2017, we still await the outcomes. According to some analysts, however, the implementation of this low-carbon city initiative has proved to play a positive role in reducing carbon emissions in the pilot cities (Cheng et al. 2019). Assessing the achievement of carbon-intensity targets during the 12th five-year period showed that the decreases in carbon intensities in the pilot cities were significantly higher than the national average. In 2019, a 'Report on the Evaluation of Chinese Green and Low-carbon Cities' was released, which comprehensively evaluated the green and low-carbon performances of 169 Chinese cities, including the 71 low-carbon pilot cities. The report showed that in general, low-carbon pilot cities had a higher performance than non-pilot cities. Moreover, the performances of the first batch of pilot cities was significantly

Table 1 National low-carbon pilot cities in China. Source: Cheng et al. (2019).

Group	Number of cities	Names of cities
First batch (2010)	8	Baoding, Chongqing, Guiyang, Hangzhou, Nanchang, Shenzhen, Tianjin, and Xiamen
Second batch (2012)	27	Beijing, Chizhou, Ganzhou, Guangyuan, Guangzhou, Guilin, Huai'an, Hulun Buir, Jilin, Jinchang, Jincheng, Jingdezhen, Kunming, Ningbo, Nanping, Qingdao, Qinhuangdao, Shanghai, Shijiazhuang, Suzhou, Urumqi, Wenzhou, Wuhan, Yan'an, Zhenjiang, and Zunyi
Third batch (2017)	36	Ankang, Changsha, Changzhou, Chaoyang, Chengdu, Chenzhou, Dalian, Fuzhou, Hefei, Huaibei, Huangshan, Ji'an, Jiaxing, Jinan, Jinhua, Lanzhou, Lasa, Liuzhou, Lu'an, Nanjing, Pu'er, Quzhou, Sanming, Sanya, Shenyang, Weifang, Wuhai, Wuzhong, Xiangtan, Xining, Xuancheng, Yantai, Yinchuan, Yuxi, Zhuzhou, and Zhongshan

better than those of later batches, indicating that the effectiveness of the policy takes longer to manifest itself. The report verified the positive outcomes generated by the Low-carbon City Initiative and recommended further deepening and scaling-up of the pilot scheme in China.

The 'Ten Cities, One Thousand Vehicles' program
As early as the period of the 8th five-year plan (1991-1995), the Chinese central government started developing new energy vehicles (NEV)s. On the one hand, the NEV industry was regarded as a strategic industry with emerging advanced technologies that can ensure energy security, promote industrial restructuring and create new job opportunities; on the other hand (echoing global environmental challenges), considered as a substitute for ICE vehicles, NEVs were expected to mitigate the impacts of climate change and decarbonize the energy system. The implementation of an NEV industry has been highlighted in many national plans and strategies. A key national initiative for implementing NEV in cities is the '*Ten Cities, One Thousand Vehicles*' program. This initiative was launched in 2009 with the aim of introducing a thousand NEVs in ten cities every year for the following three years. The demonstration focused on public sectors such as government fleets and public transport. A total of 25 cities were selected as pilot cities for the initiative (Table 2). Under this initiative, the purchase of NEVs and the construction of charging infrastructure were subsidized by both the central government and local governments. The program planned to promote 53,697 vehicles in the 25 pilot cities. By the end of 2012, only half of the intended target had been achieved (Han et al. 2014). Seen from the perspective of implementation, the initiative can hardly be labelled a success. Nevertheless, the '*Ten Cities, One Thousand Vehicles*' program acted as a prelude to large-scale subsidized programs for NEVs launched at later stages. Since 2015, according to data released by the China Association of Automobile Manufacturers, the market for NEVs in China has expanded significantly, their market share having increased from 1.34% in 2015 to 4.68% in 2019.

The Energy Transition in Zhangjiakou City

Zhangjiakou, a city of 4.4 million people in Hebei Province, sets an example to other cities in China and worldwide of how to take advantage of renewables and transform an energy system. Zhangjiakou possesses abundant renewable energy resources and has the potential to lead the world in low-carbon development. Over the past decade, the city has stepped up its efforts to deploy renewable energy systems. In 2017, renewables accounted for 73% of the city's total installed capacity and for around 45% of its total electricity output. However, there is still the potential for 30 gigawatts (GW) of solar photovoltaic (PV) and 40 GW of wind generation. The State Council of China has designated Zhangjiakou to become the country's first-ever National Renewable Energy Demonstration Zone. By 2050, the city could increase its use of renewables from less than half to nearly three quarters of its electricity mix. This is what an ambitious energy transformation plan for 2050 sets out to do. The municipal authorities in Zhangjiakou City, in co-operation with the China National Renewable Energy Centre (CNREC) and the International Renewable Energy Agency (IRENA), have adopted this ambitious thirty-year road map to phase out coal-fired power generation and scale up solar and wind power instead. The city is a pioneer in developing a comprehensive plan which includes changing technologies in use (e.g. from blast furnaces to electric arc furnaces in its steel production), smart manufacturing, hydrogen production and smart-grid technologies.

Source: IRENA 2019.

Mandatory implementation of building-integrated solar water-heating systems
The building sector is a main contributor to energy consumption and carbon emissions in urban areas. Statistics show that the energy consumption of buildings accounts for 20.7% of the total end energy consumption in China (Cai et al. 2009). The Chinese government therefore regards the building sector as a critical arena for decarbonizing the energy system and introducing renewable energy to buildings constitutes a crucial part of urban energy transitions (He et al. 2015). In light of this, governments at multiple governance levels (i.e. both national and provincial

Table 2 Pilot cities in the 'Ten Cities, One Thousand Vehicles' initiative

Group	Number of cities	Names of cities
First batch	13	Beijing, Changchun, Changsha, Chongqing, Dalian, Hangzhou, Hefei, Jinan, Kunming, Nanchang, Shanghai, Shenzhen, Wuhan
Second batch	7	Guangzhou, Haikou, Suzhou, Tangshan, Tianjin, Xiamen, Zhengzhou
Third batch	5	Chengdu, Huhhot, Nantong, Shenyang, Xiangfan

level) have introduced a series of policy instruments to implement building-integrated renewable-energy systems in urban areas, the application of solar energy having become a central focus.

In 2006, an '*Implementation Opinion on the Application of Renewable Energy in Buildings*' was published, stressing the necessity of scaling up renewable energy use in the building sector. Building-integrated solar water-heating technology was specified as one of the key areas for implementation. In 2007, the '*Notice on Accelerating the Application of Solar Thermal Systems*' required provincial and urban governments to accelerate the application of building-integrated solar water-heating systems in buildings. According to incomplete statistics, by 2016, mandatory regulations had been enacted in twelve provinces and 25 cities in China requiring the integration of solar water-heating systems in newly built public and residential buildings under twelve floors. This mandatory policy has boosted market expansion in urban areas. However, it did not work well in all cases. In many cities, it was reported that installed solar systems were being left unused. In Shenzhen, for instance, of the 250 solar projects that were constructed, at least 56 had been left unused, representing a total investment of more than 90 million RMB.

The International Dimension of Energy Transitions in Urban China

International participation in developments in renewable energy in China in connection with the urban energy transition have increased. China benefits greatly from international cooperation in its efforts to achieve low-carbon urban development, such as accessing finance and technologies, developing human resources and enhancing the policy framework. According to one empirical study (Cheshmehzangi et al. 2018) of Shenzhen's International Low Carbon City (ILCC), a collaborative project on developing low-carbon city-planning initiatives in China in cooperation with multiple international partners (Germany, Italy, France, Australia and the US), Shenzhen, one of China's largest and richest high-tech cities, shows that the ILCC initiative benefits significantly from international cooperation. The study concludes that the positive roles of international collaborators in the success of Shenzhen's ILCC indicates 'a new and unique model of low carbon- and eco-development that includes multiple international actors, multiple involvements and multiple roles in the low-carbon transitions, which will provide a feasible technological integration and vibrant model for other cases' (Cheshmehzangi et al. 2018: 74).

China and Denmark are also cooperating closely in China's ambition to increase its share of non-fossil fuels in primary energy consumption to about 20%. According to the Danish Energy Agency Partnership Program (2017-2020), Denmark will support China's energy transition to higher shares of renewable energy with experience and technical expertise based on the experience of the transition in the Danish energy system. Currently the two countries are engaged in many on-going projects in China in the areas of green development, renewable energy, district heating, quality offshore wind energy, etc. (Danish Energy Agency 2017). Chapter 8 in this report provides lessons from Sino-Danish collaboration on clean district heating and its integration into urban energy systems.

The challenges of the energy transition faced by Chinese cities

Of all the energy-related challenges that result from China's rapid industrialization, especially its unprecedented urbanization in recent decades, such as energy security, energy affordability and environmental sustainability, energy security is obviously the top concern. According to a research study based on a large amount of data (Li et al. 2019), urbanization can play a positive role in promoting energy efficiency that increases energy security. This is due to improvements in energy efficiency that are easier to achieve in urban areas than in rural areas, such as the economies of scale involved in district heating (Li et al. 2019). Despite some achievements, Chinese energy efficiency still needs to do more to reach the average level of European and OECD countries (Voïta 2018), which may go hand in hand with urbanization.

China has taken an aggressive approach to advancing energy transitions in urban areas. These initiatives, however, have had mixed outcomes. For instance, although the low-carbon initiative has now expanded to more cities in China, the scheme is often criticized for lacking an integrated vision of how to transform cities into low-carbon cities and the irrational designs of policies at the local level, which often lead to distortions in resource allocations and a loss of efficiency (Shinn 2008, Cheng et al. 2019). Similar problems have emerged in the mandatory implementation of building-integrated solar water-heating systems, mainly due to a mismatch between local contexts (e.g. building orientation and residents' energy use habits) and the targeted technology (Huang et al. 2018).

This reminds us that urban energy transitions are multifaceted processes that involve multiple urban actors and that interact closely with local economic and socio-spatial contexts. On the one hand, urban development priorities might define local governments' decisions regarding transition pathways; on the other hand, the decarbonization of the urban energy system would inevitably reconfigure urban infrastructure and reshape residents' social practices (Huang and Broto 2018). It is thus imperative for political visions to suit local contexts if they are to induce real changes. The dominance of a top-down approach in China's energy transition might result in a lack of flexibility, openness and inclusiveness, which are imperative if urban experimentation is to thrive. Although top-down policy measures can be effective and efficient in practice, they might also carry the greater risk and higher costs of transition failures. This institutional limitation is a major challenge faced by decision-makers in promoting urban energy transitions.

Conclusion

Cities have become important 'actors' in global efforts to transform economies from fossil fuels to green energy. This is true both globally and in China. In this chapter we have reviewed the drivers, developments and challenges of energy transitions in urban China.

In terms of the drivers of energy decarbonization in urban China, we have highlighted energy security as one motivation and the underlying aim of constructing an 'ecological civilization' as another. However, we also emphasised the proactive attention being paid to green innovation capacity-building. Chinese cities are increasingly seeking to create and utilize green windows of opportunity to enhance the city-level innovative capacity of enterprises and relevant organizations (see Lema et al. 2020; also Chapter 10 in this report).

We have also described the ambition and increasing traction of city initiatives across the People's Republic, including low-carbon pilot cities and focused initiatives regarding sustainability-oriented technologies such as new energy vehicles and solar water heaters. As we showed, there is an important international dimension to these initiatives in which China both benefits from and contributes to collaboration revolving around the creation of new directions in urban planning and development.

Finally, we have stressed that, while China has already made great strides in achieving urban energy transitions, there are still significant challenges to be overcome. We have also emphasised how bottom-up approaches may help to avoid city-level failures of the transition (Huang and Broto 2018) and facilitate the creation of just sustainabilities in urban communities (Agyeman and Evans 2003).

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13 China's pragmatic experimentalism towards sustainable transition: Wind power and Sino-Danish collaboration

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The boom, bust and re-emergence of China's wind power market

China has in recent years astonished the world with its rapid emergence as a new global 'green leader'. No other sector has demonstrated China's capability of rapid industrial upgrading and catch-up in the green sector better than wind power (Mathews and Tan 2014; Lewis 2013; Korsnes 2014; Kirkegaard 2015; Delman 2020).

This transformation has been enabled through adaptive changes in Chinese policies and pragmatic governance of Sino-foreign relations. China started experimenting with wind resource mapping in the 1980s. However, the country's early adventures in wind power were marked by a series of fragmented and scattered experiments, plagued by indecisiveness and ambivalence as to whether to make a coordinated and focused effort to nurture Chinese manufacturing capabilities in this area. It was only relatively late that China decided to enter the wind power market, but it proved to be a grand entry. With the implementation of the Renewable Energy Law (2005/2006), China's wind turbine industry immediately started to grow at an unprecedented pace. China rapidly became the world's largest wind power market in terms of installed capacity: China's installed wind power capacity was only 0.8 Gigawatts (GW) in 2004 but reached around 45 GW by 2010, making China the world leader in total installed capacity, a position it still holds with 234 GW installed by the end of 2019 (Andrews-Speed 2012; GWEC 2020; Lewis 2007, 2013; Klagge et al. 2012; Kirkegaard 2019; Lema and Ruby 2007; Zhao et al. 2012). At the same time, Chinese wind turbine manufacturers emerged in large numbers, including Goldwind, Sinovel and Envision (Lewis 2013; Kirkegaard 2015). Meanwhile, the rapid boom in installed capacity caused a host of problems, particularly in terms of wind turbine quality, high rates of wind power curtailment and a significant number of wind turbines that were not connected to the grid. However, through agile government intervention in energy and science, technology and innovation. China's wind turbine industry was rapidly steered from a trajectory of upscaling and poor quality towards one of upgrading and an agile 'turn to quality' (Kirkegaard 2019).

Today, China is greening its electrical power sector at an unprecedented rate through world record investments in renewable energy, and particularly in wind power. As a recent sign of its serious intent, China's proclaimed 'Energy Revolution' (néngyuán gémìng, 能源革命) strategy lays out the clear ambition to strengthen grid capacity, expand distributed generation and improve the integration of renewable energy into the electrical power system (Chung and Xu 2016; Communist Party of China Central Committee and the State Council 2015; Dupuy 2016; Liu and Kong 2016; NEA 2015; Kirkegaard 2019).

Based on interviews with industry and policy actors, and document analysis, in China and Denmark - particularly the analysis of Kirkegaard (2015, 2017, 2019) - around China's wind power sector, we show how China's entry onto the global wind power stage has followed a cycle of boom, bust and re-emergence. China's emergence has been framed and mobilised through a distinct 'Chinese fragmented authoritarianism' (Kirkegaard 2019; Kirkegaard and Caliskan 2018) and a particular mode of Chinese innovation that allows for experimental trial-and-error at the meso-level, while simultaneously allowing unforeseen technological issues in wind turbines to quickly materialize. This has at times necessitated prompt government action, and has facilitated accelerated learning and innovation (Kirkegaard 2019). This empirical context sets the scene to explain the implications for Sino-Foreign, or in this case, Sino-Danish, collaborations.

Understanding the rollercoaster journey of Chinese wind power through pragmatic experimentalism

The early rise of China's wind turbine industry and wind power market materialized through a substantial reliance on Foreign Direct Investments (FDI) that ensured technology transfer. China's 'trade-market-access-for-technology' strategy has helped to attract foreign companies to China, e.g. assisted by the local content requirements, which pushed foreign companies to set up manufacturing in China in order to be able to access the Chinese market. This was already seen in the *Ride the Wind Programme* (1996) and later in Chinese state concessions for wind power development in the early 2000s, with the evaluation criteria requiring a certain amount of the equipment to be produced in China (Lewis 2013). The industry-oriented policy of local content requirement was abolished in 2009, but by this point almost all Western wind turbine companies had already set up manufacturing in China. In particular, the Ride the Wind Programme (1996) promoted the formation of Sino-foreign joint ventures, and over time, foreign companies were attracted by the vast size of China's market. Major foreign wind turbine manufacturers operating in China include the Danish company, Vestas, as well as Suzlon, Gamesa and, more recently, General Electric and Siemens (Lewis 2013; REN21 2009a in García 2013; Gosens and Lu 2013; Zhao et al. 2012b). Component suppliers and emerging suppliers of Knowledge-Intensive Business Services (KIBS) (Schmitz and Strambach 2009; Haakonsson et al. 2020) have provided expertise across multiple areas, such as software tools for certification and design. Many of these foreign suppliers are Danish (e.g. Mita Teknik, DEIF) and have contributed substantially to the rapid catch up of Chinese wind turbine manufacturers and component suppliers. This input has been supplemented by other financial instruments that helped to build up an industrial base and attract both FDI and the localization of foreign companies in China by means of economic incentives, such as lower import tariffs for renewable energy equipment, investment and R&D subsidies, tax breaks and favourable pricing.

Learning from technology and knowledge transfer, the Chinese wind turbine industry was soon in a position to undercut Western manufacturers. Around 2010, however, the industry began to witness 'frequent reports of quality problems and technical difficulties of domestically manufactured wind turbines', such as fractures of blades and shafts, generator fires, gearbox ruptures and brake failures (Lian and Wu 2011 in Klagge et al. 2012:376). Consequently, Chinese wind turbine manufacturers struggled to secure international certification. While China had been able to produce wind turbines at a much lower price than the least expensive models offered by their foreign competitors (Nahm and Steinfeld 2014), the central government's 'preference of industry creation, and hence quantity before quality' (Korsnes 2014:192) had created massive quality problems in terms of underperformance, both of wind power generation and average annual wind utilisation. This poor performance was reflected in component failures, low capacity, an inability to connect to the grid and even major accidents (Cherni and Kentish 2007; García 2013; Gosens and Lu 2014; Kirkegaard 2015, 2019; Klagge et al. 2012; Lewis and Wiser 2007). It became clear that many wind farms in China were not generating the energy that was expected from wind farms of their installed capacity. Soon the industry was suffering from an overheated wind power sector, with abundant overcapacity, increased competitive tension between Chinese and foreign industry actors, as well as difficulties in achieving international certification and fulfilling export ambitions. While the reasons behind these problems were manifold, they were primarily related to fragmented planning and coordination between local and central spheres, policies that emphasized price over quality, targets for installed capacity (Gigawatt/GW) instead of generated electricity (Gigawatt/hour), a lack of certification requirements (Kirkegaard 2015, 2019) and a focus on applied science over basic research in STI policies (Cao 2004).

What is more interesting than the 'bust', however, is the impressive capability of the Chinese government, by means of agile policy adjustments, to steer the sector through the crisis towards a 'recovery' that has reinstalled China as a leading wind power nation, as well as one that increasingly competes and collaborates at an equal level with foreign counterparts that have benefitted from a much longer experience of working with wind turbine technology and integration. To resolve the quality crisis, the wind power sector was steered by government interventions to fine-tune turbine technology (though higher focus on quality and basic research) and to upgrade core technologies and develop indigenous designs, addressing risk and uncertainty through enhanced emphasis on certification and standardisation.

This push for 'Scientific Development'[1] to 'recover' the sector has been nurtured, since 2012, by central government policies, plans, standards, targets and regulations, together instigating an imminent potential 'turn to quality' (Kirkegaard 2015, 2019). This was particularly corroborated in the *12th Five-Year Plan for the Scientific and Technological Development of Wind Power* (2012, State Council and Ministry of Science & Technology (MOST)). The strengthened focus on quality was reiterated in China's 13th Five-Year-Plan (2016–2020) and the imminent Energy Revolution (2015), where focus shifted from capacity expansion towards quality and efficiency. Central to this transformation was the Medium- to Long-Term Plan for Scientific & Technological Development (MLP 2006-2020), which introduced the notion of 'indigenous innovation', and has been restated and further elaborated through a number of policies, plans and strategies. Other major interventions included the introduction of stricter standards and certification requirements (Lewis 2013; Kirkegaard 2019; Ernst 2013); targets for generated electricity (García 2013; Lema and Ruby 2007:3888; Liu and Kokko 2010:5524; Bloomberg 2012; Korsnes 2014); enhanced

1 The influential notion of the term 'scientific development(alism)' (kēxué fāzhǎn guān, 科学发展) was first introduced in 2003 by President Hu Jintao (Christensen 2013:85-86), and later enshrined in Chinese Communist Party (CCP) doctrines, which marked its legitimisation (Christensen 2013:86). To achieve scientific development, the development of indigenous innovation capabilities (Zìzhǔ chuàngxīn, 自主创新) in science, research and within core technologies has been construed as indispensable (Andrews-Speed 2012; Christensen 2013; Fan 2006:709–717; Lewis 2013; Mathews and Tan 2015; Meidan, Andrews-Speed and Xin 2009).

incentives for turbine quality (e.g. through energy pricing and financial support schemes) (Kirkegaard and Caliskan 2018; García 2013; Zhao et al. 2012:228); centralisation of control and planning (Korsnes 2014; Lewis 2013:74; Kirkegaard 2019); and upgrading of core technologies, such as control system software and simulation tools for design and certification (Kirkegaard 2019; Haakonsson et al. 2020). Indigenous innovation in core technologies has also been critical for success in instigating a 'turn to quality', and for getting the industry back on track (12th Five-Year Plan for the Scientific and Technological Development of Wind Power, MOST 2012).

Through the process of 'boom-bust-and-recovery' and in line with China's fragmented authoritarianism (Lieberthal 2004), the Chinese government has oscillated between what can be termed 'decentralised fragmentation' and 'centralised authority', in order to achieve development targets (Lieberthal 2004; Andrews-Speed 2012). Decentralisation of authority (or 'decentralised fragmentation'), in terms of approvals of new wind farms, alongside a certain ambiguity in terms of implementation of targets, has been beneficial for the period of accelerated growth in the wind industry, while centralisation of authority, in 2011, was aimed at slowing growth in a period of severe overcapacity (Andrews-Speed 2012; Korsnes 2014:196; Breznitz and Murphree 2011; Kirkegaard 2015, 2019). What seems even more intriguing is how, somewhat paradoxically, it appears that the quality issues that had surfaced in China's wind turbine industry were pragmatically allowed by the state. This transpired through permitting local provinces and wind farm developers to develop and experiment with wind turbine technology innovation and wind farm development without central control. This, in turn, produced a number of technological quality issues to quickly emerge, while the central government did not intervene until the very last minute. Even though the Chinese state may not have intended to induce the number of quality issues that surfaced, it also did nothing to prevent them from happening until the brink of collapse. This strategy is linked to learning through 'failure' rather than cracking down on it from the outset (Kirkegaard 2019). It also relates to a particular mode of 'innovation' at the meso-scale (Kirkegaard 2019), enabled through a process of "pragmatic, interactional, adaptive, solution-oriented collaborative efforts [between Chinese and foreign actors] (Delman 2020:1) that has enabled the adaptive governance and readjustment of Chinese energy and STI policies."

Discussion: The role of Sino-foreign (Sino-Danish) collaboration in wind power – and future prospects

From the context set out, we discuss prospects for Sino-foreign collaborations in wind power.

The impressive – but bumpy – development of China's wind power market cannot be understood without an appreciation of the contribution of technology and knowledge transfer. Sino-foreign collaborations have played an indispensable part in China's upgrading of its wind turbine industry. In particular, Denmark has played a critical role: Sino-Danish collaborations in the area have a long history, starting with the National Laboratory for Renewable Energy, Risø (now under the Technical University of Denmark, the Department of Wind Energy), with scientists being sent to China to assist in the mapping of wind resources – a collaboration that has continued for many years.

Diplomatic-Scientific relations between China and Denmark have also been strong in the wind power field. Under the Sino-Danish Renewable Energy Development Programme (RED) (2009-2013) - jointly developed by the Chinese and Danish governments and comprising two components (the development of the China National Renewable Energy Centre (CNREC) in Beijing and joint Sino-Danish renewable energy projects) - projects in wind turbine testing and certification, among others, have taken place. In 2012, the Chinese energy authorities officially opened CNREC in close collaboration with the Danish Energy Agency, working together on developing strategic energy policies, state-of-the-art methodologies and tools to encourage the use of renewable energy in the Chinese energy system, leveraging Denmark's long experience with and approach to energy system planning. Over time, CNREC has become a major resource for Chinese policy makers seeking expert advice and analysis on renewable energy (ens.dk; Kirkegaard 2019). Overall, China's wind power sector has developed through a close collaboration between Chinese authorities and energy policy actors with international partners (Delman 2020; Lewis 2013; Kirkegaard 2015), as Denmark represents "a best-practice learning case, and through a strategic government-to-government partnership, [Denmark] has gradually become one of China's preferred strategic policy interlocutors on energy politics" (Delman 2020:1).

In addition to diplomatic collaborations, the rapid upgrading of Chinese wind turbine manufacturers - such as Goldwind, Envision and Mingyang, which have emerged as new 'Dragon Multinationals' (Mathews 2016) - cannot be understood without considering them in the light of China's integration into global innovation networks. These Chinese companies are increasingly able to manufacture competitive, state-of-the-art wind turbine systems, and claim to be integrated into global learning and innovation networks as they experiment with control system software, indigenous (homegrown) designs and software applications (interviews; Lewis 2007, 2013:166; Mathews 2016; Silva and Klagge 2013). As Mathews and Tan (2015) have argued, China may well be able to make renewable energy and low-carbon technologies 'synonymous with its own industrial revolution', simultaneously 'breaking the "carbon lock-in" that has delayed the energy revolution in other developed countries' (Mathews and Tan 2015:148), while moving beyond its current stage as the 'world's factory'. China's rapid upgrading has also seen the strategic use of KIBS, which have adopted a business model focused on licensing out technologies (Haakonsson et al. 2020), a trend that reached China along with the more generic organizational decomposition of innovation processes (ODIP) (Strambach 2008).

For many years, however, both Sino-Danish and Sino-Foreign supply chain relations were marked by a one-way technology transfer, backed by China's renowned and notorious strategy of 'trade market access for technology strategy'. Built on the idea of tapping into foreign technologies and innovation (Klagge et al. 2012) through a linking-leverage-learning strategy (Mathews 2002), Chinese companies and research institutes integrated themselves into global value chains and increasingly into global learning (Lewis 2013) and innovation networks (Kirkegaard 2015). Taking advantage of the impetus behind industrial policy, the focus in the wind industry had been on speed and upscaling, rather than on quality and basic research (Gosens and Lu 2013; Kirkegaard 2015). However, pragmatically allowing the 'quality crisis' to emerge laid bare some of the inherent weaknesses of technology and knowledge transfer. Indeed, since 2004, 'indigenous innovation' has become institutionalised as part of China's doctrine of 'Scientific Development' (Kirkegaard 2015). The quality crisis however shed light on the limitations of such capabilities, and in turn emphasized both the need to develop indigenous innovation capabilities in core technologies, and the need for basic research. This then adversely impacted on Sino-Foreign and Sino-Danish supply chain relations, resulting in power struggles over access to key technologies, such as software algorithms (Kirkegaard 2015). The 'turn to quality' around 2012/13 that had been envisaged through STI policies is a trend that continues to today, where an enhanced focus on indigenous and open innovation, alongside open cooperation, is being reiterated. This was clearly reflected in Xi Jinping's speech to scientists in September 2020 where he argued that China must continue to accelerate technological innovation and promote quality, for example by strengthening basic research (Xinhua, 11th Sep. 2020). Interestingly, a major strategy is to ensure that [China] "*strengthens international scientific and technological cooperation. China needs to be more proactive in integrating into the global innovation network and enhance our technological innovation capabilities through open cooperation. The more we face the blockade and suppression, the less China can engage in self-enclosure and self-isolation. Instead, China must implement a more open, inclusive, mutually beneficial and shared international science and technology cooperation strategy".* On the one hand, China is persisting in seeking to improve its capacity for independent (indigenous) innovation, laying the foundation for sound international collaboration, while, on the other hand, it recognizes "*it is necessary to promote international scientific and technological exchanges and cooperation with more open thinking and measures. Under the current situation, it is necessary to pragmatically promote international scientific and technological cooperation*". This is exactly what produced the somewhat antagonistic forces of simultaneous competition and collaboration during the 'turn to quality'.

However, we note the reiteration of the need for more open innovation and basic research in core technologies to move China towards 'the quality, originality, and contribution of research' (NDRC 2016, p.1) as a signal that Sino-Foreign and Sino-Danish collaboration may enjoy a bright(er) future. Indeed, the 'turn to quality' has made Sino-Danish supply chain relations more stable as Danish and Chinese companies increasingly compete on a more level playing field, rather than competing against each other based on divergent criteria (quantity/price versus quality/innovation). When the criteria are moving together towards a focus on quality, it may be easier to collaborate in a Chinese market that is rapidly evolving. The joint focus on quality, such as ensuring optimal and stable energy output, and optimal system integration, should stimulate new joint focus areas and may bode well for enhanced collaboration. At the same time, as Chinese actors have rapidly upgraded, Western companies may increasingly be able to learn from Chinese companies, for example, in terms of implementing effective 'cost-out' strategies and accelerating innovation processes (but without jeopardizing quality); that is, there may be new and exciting opportunities for Western turbine manufacturers, component suppliers and research institutes to learn from Chinese partners in striking a new balance between the Chinese trial-and-error approach and price-focused strategy of accelerated learning, versus the Western more risk-adverse and certification-focused strategy (Kirkegaard 2019). Indeed, we could claim that Denmark and 'the West' have something to learn from China in terms of industry development; ensuring rapid upgrading through pragmatic experimentalism. This would have to take place within an entirely different political context, and the social, environmental and economic costs should be evaluated against the potential for rapid development and learning.

In summary, while the current global political backdrop is marked by increasingly strained China-US and China-EU ties, and an external environment characterised by rising protectionism from both the US and China, at the same time as we are facing a global economic downturn, China has sent a clear signal with President Xi Jinping's speech on Chinese Science & Technology Policy in September 2020. We believe, given the strong background in diplomatic, research and business collaboration between China and Denmark, and taking China's upgrading into account, there is hope for enhanced collaboration in the future, while being mindful of issues of IPRs and other trade-related and political-economic concerns.

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14 Financing the global low-carbon energy transition: China's dual role domestically and overseas

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Context

Climate change mitigation and adaptation have become key priorities of governments around the globe. Yet, there is growing criticism that current climate pledges are not sufficient to curb carbon emissions and stop severe global warming. According to a recent report by leading climate scientists, 75% of climate pledges are "partially or totally insufficient to contribute to reducing GHG emissions by 50% by 2030" (Watson et al. 2019, p. 4). It has been acknowledged that accelerating the transition to a green economy will not only require a significant increase in public and private investments but also new instruments to mobilize a wide range of funding sources (Semieniuk and Mazzucato 2018; Buchner et al. 2019). As the energy sector[1] accounts for two-thirds of global greenhouse gas emissions, decarbonizing it is critical to efforts to combat climate change (IEA 2019; IRENA 2017).

Since 2006, China has developed into the world's largest energy investor (IEEFA 2017; Semieniuk and Mazzucato 2019).[2] Taking into account all investments in renewable capacity, China committed $758 billion between 2010 and 2019[3], followed by the United States ($356 billion) and Japan ($202 billion) (FS-UNEP 2019).[4] Indeed, in 2017, China accounted for almost half of the world's renewable energy investments (Murdock et al. 2019) and the country has dominated solar and wind investments for more than a decade (Kong and Gallagher 2020). However, China's domestic versus overseas energy investments speak different languages: while renewables account for almost half of energy investments domestically (IEA 2020), the share of renewables in financing overseas is only 10% (Cabré et al. 2018)[5] In fact, 80% of China's policy banks' energy investments outside the country are in fossil fuels (Gallagher and Qi 2018). Despite global financial institutions increasingly moving away from coal, China has recently committed $36 billion funding to 102 gigawatts[6] (GW) of coal-fired power plants outside the country and continues to be the largest international funder of coal plants overseas. This scenario jeopardizes the country's position as the world's clean energy leader (IEEFA 2019a; Climate Transparency 2019).

This is a cause for major concern since China is rapidly expanding its influence in global infrastructure investments as part of the Belt and Road Initiative (BRI), but to date has displayed little ambition to align its overseas investments with the demands of the Paris Agreement (Voituriez 2019; Zhou et al. 2018). In fact, countries have to surpass their current nationally determined contributions (NDC) to limit global warming to well below 2°C. (UNDP et al. 2020; Levin and Fransen 2015). Moreover, as the largest emitter of greenhouse gases in the world, accounting for 26.8% of the global total (Watson et al. 2019), the action China takes on the climate can serve as a model for other emerging economies. This chapter provides an overview of China's dual role in financing the energy transition. We show that China's financial system is geared towards state-owned enterprises (SOE), a tendency which favours fossil fuel to the detriment of renewable energy projects overseas.

The chapter is organised as follows. Section 2 provides a general overview of China's energy investments. Section 3 focuses on the financing barriers Chinese energy companies face when moving overseas, exposing a bias in the Chinese financial system towards SOE fossil fuel companies. Section 4 discusses policy options for the five main actors that can facilitate financing to renewable energy projects overseas. Section 5 concludes the chapter with a summary of key findings and their relevance to policy making.

1 Encompassing energy production and use.
2 When low-carbon energy became a priority in China's 11th Five-Year plan and the renewable energy law came into effect.
3 First half of 2019; excluding large hydro (FS-UNEP, 2019).
4 The sum of all European investments is $698 billion (FS-UNEP 2019).
5 40% of China's overseas investment was reportedly spent on coal projects (Watts 2019).
6 This represents 26% of all coal plants under development outside China (399 GW), according to IEEFA (2019b).

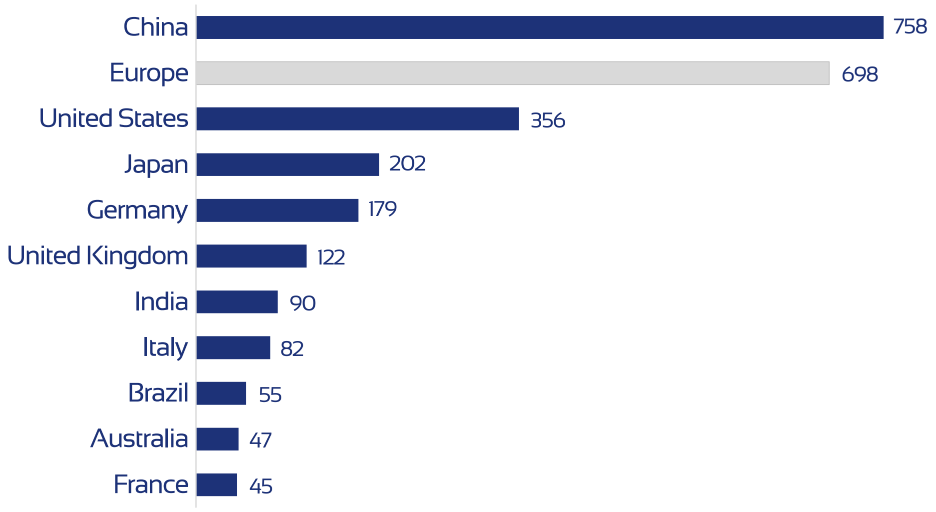

Figure 1 Renewable energy investment capacity between 2010 and 2019 (in USD bn) (Source: FS-UNEP 2019). Note: Data for 2019 covers the first half of the year.

Overview of China's energy investments

We start by providing a brief overview of China's domestic and overseas energy investments and pointing out the most important trends over the last years. The term 'energy investments' refers to all available financing instruments including both public and private debt, and equity and concessional loans. In terms of the split between these sources, total financing in China is made up of approximately 85% loans, 10% bonds and 5% listed equity[7] As the largest financial institutions in China, about 90% of the loan proportion comes from China's 21 main banks, namely three policy banks, six large state-owned commercial banks and 12 nationwide incorporated banks. Their total outstanding loans to renewable energy amounts to RMB 1,610 tn, which represents 20% (RMB 8.296 tn) of all loans for green investments (CBRC 2017). Overall, green loans make up only 10% of all loans by the 21 banks. This data is available in China due to a green credit statistics system established in 2014 by the China Banking Regulatory Commission (CBRC), which requires mandatory disclosure from China's 21 largest banks. As banks in western markets do not share a similar disclosure requirement and green definitions differ across geographies, there are no comparable international statistics.

China leading renewable energy investments

A central milestone for China's explosive growth in green investments was the country's Renewable Energy Law that came into force in 2006. Until today, it can be considered China's most influential policy instrument, introduced to stimulate unprecedented growth in what was a marginal renewable energy sector. Besides setting mid and long-term targets and prioritizing renewables over other power sources in the grid system, the law created a Renewable Energy Development Fund, financed through a surcharge on end-consumers electricity bills (Wang et al. 2016).

Figure 1 shows China's dominance in renewable energy investment capacity between 2010 and 2019, amounting to $758 billion, exceeding the combined sum of European countries. Cumulatively since 2010, China is the largest renewable energy investor despite showing a downward trend from $145.9 billion in 2017 to $91.2 billion in 2018, when the phase-out of solar subsidies deterred investment (Murdock et al. 2019). Indeed, Table 1 shows that China accounted for the largest proportion of renewable energy investments on a global scale. Chinese investments in the power sector as a whole easily outstrip its investments in fossil fuels.

When taking a closer look at how these renewable energy investments translate into deployment of renewables, we can see that China's domestic market accounts for almost one-third of total renewable power capacity in the world, with wind (36%), solar PV (35%) and hydro (28%) at the forefront of China's renewable energy leadership (Table 1). This shows that China's renewable energy investments have been mainly channeled towards the domestic market in the aftermath of the 2006 Renewable Energy Law, while international deployment remains comparatively low. This is especially true for the wind power industry, where Chinese lead firms in 2017 installed less than 3% of their manufactured turbines outside China (FTI 2018).

In order to evaluate recent trends, we looked at newly added capacity in 2019. While no comprehensive investment statistics are available, Figure 2 shows that renewables made up 58.7% of newly added capacity in 2019, and 52% when excluding hydro power (CEC 2020). As renewables have higher upfront investment costs, they

7 Concessional loans are part of the 85% figure as it is not possible to calculate them separately. This subdivision is not disclosed by policy and commercial banks and Chinese definitions are flexible; determining concessionality is difficult with limited information on loan portfolios.

Table 1 Cumulative renewable energy capacity in GW per source as of 2018, world and China. Source: Author's compilation based on Murdock et al. 2019.

Technology	World (GW)	China (GW)	Share (%)
Wind	591	210	36
Solar PV	505	176	35
Hydro	1,132	322	28
Bioenergy	130	17,8	14
Concentrated solar power (CSP)	5.5	0.2	4
Geothermal	13.3	0.02	0.1
Total	**2,378**	**727**	**30.5**

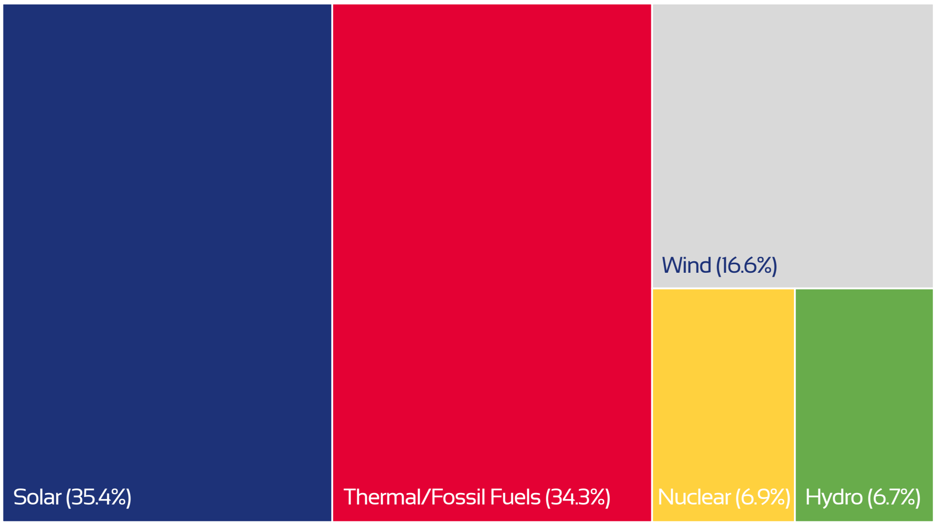

Figure 2 2019 added power generation capacity by energy source.
(Source: China Electricity Council 2020)

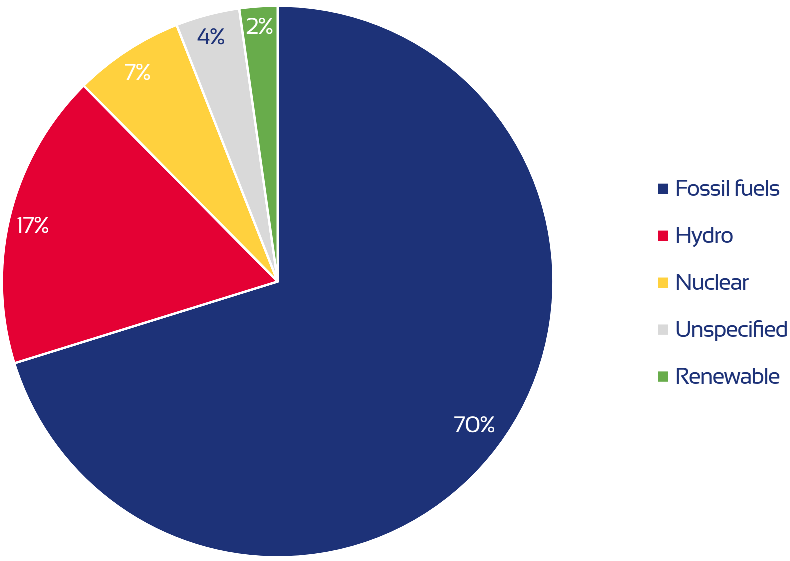

Figure 3 China's global energy finance per source
(Source: Gallagher and Kevin 2019). Note: Data covers CBD and CHEXIM.

Table 2 2019 investment proportions in fossil and renewable energy across sectors and geographies. Approximations based on various sources such as Zhou et al. 2018; IEA 2020; CEC 2020; Dong and Ye 2018. (Source: Authors' summary). Note: "Hydro" refers to mid- and large hydropower generation.

Geography	Energy sector as a whole (Power generation plus energy supply and electricity networks)			Power generation		
	USD	Fossil / renewable split	Fossil / renewable split (w/o hydro)	USD	Fossil / renewable split	Fossil / renewable split (w/o hydro)
Global	1,480 bn	72 / 28 %	75 / 25 %	480 bn	25 / 75 %	36 / 64 %
Chinese domestic	370 bn	56 / 44 %	64 / 36 %	122 bn	15 / 85 %	23 / 77 %
Chinese overseas (BRI countries)	60.3 bn	87 / 13 %	91.4 / 8.6 %	21.3 bn	66 / 34 %	78 / 22 %

represented about 80% of Chinese domestic power investment in 2019, even when disregarding mid- and large hydro (Dong and Ye 2018; IEA 2020). Though this is impressive, it is notable that according to IEA's (2020) calculation of energy investment required to meet the Sustainable Development Goals (SDGs), China cannot add any fossil fuel capacity at all unless it is equipped with carbon capture and storage technologies.

China's global energy finance dominated by fossil fuels

Compared with the scale of domestic investments, Chinese investment in renewable energies overseas is still at a very early stage. As shown in Figure 3, China's global energy finance from policy banks is dominated by fossil fuels (70%) whereas renewables (excluding hydro) only represent 2% (Gallagher and Kevin, 2019).

Figure 4 shows Chinese energy investments from commercial banks, the Silk Road Fund, SOEs and private companies, for which the trend of mainly financing fossil fuels persists. Indeed, it can clearly be seen that renewables only make up the largest proportion of financing from the private sector. Further, when excluding hydro power, renewable investments from syndicated loans and exclusive policy bank loans are reduced by two-thirds. Though private owned enterprises only make up 8% of Chinese overseas energy investments, they account for 65% of renewable power generation minus hydro.[8]

Table 2 compares domestic and overseas energy investment data to the global context. While China performs better than the global average domestically, it performs significantly worse than the global average overseas. It is notable that Chinese domestic power generation investment is 85% in renewables, while the overseas percentage is only 34%. If we further exclude medium- and large hydro power, which are neither considered green nor renewable by most current definitions, these figures are 77% and 22%, widening the gap even further.

Barriers to China's renewable energy investments overseas

General barriers to renewable energy project finance

There are general and country-specific financing barriers to renewable energy projects. On a generic level, renewable energy projects are capital intensive and require higher upfront investments. However, they benefit from considerably lower and stable operating costs compared to conventional energy. Oil, gas and coal are subject to substantial and unpredictable price fluctuations as

8 Based on figures provided by Zhou et al. 2018.

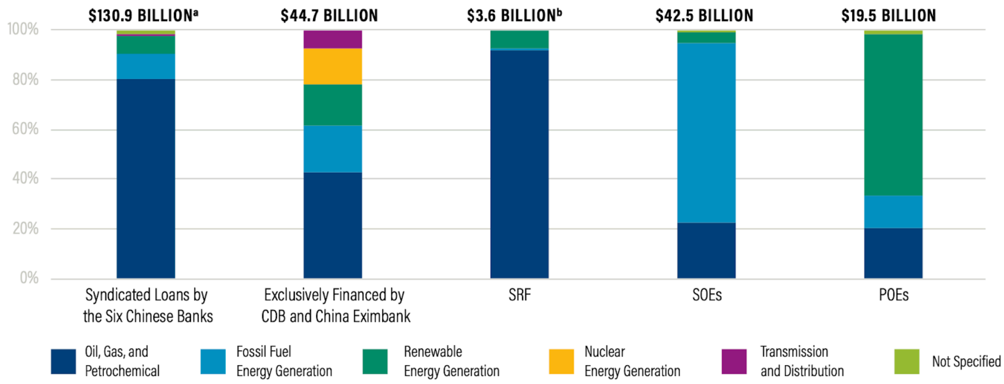

Figure 4 China's energy sector financial flows to BRI countries from 2014-2017 (Source: Zhou et al. 2018).

Table 3 Ownership structure of leading wind turbine, solar PV and fossil fuel companies in China

Sector	Firm	Global market	Type	Government ownership
Wind turbine	Goldwind	13.8%	Public	43.33% (Three Gorges New Energy)
	Envision Energy	8.4%	Private	
	Mingyang	5.2%	Public	7.3% (ICBC Int. Investment)
Solar PV	Jinko Solar	12.8%	Public	
	JA Solar	9.7%	Private	
	Trina Solar	8.9%	Public	
		Consolidated revenue 2018		
Fossil fuels	China National Petroleum	$340 bn	SOE	81% (China National Petroleum Corporation (SASAC))
	Sinopec Group	$314 bn	SOE	70% (Sinopec Group (SASAC))
	China Energy Investment*	$76 bn	SOE	100% (SASAC)
	China National Offshore Oil	$22 bn	SOE	64.44% (China National Offshore Oil Corporation (SASAC))

Source: Author's compilation based on Wang (2019), GWEC (2018), corporate annual reports. Note: An 'SOE' is defined as the government holding more than 50% of equity under its ultimate control. Government ownership includes both directly and indirectly controlled equity. *Formerly Shenhua and Guodian.

recently demonstrated by the US benchmark price for crude oil temporarily dropping below zero. The paradigm shift[9] in financing renewables marks a clean break from traditional energy business models. Hence, accelerating progress towards a green economy requires transforming the current financing paradigm based on short-term lending. The International Renewable Energy Agency (IRENA) emphasizes the urgent need to "develop finance innovations to transform the cash flow from fossil fuel consumption expenditure over time into upfront capital for renewable energy projects" (IRENA 2019, p. 50).

Barriers specific to financing Chinese renewable energy projects overseas

China's country-specific barriers to investing in renewable energy projects can be divided into the regulatory, financial and administrative spheres. A recent report published by Greenovation Hub and Tsinghua University (Ma 2020) identifies key reasons why Chinese renewable energy investments overseas[10] remain largely unexplored. According to the report, the following factors explain China's comparatively low level of renewable energy financing overseas: (i) delayed payment of subsidies, (ii) higher price competition overseas, (iii) insufficient support from credit insurance agencies, (iv) high financing costs, (v) limited access to project financing, and (vi) lack of cooperation with foreign financial institutions. While these obstacles are similar for renewable energy companies from other countries, the report by Ma (2020) analyses the specific context of Chinese companies.

First, delayed subsidy payments have been the result of lengthy administrative processes and the constantly growing deficit of China's Renewable Energy Development Fund, which now amounts to $28 bn (Energy Iceberg 2020). In Europe, subsidies are paid by host countries, however most Chinese overseas renewable energy projects are located in developing countries that have limited subsidy schemes. A delay in the payment of subsidies leads to insufficient funding capacity for overseas investments, an obstacle that particularly impacts private companies. Second, in recent years many overseas markets have shifted from a fixed feed-in-tariff to a competitive auction-based system (Dai et a., 2020; The Economist 2018). As China is still in the process of shifting towards these competitive mechanisms, the ability of Chinese companies to bid for overseas projects is limited, putting them at a disadvantage when faced with fierce competition from international and local enterprises. Third, insufficient support from China's export credit insurance companies often leads to non-viability of project financing, as China's financial institutions often lack the experience to evaluate host country risks. This may be due to the high exposure of the Chinese Export and Credit Insurance Corporation (Sinosure) to the energy sector (Li 2019). Fourth, as China has a closed capital account that translates into higher financing costs, borrowing foreign currencies from Chinese banks tends to be more expensive than borrowing from international banks (Ma 2020). In addition, companies have to secure export credit insurance from Sinosure, rather than using international export credit agencies, further exacerbating their financing costs. Fifth, Chinese renewable energy companies have limited access to project financing from Chinese financial institutions, a particularly important

9 From financing short to long-term and from financing operating costs to financing upfront costs.

10 Based on interviews with Chinese companies and financial institutions investing in BRI countries.

source of finance for large-scale on-grid projects with an installed capacity of 10 MW and above (FS-UNEP 2010). Therefore, they have to deploy corporate finance based on their balance sheets, leading to heavy debt burdens and limited financing capabilities going forward, especially for private firms (Ma 2020). The impact on renewables is particularly adverse because their dependence on project finance is far greater than projects based on fossil fuel technologies (Steffen 2018). Finally, to date there has been little cooperation between Chinese and foreign finance institutions that have more experience in financing renewable energy projects overseas. This may be particularly detrimental in providing long-term project finance to Chinese companies (Ma 2020).

It is worth noting that some of these barriers apply to Chinese overseas investments in general, across different sectors. However, as mentioned above, renewable energies are capital intensive and necessitate high upfront costs (in contrast to conventional energy sources such as gas or coal-fired power plants) that are associated with higher (perceived) risk. Hence, the combination of technology- and China-specific barriers results in a significantly higher hurdle to overcome in opting for renewable vis-à-vis conventional energy investments.

Chinese financial system favouritism of state-owned over private companies

Adding another layer to this problem, Chinese renewable energy companies are traditionally private while fossil fuel companies are largely state-owned, as shown in Table 3. Despite multiple state-owned companies increasingly diversifying into renewables,[11] Chinese lead firms in the renewable energy sector are still not majority-owned by the state. The essential reason for this is historical, as China used to be purely reliant on fossil fuels at a time when all companies were state-owned. As the economy liberalized to some extent, these fossil fuel companies were kept as strategic companies, leaving renewables to develop largely inside the private sector. The incentive for conventional state-owned energy firms to diversify into renewables is the result of government policies that require a certain percentage of investments to be in renewables.[12] For example, the world's largest power producer,[13] the China Energy Investment Group (formerly Guodian and Shenua Group), owns both China's largest project developer in wind power, Longyuan, and China's eighth largest wind turbine manufacturer, United Power. As the Chinese financial system is skewed in favor of SOEs, fossil fuel companies receive the financial support they need to overcome barriers in the energy sector in general, and the fossil fuel industry in particular, when moving abroad. An exception is the state-owned China Three Gorges company (historically associated with hydropower) that has made major renewable energy investments overseas in the past decade (IEEFA 2018). However, on a general level and because they are mainly private, financial support is not equally provided to renewable energy companies. This ultimately means that the Chinese financial system provides a clear advantage to fossil fuel companies over renewable energy companies when they are looking to move abroad. This lack of support for Chinese renewable energy companies moving abroad is evidenced by obstacles (iii), (iv), and (v), mentioned above.

It is reasonable to conclude that the stark contrast between Chinese domestic and overseas renewable energy investments can be explained by (i) general financing barriers for renewables based on the existing financing paradigm, (ii) multiple systemic factors that entail extremely high financial burdens and low viability of renewable energy projects overseas, and (iii) a general favouritism of the financial system towards state-owned energy enterprises, which are to a large extent fossil-fuel based. At the same time, a lack of overseas experience and an operational track record leads to insufficient bankability, which prevents many Chinese firms from accessing finance from foreign institutions. In order to disrupt this vicious circle, Chinese renewable companies have been experimenting with different forms of market entry. For example, Goldwind, China's leading wind turbine manufacturer in terms of market share, entered the Australian market by simultaneously becoming project owner (acquiring land), project developer, turbine supplier and renewable energy assets retailer, a highly unconventional scenario in the wind energy sector.

Discussion: Five central actors that can facilitate Chinese financing for Chinese renewable energy projects overseas

All the barriers identified above can be overcome through adequate support from financial institutions. Through exerting a higher degree of state governance of relevant financial institutions and the operation of the financial system as a whole, the Chinese government has a number of policy options available. These collectively need to change the status quo by easing access to finance for Chinese renewable companies relative to fossil fuel companies. The five most important types of actors to be targeted by such policies are (i) policy banks, (ii) state-owned commercial banks currently financing the majority of Chinese overseas energy projects, (iii) smaller financial institutions which are currently not involved in this type of financing overseas, (iv) Sinosure, which today primarily insures fossil fuel projects, and (v) Chinese energy, utility and construction companies that can expand further into renewables. While a wide range of available tools, both in and outside financial institution governance, can shape

11 For example, Shanghai Electric diversified into offshore wind through a joint venture with Siemens in 2014 (Dai et al. 2020).

12 In 2017, China started to reorganize its largest state-owned power generators, which has been perceived as an effort to move away from their domestic reliance on coal (IEEFA 2018).

13 In terms of installed capacity.

the issue, we highlight some of the policies with the greatest potential for the five types of organisations.

Chinese policy banks

As the single largest source of Chinese overseas energy financing, changing the behavior of CDB and EXIM banks would have a significant direct and perceived effect in the eyes of commercial banks. The Chinese government has complete authority to green their lending as they are managed directly by the Chinese State Council and regulated by the China Insurance and Banking Regulatory Commission. Key policy options include negative screening of the most polluting projects, such as coal, alongside proportional commitments to green or climate financing in a similar way to most countries' development banks and multilateral development banks. Another policy approach is to minimize harm by implementing environmental and social safeguards, as well as public disclosure of standards and project assessments. Initiatives such as a shift from using the lowest standards between China and the host country to using the highest, is an easy-to-implement change, as suggested by Voituriez et al. (2019). A third key policy option is to increase disclosure by following the praxis of the International Development Finance Club, of which CDB is already a member, and to categorize and publish data based on the OECD DAC format, which is open to non-DAC members, such as China, as well as the deployment of the broader concept of Total Official Support for Sustainable Development (TOSSD).

Chinese national level state-owned large commercial banks

The second largest source of financing derives from four large state-owned commercial banks, ICBC, BOC, BOC, and CCB. While these banks are publicly listed, the Chinese state is their largest shareholder and has a comprehensive mandate to govern their behavior through a number of channels, including CCP party committees established within the banks. Key policy options to increase their financing for renewable projects include 'window guidance', where State Council, China Banking and Insurance Regulatory Commission (CBIRC) and Green Finance Committee policies provide an official mandate to the banks to move away from business-as-usual and fossil fuel projects. Direct financial incentives can also be strengthened, such as the recently implemented, innovative and green macroprudential measures, giving banks a higher interest rate on their central bank deposits depending on how green their overall performance is. Furthermore, CBIRC can directly require the banks to publish the Financial Stability Board's Task Force on Climate Related Financial Disclosure, an increasingly common format that includes both current climate risk as well as strategies to minimize such risk.

Chinese smaller commercial banks

As shown above, Chinese domestic renewable energy projects are financed by the four large banks, but smaller banks also play a role. However, the smaller banks provide very limited overseas financing. Conversely, as fossil fuel SOEs are mainly financed by the large commercial banks domestically, they can rely on this relationship to expand their overseas operations. Consequently, if relying on existing relations were possible for smaller banks investing in renewable energy, international expansion would be substantially smoother. However, CBIRC policies that require smaller banks to meet stringent governance and management standards inhibit their operational ambitions. These standards include securing the approval of the Central Bank's State Administration of Foreign Exchange (SAFE) to transfer money across borders and use foreign currencies. These impediments are exacerbated by smaller banks being subject to a higher cost of capital than the big four, particularly internationally, in addition to the costs of establishing overseas branches (the big five's branches have been in place for many years). Regulators could reduce barriers and actively encourage overseas lending, while obliging Sinosure to cover this lending in order to reduce smaller banks' risk exposure. While local banks are small in comparison to the largest Chinese commercial banks, they are large by international standards and certainly mature enough to manage international loan portfolios.

Sinosure Export and Credit Insurance

While insuring the majority of Chinese overseas fossil fuel energy investments and often working as the actor who gives a project the green light (Wei and Baxter 2018), the state-owned Sinosure has to this point only insured a limited number of renewable energy projects. Chinese commercial banks would be more willing to lend to renewable energy projects if Sinosure was able to match their endeavor. As Sinosure is already significantly exposed from Chinese loans to coal projects, this is a limiting factor for expanding into renewables (Li 2019). Consequently, it may require the Chinese State Council to insist Sinosure extends its coverage to prompt a more decisive shift from their business-as-usual model of insuring fossil fuels. Options include placing stringent quotas on maximum coal exposure as well as on minimum proportions allocated to green energy. An additional option often discussed is for Sinosure to require projects to use an independent third party to carry out an environmental and social impact assessment to a high standard. This would inevitably reduce financing to polluting projects that are insured under current practice, thus freeing up insuring capacity for green projects. Furthermore, Sinosure could improve the insurance terms for renewable energy projects by offering, for example, longer terms, lower acceptance thresholds and broader cover (Ma 2020).

Chinese state owned energy, utility and construction companies

The final actor that can facilitate financing towards Chinese renewable energy projects overseas lies outside the financial system itself, namely Chinese SOE energy, utility and construction companies. While financing in the form of loans comes from policy and commercial banks, actual investments in energy assets derive from SOE companies in the form of equity stakes through greenfield investments, and mergers and acquisitions, amounting to USD 115bn in 2019 (Li et al, 2020). While these assets are mainly in fossil fuels, a gradual increase in renewable assets is evident. As SOEs have access to Chinese financing for overseas projects, shifting companies into renewables circumvents the obstacle of renewable companies being disadvantaged as private companies. SASAC, as the state representative owner of many companies in this category, could alter companies' strategies to gradually increase renewables in their asset mix. This evolution could follow the practice of international fossil fuel companies becoming low carbon companies, such as Engie, Ørsted and Iberdrola.

Conclusion

This article has highlighted that while China is the world's largest investor in renewable energy, its overseas energy investments are primarily in fossil fuels. This is problematic as countries across the globe need to transition towards low-carbon development trajectories to meet the 1.5 degree warming target of the Paris Agreement. As China is a leader in renewable energy technology, not adequately deploying this expertise outside the country is a lost opportunity, both for China and the world. The scale of the problem is highlighted by the fact that power generation investment in renewables domestically is 77%, when excluding medium- and large hydro, while overseas it is only 22%.

The critical barrier to Chinese renewable energy companies moving overseas is their lack of access to financing. The generic barriers to renewable energy include higher upfront costs and other expenditure, and income cycles that differ from traditional energy finance models. A country-specific barrier is the lack of support from financial institutions, in the form of loans and insurance. The key reason for this problem is that the largest Chinese financial institutions, the four large Chinese state-owned commercial banks, as well as China Development Bank and China Exim Bank, favour state-owned enterprises (SOEs) over private companies. Given that the energy sector is characterized by fossil fuel technologies and assets being primarily held by SOEs, with renewable energy in the hands of private companies, favouritism towards fossil fuels is to be expected.

This favouritism can be overcome through a range of policy options addressing five types of actors, namely 1) policy banks, 2) state-owned commercial banks that currently finance the majority of Chinese overseas energy projects, 3) smaller financial institutions currently not involved in this type of financing overseas, 4) Sinosure, which today primarily insures fossil fuel projects, and 5) Chinese energy, utility and construction companies that could expand into renewables.

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15 Small hydropower sustainability evaluation for the Belt and Road Initiative

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Introduction

The question of whether large hydropower provides ecological protection is still controversial. However, small hydropower projects (less than 50MW) are flexible and can be operated either independently or can be connected to the main grid. Small hydropower projects may be adopted when specific environmental and ecological requirements have to be met and are a potential option for remote regions that cannot be connected to the main grid in the short term. They may also generate socio-economic and environmental benefits, such as electricity supply, poverty alleviation, energy structure optimization and carbon emissions reduction.

The Chinese government sees the development of small hydropower as an important step and has emphasized the importance of evaluating green hydropower to support the country's sustainable development. The National Energy Administration released the *13th Five-Year Plan for Hydropower Development of China* in November 2016. Based on the concept of watershed ecological protection, the plan argues that hydropower development should be determined scientifically to maintain the basic ecological functions of rivers. The Ministry of Water Resources published *The Guiding Opinions for Accelerating the Development of Green Small Hydropower* in December 2016, promoting its broad benefits in terms of protecting ecology and the environment, saving energy, reducing emissions and enhancing livelihoods.

An overall national and international assessment of small hydropower includes *The World Small Hydropower Development Report 2016,* prepared by the International Center on Small Hydro Power, and the *Global Hydropower Industry Annual Development Report 2017,* published by the National Research Center for Sustainable Hydropower Development. The first report examines global small hydropower from the perspective of hydropower resources and electrification rates (UNIDO 2016). The second report provides a comprehensive analysis and summary of the development of the global hydropower industry from the perspective of the development of the industry itself, climate change, technology, costs, employment, investment and financing (NRCSHD 2018).

Different from more traditional small hydropower assessments, those focusing on sustainability should fully encompass factors such as ecological protection, social perception, management and economics to ensure a coordinated relationship between protection and development.

Though other studies have proved useful, there is still much to do. For example, a set of quantitative indicators and methods is required to make a comprehensive evaluation of the sustainability of small hydropower at the national level. Further, our understanding of the overall level of small hydropower development in countries participating in the Belt and Road Initiative (BRI) is not sufficient. Therefore, we have built a small hydropower sustainability evaluation index system covering four areas: Ecology and Environment, Social, Economic and Political. We adopted the AHP-Fuzzy Comprehensive Evaluation Model (see below) to evaluate the sustainability of small hydropower development in specific countries.

Research region

In an important move, Chinese President Xi Jinping proposed the Silk Road Economic Belt and 21st Century Maritime Silk Road (BRI) when he visited Central Asia and Southeast Asia in September and October 2013. The initiative received a positive response from participant countries and the scheme was rapidly put into operation. The National Development and Reform Commission of China released *Vision and Proposed Actions Outlined on Jointly Building the Belt and Road*, a report that drew attention to the propitious cooperation evident in clean and renewable energy, particularly hydropower (NDRC 2015).

Connecting the Association of Southeast Asian Nations, the Arab League, the African Union and the European Union, the Asia-Pacific and European Economic Circles are on either side of the Belt and Road. The majority of the 65 BRI participant countries are emerging economies or developing countries (Fig. 1-2).

In 2014, the population of BRI countries was 4.4 billion and their aggregated economic volume was $21 trillion, equivalent to 63% and 29% of global totals, respectively (Yu et al. 2015). Most of these countries face problems of slow economic and social development, and degraded ecological quality. In addition, they suffer from isolated geo-political relationships which have led to regional power shortages.

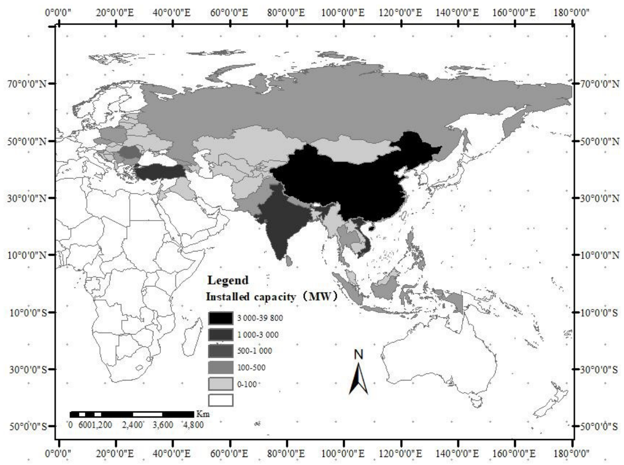

Figure 1 Installed Small Hydropower Capacity of participant BRI countries (MW)

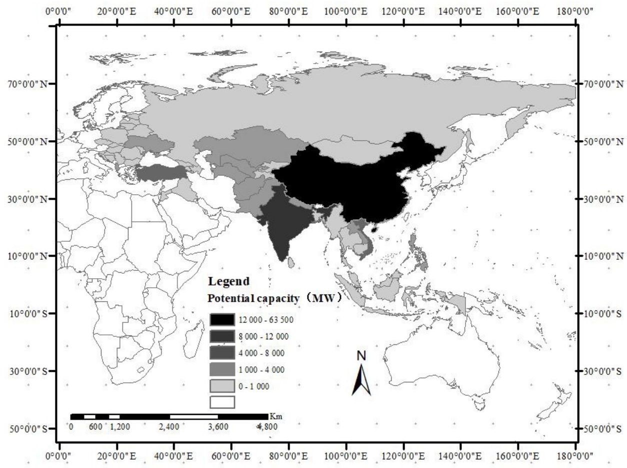

Figure 2 Small Hydropower Potential Capacity of participant BRI countries (MW) Source: Both base maps are from the Map Technology Review Center of the Ministry of Natural Resources.

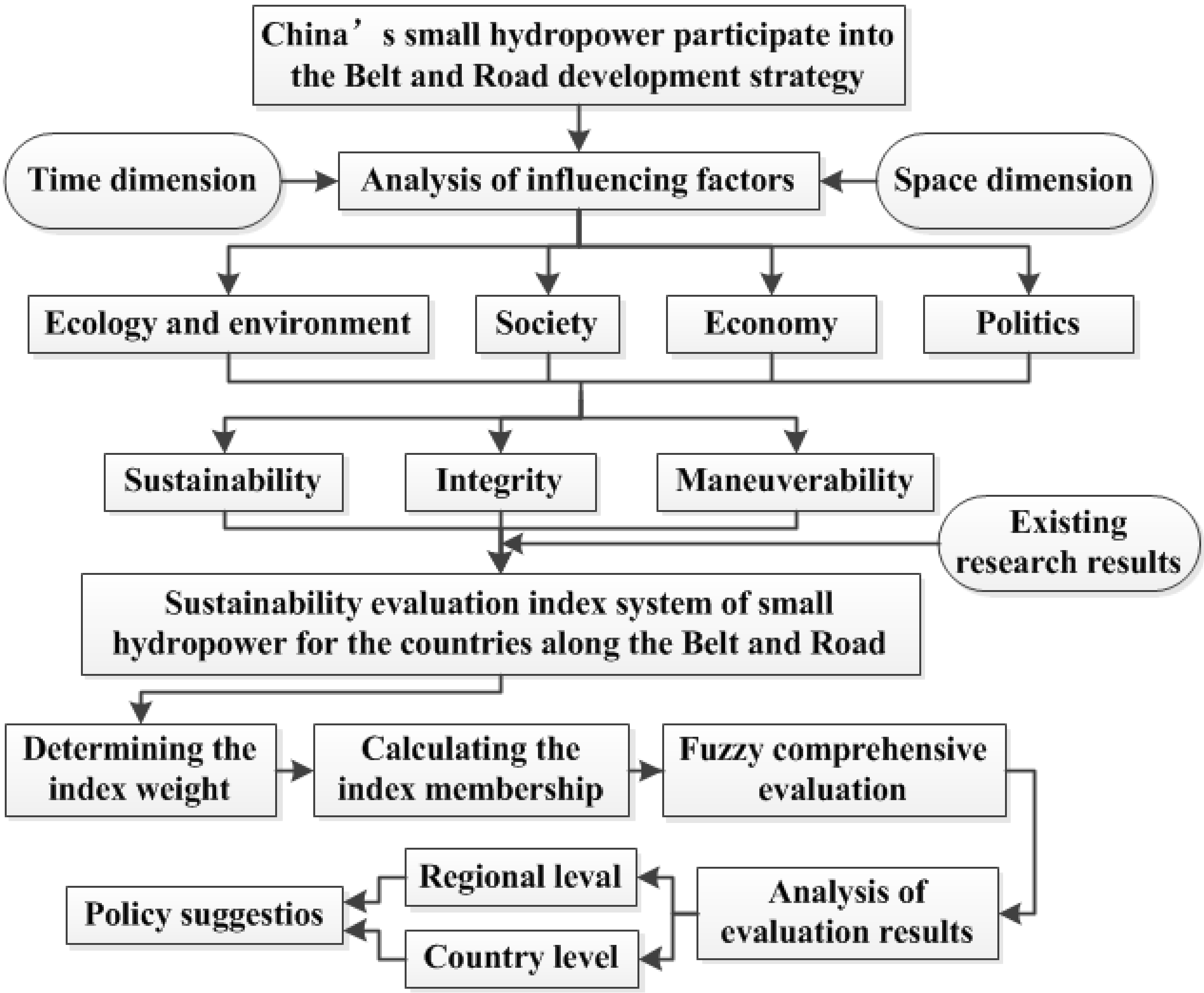

Figure 3 Logical framework of small hydropower sustainability evaluation for BRI participant countries.

Table 1 Review of small hydropower sustainability evaluation index systems, nationally and internationally.

Serial number	Name	Index type	Remarks
1	Low impact hydropower certification	Includes river flow, quality, fish flows, fish protection, watershed protection, endangered species protection, cultural resources preservation, public entertainment functions: eight aspects, 25 indices.	Qualitative analysis
2	Green hydropower certification	Includes hydrological characteristics, river connectivity, sediment and terrain, landscape and habitat, biotic community: five aspects, 11 indices.	Qualitative analysis
3	Hydropower sustainability assessment protocol	Includes environment, society, technology and economy/finance: four aspects, 23 indices.	Qualitative analysis
4	Indicator system for comprehensive evaluation of the sustainable development of small hydropower	Includes drivers, pressure, state, influence and response: five aspects, 28 indices.	Qualitative analysis
5	Indicator system for evaluating thesustainable development of small hydropower	Includes productivity, stability, protection, feasibility and acceptability: five aspects, 26 indices.	Qualitative analysis
6	Evaluation for green small hydropower station	Includes environmental protection, social development, economic benefit and safe operation: four aspects, 12 indices.	Qualitative analysis
7	Evaluation standard for green small hydropower station	Includes environmental evaluation, social evaluation, management evaluation and economic evaluation: four aspects, 14 indices.	Quantitative analysis
8	Indicator System for green small hydropower station	Includes natural ecology and social environment: two aspects, 16 indices.	Quantitative analysis

Many BRI participant countries have huge hydropower resources. Their installed capacity and potential capacity are 53.3GW and 130GW[1] (<10MW), accounting for 68.1% and 59.9% of 2014 global totals, respectively (UNDP 2015). In the context of the global response to climate change, the economic and social development of these countries' rural areas is on the rise and demand for small hydropower is significant (Zhu 2004, Liu 2016). Due to conceptual, economic and technical conditions, the potential of small hydropower has not been fully exploited. The promotion of the BRI will instigate new opportunities and challenges to how international cooperation plays a role in small hydropower development in China.

Methodology and data source

Evaluation index system

Research status
Most evaluation index systems for small hydropower are qualitative. The Evaluation Standard for Green Small Hydropower Stations of China and a number of other studies have conducted quantitative analyses. We summarize some of the qualitative and quantitative systems in Table 1.

Principles for index selection
Constructing a sustainability evaluation system for small hydropower should comply with the following principles: (1) Sustainability: the exploitation and utilization of hydropower resources and water resources should be based on a coordinated relationship between protection and development. (2) Integrity: all of the evaluation indices should be treated as a whole to increase the connections among them. (3) Maneuverability: the evaluation indices should be consistent with the development characteristics and current scenarios of small hydropower and the data to calculate the indices should be available. In line with these principles, we chose quantitative indices and set appropriate evaluation standards (Liu et al. 2010).

The design of the index system
In compliance with the above principles, from the dimensions of time and space and the aspects of economy, society, ecology and environment, and management, we analyzed the influencing factors of small hydropower sustainable development. We built a logical framework of small hydropower sustainability evaluation for BRI participant countries by drawing on research results while also taking into account the current scenarios in participant countries (Fig. 3).

On this basis, we built an index system that considers ecology and environment, society, economy and politics. Sixteen final indices were selected (Table 2). It should be noted that in research results the "management" index type is often used by single small hydropower stations. However, at the level of the Belt and Road, "management" should be envisaged as "macro-management,"

1 The installed capacity of small hydropower below 10 MW.

Table 2 Review of small hydropower sustainability evaluation index systems, nationally and internationally.

Primary index	Serial number	Secondary index	Definition
Ecology and environment status (A)	A1	Forest coverage	The ratio of forest area to total land area in a country
	A2	CO_2 emissions per capita	The ratio of total carbon emissions to total population in a country
	A3	Global Environment Facility (GEF) benefits index for biodiversity	A comprehensive index considering the diversity of national representative species, threatened conditions and habitat species
Social status (B)	B1	Renewable freshwater resources per capita	The ratio of renewable freshwater resources to total population in a country
	B2	Rural population proportion	The ratio of rural population to total population in a country
	B3	Rural electrification rate	The ratio of the population who receive power supply to total population in a country
	B4	Electricity consumption per capita	The ratio of electricity consumption to total population in a country
	B5	Human development index	A comprehensive index considering life expectancy, educational level and quality of life
Economic status (C)	C1	Per capita GDP	The ratio of GDP to permanent residents in a country
	C2	Waterpower utilization rate of small hydropower	The ratio of installed capacity to potential capacity of small hydropower in a country
	C3	Installed capacity proportion of small hydropower	The ratio of installed capacity of small hydropower to total installed capacity
	C4	National economic index	A comprehensive index considering import and export of natural resources, economic rent of natural resources, foreign direct investment, exchange rate volatility
	C5	Energy consumption intensity	Index refers to the amount of energy consumed by the unit of economic benefit. The lower the intensity, the higher the energy efficiency
Political status (D)	D1	National political index	A comprehensive index considering political risk, degree of corruption and criminal cost
	D2	Policy communication index	A comprehensive index considering the effects of political mutual trust, cooperation mechanisms and the political environment
	D3	People-to-people communication index	A comprehensive index considering tourism, science, education and folk exchanges, etc.

Remarks: in view of data availability at country level, the index system has the defect of time consistency.

namely the political status of a country.

Data source
This paper involved 16 indices corresponding to 65 BRI participant countries, and dealt with a total of 1040 sets of evaluation data. To ensure the reliability of the basic data, they were taken from databases, books and research reports in related fields, such as the databases of the World Bank, the United Nations Development Program and The World Small Hydropower Development Report 2016. Due to availability of data, in 2014 basic data for 46 countries were obtained in the data collection process (Table 3).

Table 3 List of BRI participant countries involved in this paper

Region	Nation
2 countries in East Asia	China, Mongolia
8 countries in Southeast Asia	Malaysia, Indonesia, Myanmar, Thailand, Laos, Cambodia, Philippines, Vietnam
6 countries in South Asia	India, Pakistan, Bangladesh, Afghanistan, Sri Lanka, Nepal
5 countries in Central Asia	Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, Tajikistan
7 CIS countries	Russia, Ukraine, Belarus, Georgia, Azerbaijan, Armenia, Moldova
4 countries in West Asia	Iraq, Jordan, Lebanon, Turkey
14 countries in Central and Eastern Europe	Poland, Lithuania, Estonia, Latvia, Czech Republic, Slovakia, Hungary, Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Albania, Romania, Bulgaria

Evaluation model
American operations researcher Thomas Saaty proposed the AHP method in the 1970s, a hierarchical and structured decision-making method for systematic analysis of multiple indices in a programme. It is a method that combines qualitative and quantitative analysis (Klos and Trebiina 2014, Socaciu et al. 2016) and is a simple way to make complex decisions with multiple objectives and multiple criteria, or without structured features. The method employs the characteristics of applicability, simplicity, effectiveness and systemization, and is widely applied in the social, economic, management and military fields (Bouzon et al. 2016, Zhu 2008). As the index system deployed in the evaluation of small hydropower sustainability is more complicated, we chose to use the AHP-fuzzy comprehensive evaluation, which is widely deployed in multi-index and multi-level complex evaluations. Determining the evaluation grade and index weight according to the membership theory of fuzzy mathematics means compound operations on multi-levels can convert qualitative judgements into quantitative evaluation. We determined the grades of evaluation as follows:

1. Defining the evaluation index set. Constructing the index set $U = (u_1, u_2,...u_n)$, U_i, represents ecology and environment, social, economic or political index, n is the total number of indices.

2. Defining the assessment set. The decision assessment set is $V = (v_1, v_2, v_3, v_4, v_5) = (1, 2, 3, 4, 5)$, where V_j represents the grade of each index based on scores given by experts, and its value can range across the comment set "excellent, good, moderate, poor, very poor" (Table 4).

Table 4 Sub-layer index evaluation standard

Comment set	Very poor	Poor	Moderate	Good	Excellent
Primary index	0-1	1-2	2-3	3-4	4-5
Secondary index	a_0-a_1	a_1-a_2	a_2-a_3	a_3-a_4	a_4-a_5

Remarks: a_i is the threshold value for secondary indices

3. Defining the weight set. As required by the AHP method, experts compared every pair of indices in each level, providing results on a 1 to 9 scale (Table 5), and performed a consistency test. The weight of each indicator can be obtained via matrix calculation, and their weight set can be established as a weight vector $W = (w_1, w_2, \ldots w_n)$, where W_i is the weight of the i-th factor.

Table 5 Score values of the judgment matrix

Score	Meaning
1	Indices i, j are similarly important
3	Indices i is slightly more important than j
5	Indices i is somewhat more important than j
7	Indices i is considerably more important than j
9	Indices i is vastly more important than j
2,4,6,8	Intermediate values between the values above
Reciprocal ($1/w_{ij}$)	The result obtained from comparing indices j and i

4. Determining the membership matrix. According to the characteristic of each index, we were able to derive the membership function. The evaluation function

$$R = \begin{pmatrix} r_{15} & \cdots & r_{15} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{n5} \end{pmatrix}$$

is calculated for each primary index. Where: R_{ij} is the membership of factor U_i to V_j;

1-5 represents the five different evaluation states - "excellent, good, moderate, poor, very poor" - that each secondary index corresponds to;

n represents the number of secondary indices under each primary index.

The threshold value in the evaluation standard is used as the inflection point to establish the linear membership function of each quantitative index. Where: x_i is the value of status of the secondary index.

$$r_1(x_i) = \begin{cases} 1, x_i \le a_0 \\ \dfrac{a_1 - x_i}{a_2 - a_1}, a_0 < x_i \le a_1 \\ 0, x_i > a_1 \end{cases} \quad (1)$$

$$r_2(x_i) = \begin{cases} 1 - \dfrac{a_1 - x_i}{a_1 - a_0}, a_0 < x_i \le a_1 \\ \dfrac{a_2 - x_i}{a_2 - a_1}, a_1 < x_i \le a_2 \\ 0, x_i \le a_0 \text{ or } x_i > a_2 \end{cases} \quad (2)$$

$$r_3(x_i) = \begin{cases} 1 - \dfrac{a_2 - x_i}{a_2 - a_1}, a_1 < x_i \le a_2 \\ \dfrac{a_3 - x_i}{a_3 - a_2}, a_2 < x_i \le a_3 \\ 0, x_i \le a_1 \text{ or } x_i > a_3 \end{cases} \quad (3)$$

$$r_4(x_i) = \begin{cases} 1 - \dfrac{a_3 - x_i}{a_3 - a_2}, a_2 < x_i \le a_3 \\ \dfrac{a_4 - x_i}{a_4 - a_3}, a_3 < x_i \le a_4 \\ 0, x_i \le a_2 \text{ or } x_i > a_4 \end{cases} \quad (4)$$

$$r_5(x_i) = \begin{cases} 0, x_i \le a_3 \\ 1\text{-}\dfrac{a_4 - x_i}{a_4 - a_3}, a_3 < x_i \le a_4 \\ 1, x_i > a_4 \end{cases} \quad (5)$$

5. Fuzzy comprehensive judgment. First, the fuzzy judgment should be conducted from the secondary index to the primary index, that is, the membership vector of the primary index is:

$$B_i = W_i \cdot R_i = (w_1, w_2, \ldots w_n) \cdot \begin{pmatrix} r_{15} & \cdots & r_{15} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{n5} \end{pmatrix} = (b_1, b_2, \ldots, b_5) \quad (6)$$

Wherein, i is the factors of the primary index, including ecology and environment *($i = 1$)*, social status *($i = 2$)*, economic status *($i = 3$)* and political status *($i = 4$)*.

n represents the number of secondary indices under each primary index. *when $i = 1$, $n = 3$; when $i = 2$, $n = 5$; when $i = 3$, $n = 5$; when $i = 4$, $n = 3$.* On this basis, we derive the fuzzy evaluation matrix $R = (R_1, R_2, R_3, R_4)^T$ of the primary index and membership vector B.

6. Using the fuzzy comprehensive index method to determine the comprehensive evaluation results of the sustainable development level of small hydropower in various countries:

$$FCI = B \cdot V = (B_1, B_2, B_3, B_4, B_5) \cdot \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix} \quad 7$$

Wherein, FCI is the score of fuzzy comprehensive evaluation; B is membership vector; and V is evaluation standard vector.

Results

Index weight and evaluation results

In order to ensure the accuracy and rationality of index weight, experts from Chinese universities, research institutes and government - including departments of water conservancy, hydropower, water resources, ecology and environment, technology and information - were invited to independently determine the score of the comparison matrix of the evaluation index system using the 1-9 Scale Method (Table 5). A total of 50 expert judgment matrices were obtained, and the final score was calculated by weighted averaging. The judgment matrix had to pass the consistency test, and CR was used to indicate the consistency ratio. When 0< CR <0.1, the consistency of the judgment matrix was considered acceptable. If the consistency test failed, the experts had to reuse the 1-9 scale method to determine scores, until the judgment matrix passed the consistency test to obtain the weight of each level of indices (Table 6).

Using the comment set and membership vector, the results of comprehensive evaluation and primary index evaluation of small hydropower sustainability in BRI participant countries were determined (Fig. 4).

Analysis of evaluation results

Regional level

The comprehensive evaluation scores of 14 Central and Eastern European countries, seven countries of the Commonwealth of Independent States (CIS), and five Central Asian countries are relatively high (>3). Rural electrification in these countries was achieved by extending main grids dominated by thermal power (Zhu 2008, Zhou et al. 2016). Their rural electrification rates have reached or are close to 100%, so the development potential of small hydropower is limited.

The comprehensive evaluation scores of four West Asian and North African countries, eight Southeast Asian countries, one East Asian country and six South Asian countries are relatively low (<3). Among them, the rural electrification rates of eight Southeast Asian countries, one East Asian country and six South Asian

Table 6 Weight of evaluation indices and evaluation criteria

Primary index	Weight	Secondary index	Weight	Very poor	Poor	Moderate	Good	Excellent
A	0.25	A1	0.0475	0-20	20-40	40-60	60-80	80-100
		A2	0.644	15.4-12.37	12.37-9.33	9.33-6.29	6.29-3.25	0-3.25
		A3	0.3085	0-20	20-40	40-60	60-80	80-100
B	0.25	B1	0.031	1-500	500-1000	1000-2000	2000-3000	3000-30000
		B2	0.1656	80-100	60-80	40-60	20-40	0-20
		B3	0.4796	0-20	20-40	40-60	60-80	80-100
		B4	0.2440	0-1390	1390-2750	2750-4110	4110-5470	5470-6900
		B5	0.0798	0-0.3	0.3-0.55	0.55-0.7	0.7-0.8	0.8-1.0
C	0.25	C1	0.0401	0-975	975-3855	3855-7880	7881-11905	11905-23000
		C2	0.4316	0-20	20-40	40-60	60-80	80-100
		C3	0.2845	0-4	8-4	12-8	16-12	20-16
		C4	0.0721	0-20	20-40	40-60	60-80	80-100
		C5	0.1717	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
D	0.25	D1	0.6413	0-20	20-40	40-60	60-80	80-100
		D2	0.2375	0-4	4-8	8-12	12-16	16-20
		D3	0.1211	0-4	4-8	8-12	12-16	16-20

Remarks: a_i is the threshold value for secondary indices

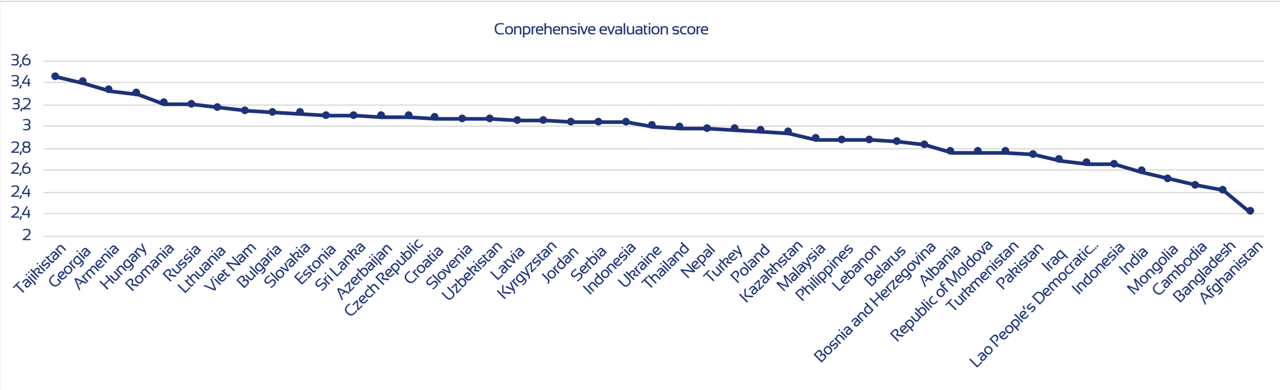

Figure 4 Small hydropower sustainability evaluation of BRI participant countries

Table 7 Evaluation results of small hydropower sustainability of BRI participant countries

Primary index	14 Central and Eastern European countries	7 CIS countries	5 Central Asian countries	4 West Asian and North African countries	8 Southeast Asian countries	1 East Asian country	6 South Asian countries	Average of 46 countries
Comprehensive status	3.06	3.09	3.05	2.89	2.84	3.03	2.67	2.96
Ecology and environmental status	3.05	3.24	2.91	3.37	3.63	2.61	3.63	3.25
Social status	4.26	4.00	3.68	3.92	2.91	3.53	2.53	3.63
Economic status	1.82	1.74	1.79	1.22	1.37	2.15	1.61	1.66
Political status	3.12	3.39	3.85	3.06	3.43	3.85	2.92	3.29

countries are 72.09, 69.9, and 66.52%, respectively. Therefore, rural electrification in these countries can be further improved. Meanwhile, waterpower utilization rates of small hydropower are 12.20, 38.46, and 14.19%, respectively, so the development potential of small hydropower is considerable. With industrialization process indices ranging from 23 to 51, they are in the early stage or starting the middle stage of industrialization. Thus, the economic and social development demand for small hydropower is strong. The rural electrification rate and industrialization process index of four West Asian and North African countries are 99.08% and 82.77%, respectively. Moving into the post-industrialization stage, the development space for small hydropower is limited (Table 7). Based on the above analysis, the key regions for Chinese small hydropower to participate in the BRI include eight Southeast Asian countries, one East Asian country and six South Asian countries.

On this basis, we analyzed the correlation between comprehensive, ecology and environment, social, economic and political evaluation results of BRI participant countries (Table 8). Comprehensive evaluation results are positively related to the four other evaluation results. From high to low, the correlations are society, economy, politics, and ecology and environment. On the one hand, the difference between any two of them is smaller than 0.08; on the other hand, a good social environment is important to the sustainable development of small hydropower. Ecology and environment evaluation results are negatively related to the other three types of evaluation. This phenomenon demonstrates that, at present, the development of small hydropower may damage the ecology and environment to different degrees in BRI participant countries. Coordination between protection and development has not been achieved in most of these countries.

Country level

Fourteen key countries were selected to further analyze the restrictive factors of small hydropower sustainability after filtering out countries whose rural electrification rates reached or approached 100%. Subsequently, we analyzed the status of their secondary indices (Table 9).

We filtered the key countries whose secondary indices were "poor" and "very poor". The proportions of "poor"

Table 8 Correlation analysis of the evaluation results for the primary indices

Primary index	Comprehensive status	Ecology and environmental status	Social status	Economic status	Political status
Comprehensive status	1				
Ecology and environmental status	0.0021	1			
Social status	0.6569	-0.4927	1		
Economic status	0.6464	-0.1429	0.2626	1	
Political status	0.4602	-0.2137	0.0865	0.1518	1

and "very poor" for the secondary indices show that the GEF benefits index for biodiversity (A3), rural population proportion (B2), electricity consumption per capita (B4), per capita GDP (C1), waterpower utilization rate of small hydropower (C2), installed capacity proportion of small hydropower (C3) and energy consumption intensity (C5) are restrictive factors for the sustainable development of small hydropower (Fig 5). Among these, the proportions of "very poor" for the GEF benefits index for biodiversity (A3), electricity consumption per capita (B4), waterpower utilization rate of small hydropower (C2) and installed capacity proportion of small hydropower (C3) are more than 70%, indicating that their degrees of restriction are higher than other indices. To date, the use of engineering and non-engineering measures to protect biodiversity has not been examined sufficiently in processes of small hydropower development. Small hydropower projects cause homogenization and discontinuity of river morphology, thus affecting habitat diversity and negatively impacting biodiversity. Waterpower utilization rates and installed capacity proportions of small hydropower should lead to the increment of rural electrification rates and electricity consumption per capita and should not be emphasized alone.

It should be noted that these restrictive factors have complex and non-linear characteristics. Influenced by both human activity and natural power, their development trends have uncertainty and time-space variation. Therefore, depending on current scenarios, different countermeasures should be implemented in countries to improve their small hydropower sustainability.

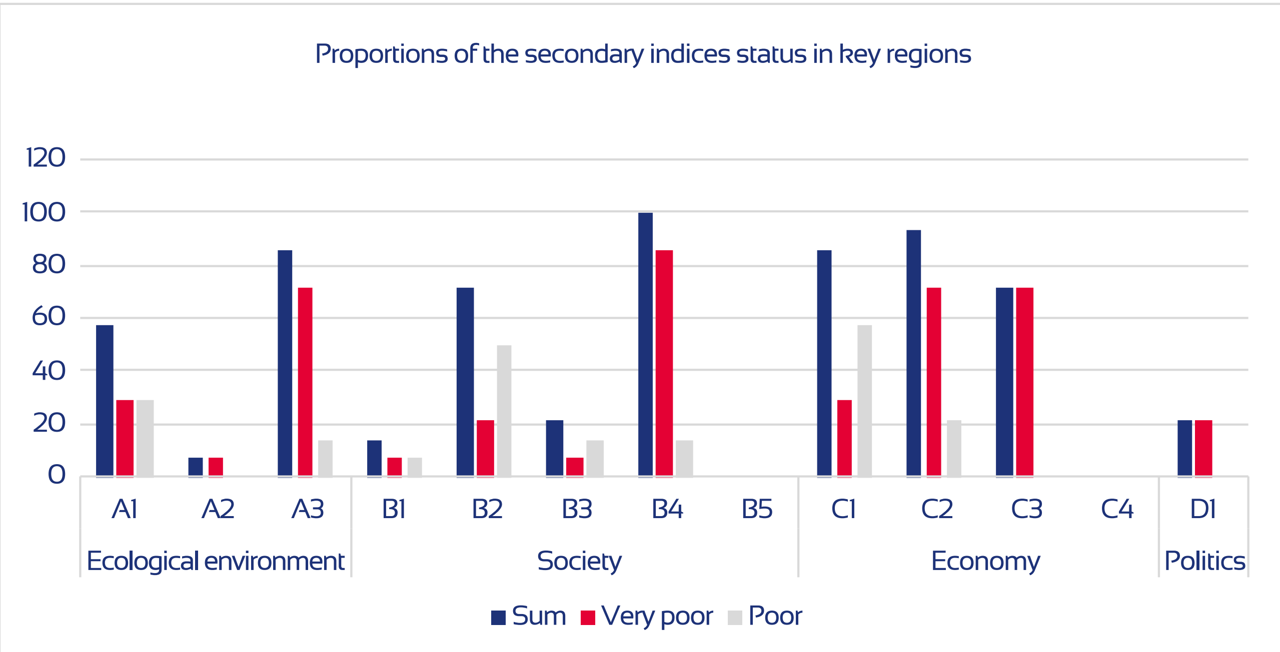

Figure 5 Proportions of the secondary indices status in key regions.
Remark: The key areas include the following countries: one country in East Asia (Mongolia), seven countries in Southeast Asia (Indonesia, Myanmar, Thailand, Laos, Cambodia, Philippines, Vietnam) and six countries in South Asia (India, Pakistan, Bangladesh, Afghanistan, Sri Lanka, Nepal).

Conclusions and discussion

Main findings

1. This study analyzes the index system quantitatively from the perspectives of ecology and environment, society, economy and politics, as well as providing a method to evaluate the sustainability of small hydropower in BRI participant countries. This study not only supports the role of China in small hydropower cooperation with other countries, but also provides a reference for promoting the sustainable development of small hydropower around the world.

2. From a regional perspective, China should participate in the construction of small hydropower in seven Southeast Asia countries, six South Asia countries and one East Asia country, all of which are included in the key BRI area.

3. From the perspective of secondary index countries, the main restrictive factors for key countries are economic factors, followed by social and political factors. The GEF benefits index for biodiversity, rural population proportion, electricity consumption per capita, per capita GDP, waterpower utilization rates of small hydropower, and installed capacity proportions of small hydropower and energy consumption intensity are restrictive factors for the sustainable development of small hydropower.

Policy suggestions

To facilitate China's small hydropower industry to take an active role in the Belt and Road Initiative in the future, we propose the adoption of the following policy initiatives:

1. In order to promote the sustainable development of small hydropower in key countries, and because economic and social indices are the main restrictive factors for the sustainable development of small hydropower in countries along the Belt and Road, we believe a new development mode for small hydropower should be deployed, namely "marginal industries + small hydropower". By combining small hydropower development with rural infrastructure construction, not only can the economic and social development of key countries be advanced, but China's surplus production crisis can also be resolved. Preliminary planning and feasibility studies should be initiated. By helping key countries develop comprehensive planning for medium and small rivers, China's small hydropower industry can successfully gain access to overseas markets. Small hydropower projects should be a funding priority for the Asian Infrastructure Investment Bank, BRICS New Development Bank and other emerging financial institutions. These financial institutions should provide financial support and investment insurance to key countries.

2. The International Center on Small Hydropower should bring together experts to build an index system for small hydropower sustainability, an initiative that can be seen as an important way of contributing to the UN Sustainable Development Goals (SDGs). The index system can then be disseminated to relevant countries, and an information platform of small hydropower sustainability can be built so that country data to evaluate the sustainability of small hydropower can be integrated to obtain relevant and accurate data in real time.

Study limitations and future directions

Overall, this paper can provide a reference for China's small hydropower industry to actively participate in the BRI. However, there is still room for further improvement in the index system and model construction, and conclusions thereof.

1. The study's index system requires further improvement. For example, in the economic field, indices of the investment and financing support for small hydropower, feed-in tariffs of small hydropower, development costs and the demand for water in various countries have considerable scientific value for measuring the economic benefit-to-cost ratio of small hydropower development. However, due to limits of data availability, such data were not included in this study. By strengthening statistical efforts in departments active in the BRI, it is expected that more representative evaluation indicators will be included.

2. The small hydropower sustainability evaluation method outlined in this paper is universal. For example, the method can be adopted to evaluate small hydropower sustainability in sub-Saharan Africa. The sustainable development potential of small hydropower in a specific country can be calculated by using this method. However, the AHP method has its limitations. Weight sets of indices were determined by scores that experts provided, so results are subjective. AHP should be scrutinized and corrected when it is applied in an analysis of the development status of countries within the Belt and Road.

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Abbreviations

AAU	Aalborg University
AI	Artificial intelligence
BEV	Battery electric vehicle
BRI	Belt and Road Initiative
CAS	Chinese Academy of Sciences
CCGT	Combined cycle gas turbine
CEM	Clean Energy Ministerial
CHP	Combined heat and power
CITIES	The Centre for IT-Intelligent Energy Systems
CNREC	China Renewable Energy Center
CSP	Concentrated solar power
CUDOS	The scientific norms of Communalism, Universalism, Disinterestedness and Organised Skepticism
CWEA	Chinese Wind Energy Association
DC	District cooling
DCC	Demand connection code
DEA	Danish Energy Agency
DECO	Denmark's Energy and Climate Outlook
DER	Distributed energy resources
DES	District energy system
DFIG	Doubly-fed induction generators
DH	District heating
DNI	Direct normal irradiation
DR	Demand-side response
DTU	Technical University of Denmark
EAST	Experimental Advanced Superconducting Tokamak
EDO	Electricity and District-heating Optimization
EEA	European Environmental Agency
EPS	Electric power system
ESCO	Energy service company
ESS	European Spallation Source
EUDP	Energy Technology Development and Demonstration
EWA	European Wind Atlas
EWLC	European Wind Load Code
FACTS	Flexible alternating current transmission systems
FCR	Frequency control reserves
FDI	Foreign direct investment
FED	Flexible Energy Denmark
FRT	Fault ride-through capabilities
4GDH	4th generation of district energy systems
GDP	Gross domestic product
G2V	Grid to vehicle
GAFAM	Google, Amazon, Facebook, Apple and Microsoft
GB/T	Power Quality Harmonics of Public Power Grid
GCM	Global circulation model
GDH	Generation of District Energy System
GEF	Global Environment Facility
GHG	Greenhouse gas
GIS	Geographic Information System
GW	Gigawatt
GWO	Green windows of opportunity
HATC	Home appliances to the countryside
HEV	Hybrid electric vehicle
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEE	Institute of Electrical Engineering
ILCC	International Low Carbon City
IPP	Institute of Plasma Physics
IRENA	International Renewable Energy Agency
KVA	Kilo volt-ampere
LCOH	Levelized cost of heat
LDTH	Low-temperature district-heating
LHV	Lower heating value
LIDAR	Light Detection and Ranging
IoT	Internet of things
MADE	Manufacturing Academy of Denmark
MI	Mission Innovation
MOST	Ministry of Science and Technology
MSW	Municipal solid waste
MSWI	Municipal solid waste inceneration
NDC	Nationally Determined Contribution
NDRC	National Development and Reform Commission
NEA	National Energy Administration
NEV	New energy vehicle
NSFC	National Science Foundation of China
OECD	Organization for Economic Co-operation and Development
P2G	Power to gas
PE	Power electronics
PEIP	Power-electronic interfaced power sources
PEST	Policy, economics, social and technology
PGSO-IP	Power and Gas Sector Outlook for Infrastructure Planning
PHI	German Passive House Research Institute
PMDD	Permanent Magnet Direct-Drive
PV	Photovoltaic
R&D	Research and development
R&I	Research and Innovation
RE	Renewable energy
RED	Renewable Energy Programme
SAT	Sodium acetate trihydrate
SDC	Sino-Danish Center
SDG	Sustainable Development Goal
SDH	Solar district heating
SGCC	State Grid Corporation of China
STI	Science, Technology and Innovation
SVG	Static VAR Generator
SVR	Static VAR Compensator
SWH	Solar water heater
SWOT	Strengths, weaknesses, opportunities and threats
TSO	Transmission system operator
UCAS	University of Chinese Academy of Sciences
UERA	International Alliance of Research Universities
UNEP	United Nations Environment Program
V2G	Vehicle to grid
VA	Volt-amperes
VAr	Volt-amperes reactive
VF	Vector-fitting
VRE	Variable renewable energy
VSC	Voltage source converter
W/m^2	Total radiation
WED	Wind Energy Programme
WRF	Weather Research and Forecasting
WTO	World Trade Organization

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