Renewable and Sustainable Energy Reviews 64 (2016) 531–542

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Solar PV and solar water heaters in China: Different pathways to low carbon energy

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ARTICLE INFO

Article history:
Received 7 December 2015
Received in revised form
15 February 2016
Accepted 16 June 2016
Available online 7 July 2016

Keywords:
Solar energy
PV
Solar water heaters
China
Low carbon innovation

ABSTRACT

This review paper examines pathways towards solar energy in China by examining two different solar energy technologies, namely solar photovoltaic (PV) and solar water heaters (SWH). The paper investigates these two case studies to understand how different pathways for low carbon innovation are promoted and challenged by China's changing financing and policy-making, and how they relate to changing practices among producers and consumers. The paper finds two distinct approaches to solar energy. Chinese solar PV is predominantly produced for the export market, relies on intellectual property-intensive technology and has received much financial and political support from the central and provincial governments. On the other side, solar water heaters are an indigenous Chinese technology that is found everywhere across China, especially in rural areas. They have developed from grass-roots levels to mass products with very little central government support. Although being largely absent from high-level discussions and policies, solar water heaters could contribute a lot to China's low carbon transitions that are driven at the local level.

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http://dx.doi.org/10.1016/j.rser.2016.06.023
1364-0321/

1. Introduction

This paper aims to review how innovation in solar photovoltaics (PV) and solar water heaters (SWH) is promoted and challenged by China's changing financial and policy-making setting, and how they relate to changing practices among producers and consumers of solar energy. This review paper aims to explore the status, prospects and politics of solar energy in China.

80% of the world's primary energy supply comes from fossil fuels, primarily oil and coal [1]. Solar energy is important as an alternative energy source as fossil fuel resources are limited and their use is associated with a number of negative environmental effects – such as global climate change and air pollution. The Intergovernmental Panel on Climate Change (IPCC) estimates that about 70% of all greenhouse gas (GHG) emissions world-wide, particularly carbon dioxide (CO_2) emissions, come from energy-related activities. This is mainly from fossil fuel combustion for electricity generation, heat generation and transport [2]. Avoiding dangerous climate change and staying below a 2 °C warming requires cutting global emissions rapidly [3]. Energy efficiency and energy from non-fossil fuels, such as renewable energy, are thus important for achieving a global low carbon transition.

China invests more in renewable energy than any other country in the world, including in solar energy. China is central to a low carbon transition: today China is the world's largest energy user and largest total CO_2 emitter [1]. China's energy use and CO_2 emissions have increased rapidly since the beginning of its economic reforms about three decades ago. In the past, China had low per capita energy use and GHG emissions and the country's historic (or cumulative) GHG emissions are also lower than many high-income countries. However, China has been catching up in recent years with regards to per capita emissions and cumulative emissions. The country's per capita CO_2 emissions are increasingly comparable with those of the European Union [1,4], and it is estimated that China may lead globally on cumulative emissions within 10–20 years [5].

At the same time as China's energy use and GHG emissions have reached unprecedented heights, the country has also become a world leader in renewable energy, most importantly in hydropower, wind energy and solar energy (both solar PV and SWH). China leads the renewable energy field globally in terms of investments, installed capacity and manufacturing [1]. China invested nearly US$ 90 billion in renewable energy in 2014 [6] and is expected to spend even more in the coming years [6,7]. Dincer (2011) stressed the role of China for the global solar energy market [62]. Duan et al. (2016) argue that solar PV could contribute significantly to China's greenhouse gas emission reduction efforts, achieving a peaking of emissions by 2030 and keeping mitigation costs to less than 3% of GDP [63].

This review paper examines pathways towards solar energy in China by examining two different solar energy technologies, namely solar PV and SWH. The paper finds two distinct and different approaches to solar energy. Chinese solar PV is predominantly produced for the export market, relies on intellectual property-intensive technology and has received much financial and political support from the central and provincial governments. On the other side, solar water heaters are an 'indigenous' Chinese technology that are found ubiquitously across China, especially in rural areas. They have developed from grass-roots levels to mass products with very little government support. Although being largely absent from high-level discussions and policies, solar water heaters could contribute a lot to China's low carbon transitions that are driven at the local level. These two different pathways to solar energy are being discussed and contrasted in this paper.

Section 2 presents the materials and methods, Section 3 elaborates the theory, Section 4 presents the findings, Section 5 discusses the findings and their implications and Section 6 concludes the paper.

2. Materials and methods

This paper is based on a review study of solar energy in China, with specific focus on the different pathways for solar PV and solar water heaters. It follows a case study methodology based on Yin [8]. Following Miles and Huberman [9], our case selection criteria consider the significance of the case, its representativeness, its theoretical relevance, and data accessibility. Solar PV and SWH are significant, because they are the most market-ready and commercialised solar technologies in China. They are representative as they are used everywhere in China. In the case of SWH, 85 million systems are installed in China and they are found in every province [10]. This case is theoretically relevant as we examine the status, prospects, politics and financing of these technologies, hence socio-political issues that tend to be under-represented in China's low carbon innovation studies. The study draws on a large number of data and materials, including data from the Chinese Statistical Yearbooks, the IEA, the World Bank, academic literature published in journals, books and working papers, and a wide range of policy documents.

Globally, China is the largest investor and manufacturer of solar PV systems and SWH. It also has the world's largest installed capacity of SWH [10,11]. Scholars have noted the differentiation between 'home grown' or indigenous innovation and technology transfer in low carbon innovation pathways [12,13]. Historically, technology transfer has played a large role in renewable energy pathways in China, particularly for wind energy but also for solar energy [13–15].

For these reasons, the solar sector presents an interesting study of indigenous innovation of low carbon technology and the dynamics of the diffusion of innovation. There are a range of other issues where PV and SWH have different pathways with different technological, economic and social characteristics and dynamics. For instance, most solar PV tends to be still rather expensive, hi-tech and unlike solar water heaters needs integration with the electricity grid which is a major bottle-neck, mainly of institutional and political nature. PV also needs to overcome higher barriers associated with intellectual property (IP) on key upstream technologies. SWH is cheaper, involves less high-tech and is a standalone technology. See Fig. 1 for a summary of these issues.

3. Theory

Recent years have seen the emergence of a large body of literature on low carbon innovation and its links to international development, including solar energy technology [11,27]. China is often considered as being in an exceptional position to lead the global low carbon transition. Its government is committed to low carbon development strategies, including building up the innovative capacity of key firms; it has made huge investments in low carbon industries and abundant capital is available; and it has a wide range of approaches in place for accessing the latest low carbon technologies. The government is also committed to tackling climate change, becoming a global leader in low carbon innovation,

Solar PV	Solar water heaters
Higher tech due to systems integration with grid	Lower tech due to stand-alone system
Partly dependent on tech / knowledge transfer	Indigenous innovation
High IP barriers	Lower IP barriers
Higher cost	Lower cost
More centralised due to integration with grid	Decentralised
Export-oriented	Domestically-oriented

Fig. 1. Key differences in solar PV and solar water heaters.

improving national energy security and creating competitive advantages and business opportunities for its firms [13].

Scholars working on the governance of social, technological and environmental change have pointed to the key role that different narratives and different forms of (incomplete) knowledge play in formulating, enabling and implementing particular "pathways" to sustainability [16]. Dominant narratives may achieve desired policy objectives, but may constrain a more holistic understanding of sustainability challenges by potentially over-seeing marginalized and locally-applicable pathways to low carbon development [16]. Research based on contemporary sustainability transitions and its politics is mainly focussing on Europe [18,19] while similar studies on China or other parts of the world are still rare.

A society-wide and economy-wide low carbon energy transition requires a move from high-carbon fossil fuel systems to low carbon energy systems. This entails a wide range of changes, including a change of people's practices and behaviours, changes to government policies and incentives, changes to innovation systems and technological approaches. This implies that along with studying technologies and their diffusion, there is a need to study world-making *power* [20–22], a missing element in most current analysis. It also requires to study how new political agents, social practices and subjectivities arise in a contested process alongside the reshaping of socio-technical systems [23,24].

Innovation and technological development are complex, messy, non-linear and part of larger economic, social and political processes [25]. Hence, innovation is a concept for which no singular definition exists. Innovation is defined here as creating something new: developing a new idea, product or service [26]. Low carbon innovation is defined here as developing and commercialising new ideas, products and services that reduce greenhouse gas emissions. It is crucial to achieving low carbon energy transitions and mitigating climate change. Developing and diffusing low carbon innovation entails a complex process of research and development (R&D), demonstration and deployment [27]. Beyond technological processes, this involves a wider enabling environment, including market creation for successfully commercialised technologies, the presence of adequate incentives and policies for firms and other organisations to engage in technological development, skilled labour, specially trained engineers and technicians. Hence the diffusion of low carbon innovation involves a wide range of actors including firms, public institutions, and research organisations [25,27].

China and other low and middle-income countries have historically depended to a large extent on international technology transfer and cooperation from high income countries for some low carbon technologies, such as wind and solar energy technology. This has changed over time as Chinese firms and institutions have developed their own productive capabilities and innovative capabilities. The concept of 'indigenous innovation' is key to this development, yet it is being perceived and interpreted differently in China and in the West. 'Indigenous innovation' is predominantly viewed by Western firms, states and business actors as innovation that has been invented, conceptualised or built by a particular country's firms or institutions. This differs from the Chinese understanding of 'indigenous innovation', which may also include innovation that has been licenced and amended, acquired (for example through mergers and acquisitions) or was developed by reverse engineering based on overseas innovation. These different definitions and their interpretation have caused conflict about intellectual property rights (IPRs) in the past [7].

Recently, innovation that is based on different forms of international technology cooperation such as networking, staff exchange schemes, joint ventures, licencing, mergers and acquisitions have played a larger role in China's renewable energy sector. In recent years, 'indigenous innovation' has also become more common in China in many sectors, including in the renewable energy sector, in a sense that innovation that has been invented, conceptualised or built by Chinese firms or institutions. This is particularly striking for solar water heaters, since China uses a specific technology, namely the evacuated tube design, which is different to the technology predominantly used in many other countries. Chinese firms also hold the large majority of the solar water heater patents worldwide. In contrast, innovation in the Chinese solar PV sector tends to be less based on indigenous innovation in a Western sense and depends more on utilising knowledge, experience, staff and networks in a globalised market. From a Chinese perspective, however, indigenous innovation may also be based on foreign knowledge, experience, staff, networks and technology acquired from and/or licenced by Chinese firms [7].

In studying two different innovation models of solar energy in China, this research has the objective to go beyond technology-focused approaches to innovation and consider the political and power dimensions of the narratives that shape these different energy pathways, as well as the perceptions and practices of consumers and producers.

4. Results

4.1. The Chinese energy sector and low carbon transitions

About 75% of China's GHG emissions come from energy generation [1,4]. Just under 80% of the country's primary energy production comes from coal[1] [28], making China's coal sector the world's largest single anthropogenic source of CO_2 [7]. Fig. 2 indicates the energy sector's large role in China's GHG emissions and the country's historic reliance on coal for energy generation. Fig. 3 illustrates the country's high reliance on fossil fuels, particularly coal.

Low carbon technologies are considered strategic by China's ruling elite to drive forward the country's competitiveness and strive for sustainable development. Hence, dedicated industrial policies emerged that have supported low carbon technologies. This was embedded in China's 12th Five-Year Plan (FYP), and is also likely to be the case in the 13th FYP [37] for the period of 2016–2020. The 12th FYP, for the period of 2011–2015, contains both binding and flexible environmental targets.

In the 12th FYP many targets concern natural resources and the environment. The most relevant binding targets for climate change mitigation, energy efficiency and non-fossil resources are as follows:

- Reducing energy consumption per unit of GDP (energy intensity) by 16% by 2015.
- Increasing the share of non-fossil energy resources to account for 11.4% of primary energy consumption by 2015.
- Reducing carbon dioxide emissions per unit of GDP (carbon intensity) by 17% by 2015 [30].

Seven new "strategic emerging industries" emerged from the 12th FYP: new energy (meaning non-fossil energy), energy conservation and environmental protection, biotechnology, new materials, new information technology, high-end equipment manufacturing and clean energy vehicles [30]. The new 13th FYP from 2016–2020 is likely to support low carbon energy technologies and climate targets even further, including solar energy targets.

The investment and policies supporting these different technologies differs markedly. China has become the global leader in investing in renewable energy. See Fig. 4 for investments. The country also has the world's largest installed renewable energy capacity, even when large hydropower dams (an industry traditionally supported by the Chinese government, which is often

[1] National Bureau of Statistic, People's Republic of China. China Energy Statistical Yearbook 2013 [26]. Beijing: China Statistics Press, 2013.

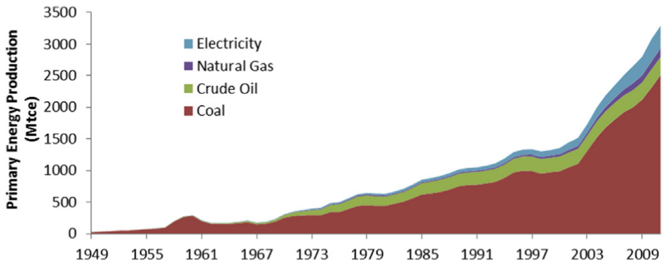

Fig. 2. Primary Energy Production by Source, Megatonnes of CO_2 equivalent for 1949–2013. Source: China Energy Databook [29].

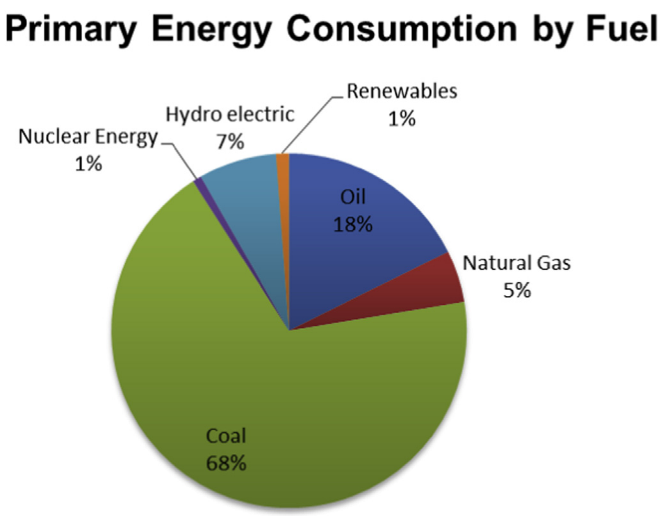

Fig. 3. China's primary energy consumption by fuel, 2013. Data from BP Statistical Review of World Energy [31].

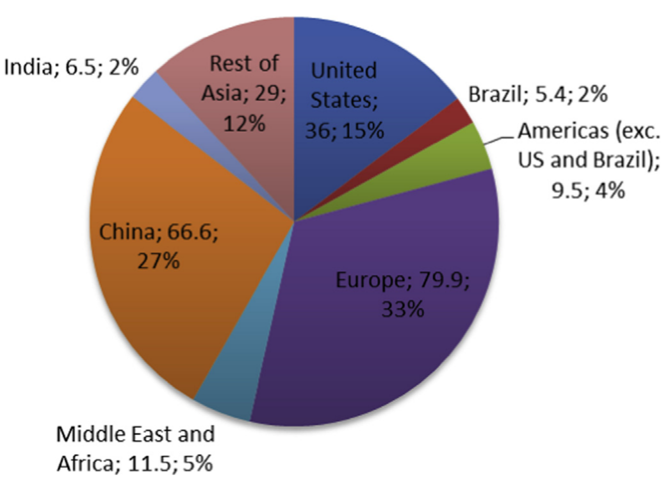

Fig. 4. Global new investment in renewable energy by region, 2013, US$ billion and percentage. Source: [32].

regarded as problematic due to its environmental, social and economic implications) is excluded. See Fig. 5 for installed capacity. Interestingly, in 2014 China invested for the first time more in renewable energy than in fossil fuels [11].

The next Section 4.2 discusses insights from solar PV and Section 4.3 discusses insights from SWH.

4.2. Solar PV

4.2.1. Solar PV: status and prospects

The photovoltaic phenomenon was first discovered by Edmond

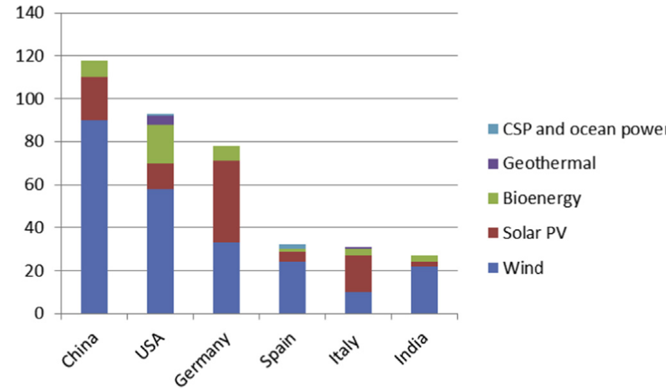

Fig. 5. Installed renewable energy capacity, top world regions and countries, 2013, GW, excluding hydropower.
Source: [11].

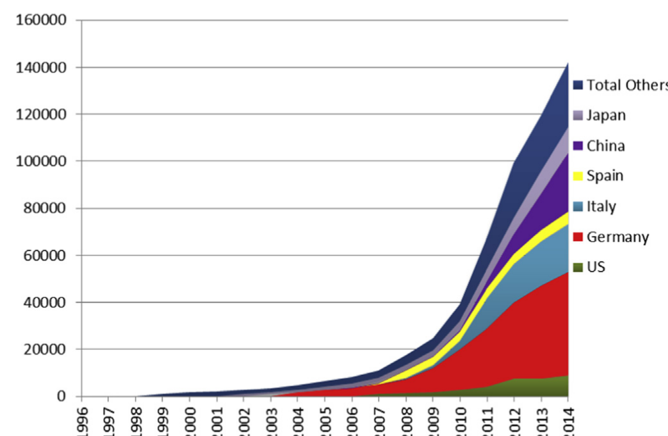

Fig. 6. Global cumulative installed solar PV capacity, in megawatts, data for 1996–2014. Data from [11,31].

Bequerel in 1839. It involves a semiconductor converting light directly into electric energy [33]. Solar photovoltaic technology has been developed and advanced over many decades. Historically, it was strongly supported through state-regulated monopolies and government initiatives in the United States, including the Department of Defence and NASA [35]. The breakthrough production of the world's first silicon PV cell occurred in 1954 at Bell Laboratories [33]. For about five decades, solar PV systems have predominantly been installed off-grid for decentralised use, and employed extensively in spacecraft and satellites. While the technology is not new, the large-scale installation of solar PV is a relatively recent development globally, which dates to the late 1990s [7].

Since the early 2000s, the world market for PV has grown exponentially, mainly driven by industrialised countries, notably Germany, Japan, Spain and the United States, as well as China. This strong growth was encouraged by policy support that has addressed the higher costs of PV generation compared to fossil fuels, particularly through Feed-In-Tariffs [34]. See Fig. 6 for an overview of the global cumulative installed solar PV capacity. In recent years, the market prices and underlying costs of PV systems have fallen dramatically, making solar PV competitive with fossil fuels in many countries. If fossil fuel subsidies were to be reduced solar PV and other renewables would be even more competitive. Bazilian et al. [40] found that a sharp fall in the price of purified silicon driven was driven by a breakthrough in China in mastering the technology for its production. As a result, the price for solar PVs fell to $2.00 per watt by 2009, and by late 2011, crystalline-silicon PV modules had fallen below the $1.00 per watt mark for

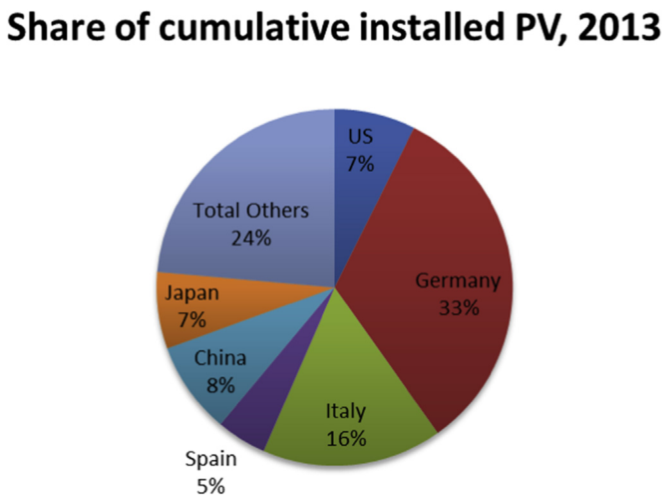

Fig. 7. Share of cumulative installed solar PV capacity in 2013. Data from [31].

the first time. Prices have since continued to fall: it is reported that top Chinese producers approached costs of only $0.50 per watt in 2013 [7,41].

By the end of 2013, China accounted for 67% of global PV module production [41]. However, China's PV industry is mainly export-oriented and the country has been slow in installing PV capacity within its own borders. China's installed capacity of solar PV accounted for about 15% of global capacity by early 2014 [41]. In its early development, the Chinese government's renewable energy policies focused on the domestic installation of wind energy, while solar PV remained an export industry for a long time. Solar PV played a role under the Clean Development Mechanism (CDM), although today China uses new organisational arrangements for technology transfer such as mergers and acquisitions and joint ventures [14,64].

Yet even today, China is slow in the uptake of domestic PV installations in comparison to the volume of its export PV sales. See Fig. 7 to compare China's share of 8% among the global solar PV installations with other leading countries [31]. The reasons for this are the relatively high prices for consumers, a lack of government incentives, technical and bureaucratic connectivity problems with the grid and the physical difficulty of installing solar PV modules as many potential consumers (particularly in urban areas) do not own or have access to roof space as the common style of housing are flats in high-rise buildings. Most PV installations in China are ground-mounted, large-scale installations, for which financial incentives are particularly crucial. However, this picture is beginning to change – as will be explained in this paper. Despite slow domestic installation rates, China has become the world's leading supplier: around 95% of China's solar PV systems are manufactured for export [42]. The country accounted for about 50% of total global solar PV production since 2010, with an export value of US$20.2 billion [1,35]. The global export of solar PV cells in 2011 accounted to about 37.675 GWp (gigawatts peak), of which the export from China was 21.157 GWp, accounting for more than 55% of the global market [38]. Today about 80% of all solar PV technology is being exported to developing countries, particularly to ASEAN countries. This is a direct result of the anti-dumping and anti-subsidy trade disputes between China vs EU and China vs USA. Imported Chinese PV systems are now more expensive in the EU and the USA due to additional trade tariffs while they remain cheap in ASEAN countries where these tariffs do not apply [59].

By early 2015, seven of the top 10 solar PV manufacturers were Chinese: Trina Solar, Yingli Green Energy, Canadian Solar (Chinese-owned), Hanwha SolarOne, Jingko Solar, JA Solar and Rene Solar. These firms made up the global top 1 to 6 and 8 of solar PV manufacturers [60].

Today Chinese PV manufacturers advocate that the quality of Chinese PV systems is similar to their Western counterparts. Chinese solar firms are less R&D-intensive compared to international companies in the solar sector, but there are indications these firms tend to file more patents, particularly to send a signal to public authorities to allocate more subsidies.

China's PV industry also recently filed a large number of patents in upstream segments, especially silicon production and ingot manufacturing. In the past Chinese PV firms were not dominant in that area and depended predominantly on imported purified silicon for PV systems production. This has now changed, suggesting a turning point to break a “technological lock” where the industry is still dependent on foreign suppliers [34].

By mid-2015, China's installed solar PV capacity had risen to more than 35 GW grid-connected capacity [1], thereby achieving the official 2015 target. China’s National Energy Administration NEA has a target of 100 GW installed solar PV capacity by 2020, even though speculations about the 13th Five Year Plan mention targets as high as 200 GW by 2020 [61]. Sun et al. [38] suggested that China's PV industry is likely to achieve grid parity on the consumption side by 2015, and the price of solar PV is today indeed competitive with the price of fossil fuels. As costs are falling and China's solar PV industry is thriving many consider the country as a crucial player for large-scale diffusion of low carbon energy technologies worldwide.

Fig. 8 shows the efficiencies of different kinds of solar PV panels between 1975 and 2015 [65]. Similar to other countries, the prevailing PV technology in China is still based on crystalline silicon cells, produced by leading firms like Yingli, Trina, JA Solar, whereas gallium arsenide-based single junction cells, multi-junction cells, thin-film solar cells based on copper indium gallium selenide (CIGS) and emerging PV technology like dye-sensitised technology are more recent innovations. This has also increased the efficiencies of Chinese PV cells from the conventional 14% to up to more than 30% for the latest cutting-edge technology in laboratory tests, a record held by AltaDevices [65], a US-based company acquired by Chinese thin-film leader Hanergy in 2014. See Fig. 8 and Table 1. A common problem is still the “Valley of Death” between product R&D and commercialisation [66,67]. Non-economic support factors such as adequate policy support are important for successful commercialisation and deployment [68].

The following section discusses the role of politics for driving forward solar PV innovation.

4.2.2. Solar PV: politics

4.2.2.1. The rise of Chinese solar PV. The Chinese government has supported R&D on solar PV since the 1950s, particularly for use in space. It was the 6th FYP (1980–1985) that first included PV science and technology projects, with research on crystalline silicon cells included in the 7th FYP (1986–1990). By the mid-1990s, China's PV module manufacturing capacity was 5 MW, although according to Zhang et al. [37:903], “much of this capacity did not meet modern international standards and actual production was only 1.4 MW.”

Solar PV played a crucial role in providing modern energy access to remote communities, In this context, the Brightness Programme from 1996 was the first national policy “to bring electricity to remote areas of western China by means of renewable energy” [37:905]. In 2002, the State Development Planning Commission (SDPC; now the National Development and Reform Commission, NDRC) launched the “Power Supply Plan for Rural Areas without Electricity in the Western Provinces and Regions” policy, which aimed for rural electrification by using solar PV and wind energy for remote, off-grid, rural households in Western China [38,42].

China's solar PV policy shifted to an “export-oriented growth stage” between 2004 and 2008 [37:906]. This was supported by the government by increasing investments in R&D, covering

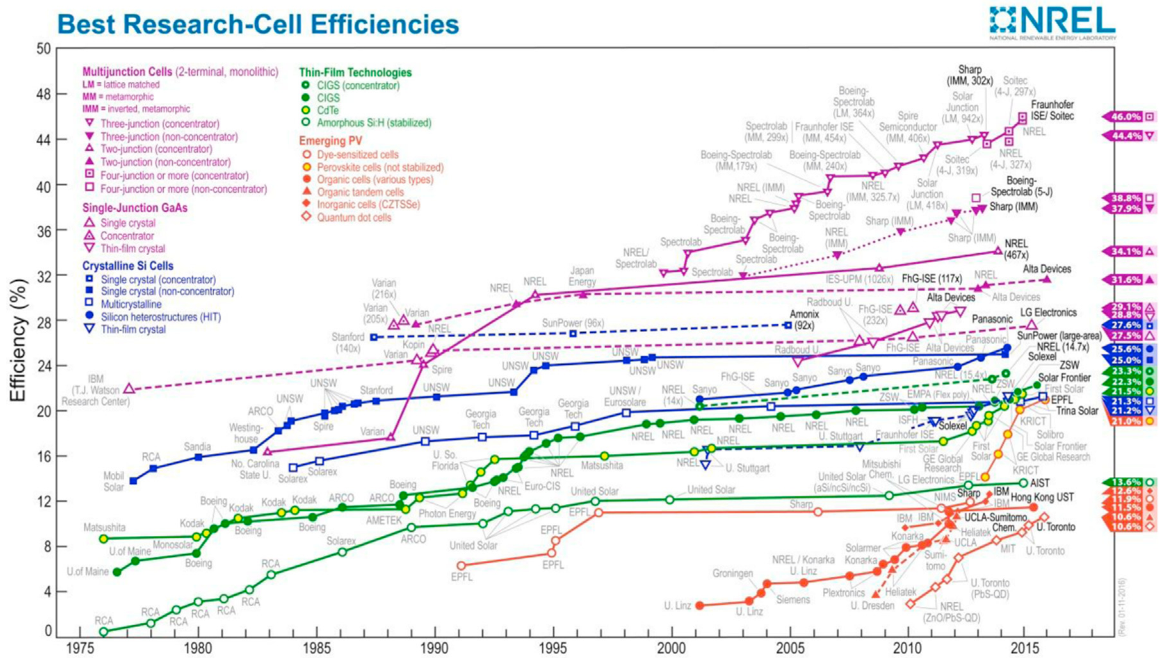

Fig. 8. Efficiencies of latest solar cell technology. Source: NREL, 2016 [65].

Table 1
Latest PV technology in China and its status.

PV technology	Status of technology
Crystalline silicon cells	Commercialised for mass market, cost-effective prices
Gallium arsenide-based single junction cells (GaAs)	R&D, mass production announced
Multi-junction cells, mainly dual-junction cells using different technologies	R&D, not yet commercially available at competitive prices
Thin-film copper indium gallium selenide (Cu, In, Ga, Se_2) (CIGS)	R&D, not yet commercially available at competitive prices, although mass production announced
Dye-sensitised cells	Early stage R&D

almost the entire solar PV manufacturing chain and establishing national key laboratories at several leading firms. Today, leading companies like Yingli Solar and Trina Solar have set up national PV key laboratories "with annual R&D investment of 592 million RMB and 610 million RMB respectively between 2009 and 2012." [38:226]. While the Chinese PV industry depended still partly on foreign technology during these years, the country stepped up its independent innovation and thereby created what the Chinese governments calls a "PV industry with Chinese characteristics" [35]. Technology transfer and technology cooperation from industrialised countries occurred particularly through purchasing manufacturing equipment, transfer of complementary know-how, foreign direct investment by multinational firms and the movement of skilled labour across borders. Key firms benefitted from this movement of foreign-educated skilled labour, including Suntech, which was China's biggest solar company for several years until its decline in 2012. Scientist and entrepreneur Shi Zhengrong, the founder of Suntech, obtained his PhD in solar PV engineering at the University of New South Wales in Sydney, acquiring Australian citizenship in the process, before moving back to China to found Suntech [34]. After the company's downfall, Chinese observers variously blamed it on the pressure from local government to expand too rapidly, Shi's own management style or external factors such as the fall of the price of polysilicon in 2011, linked to improved manufacturing abilities within China, while Suntech had long-term external supply contracts at higher prices [7].

Boosting solar PV manufacturing became part of core government strategy. This is reported to be due to the central government's "belief held since the early 2000s that China had an historic opportunity to position itself as an economic and technological leader in a global transition towards low carbon energy and that those who moved fastest in the transition to a low carbon economy were likely to gain a significant competitive advantage" [37:906].

China's 12th FYP for the period of 2011–2015 includes a dedicated five year plan for solar energy, with the aim to reduce the price of solar power and to increase the manufacturing of PV systems [39]. Other objectives are to increase R&D for key technologies, developing new, advanced technology and manufacturing processes for PV panels, promoting favourable policies for the domestic market and improving PV standards and product quality inspection and certification systems [35]. Yet, one major challenge is that solar PV is still very expensive for individual consumers and social acceptance is low [69].

China's government therefore launched further incentive policies to boost PV domestic market expansion, particularly to expand the PV output through Feed-In Tariffs (FIT), including: the State Grid Corporation of China (SGCC)'s "Relevant Opinions and Regulations on Grid Connection for Distributed PV"; the National Energy Agency (NEA)'s approval of 18 demonstration zones on distributed solar PV in 2013; and in August 2013, the NDRC's "Notice on Giving Play to the Role of Price Leverage in Promoting Healthy Development of the Solar PV Industry". The Ministry of Science and Technology (MOST) has driven forward PV R&D, with an average annual investment of around 500 million yuan (around US$81 million) toward all segments of the manufacturing chain: Poly-Silicon, wafer, solar cells, PV modules, thin-film technology, CPV, energy storage, BOS components and system engineering [7,44].

4.2.2.2. Challenges. Today it is clear that a paradox has emerged in the large-scale growth of the Chinese PV industry, with a strong orientation towards export markets without complementary policy support for the creation of a domestic market. This is partly because the Chinese government had "planned wind energy as the main strategic renewable energy for China" [38:224]. Until 2011, 90–95% of solar PVs were exported, mainly to the EU (Germany particularly) and the US. This has changed in recent years. One of the reasons is that the US have added high tariffs to the price of Chinese PVs, making them very expensive [43]. Not only did China export up to 95% of its solar PV modules, but it imported 95% of its raw materials for PV, known as the problem of *liangtou zaiwai*, or "both ends out" due to a "lack of advanced technologies in producing crystalline silicon" [47:5]. Zhang et al. [36:904] therefore argue that the transition to a low carbon economy "erratic and unpredictable… due to it being subject to external events and policy priorities from other sectors." Overlooked actors for solar PV have been China's local governments, who were encouraged by central government's messages that solar energy had a strategic priority. Consequently, they created strong incentives for local solar firms "and granted them greater preferential treatment compared to other industries" [47:5]. This preferential treatment, according to Chen [47:11-12], included: "free or low-cost loans, tax rebates, research grants, cheap land, energy subsidies and technological, infrastructure and personnel support." Local governments also often supported indigenous PV producers by instructing local commercial banks to offer concessional loans at low interest rates. One example is Jiangsu Province, home to Suntech and to some "particularly aggressive solar development policies" [37:907]. Suntech is reported to have received bank loans worth US$56 million at the end of 2005, but this amount had risen to US$3.7 billion at the end of 2012, mainly due to the ability of the municipal government to encourage local state-owned banks to provide low-interest loans to PV firms [47]. This created a fund-raining and expansion boom in the Chinese PV industry, particularly in provinces such as Jiangsu. PV manufacturers received export credits at preferential rates from the Export Import (ExIm) Bank of China and many would raise funds through overseas IPOs – a trend initiated by Suntech, which floated on the New York Stock Exchange (NYSE) in 2005. Partly, this influx of foreign capital enabled the Chinese PV industry to expand its production capacity at an unprecedented rate [37:907]; [7]. However, this also increased the risk of oversupply and over-competition problems, coupled with challenges in European export-markets after the 2008 global financial crisis [46].

This led to stronger support of the domestic solar PV market. This happened for example through the Rooftop Subsidy Programme, jointly announced by the Ministry of Finance and the Ministry of Housing and Urban-Rural Development (MOHURD), and the Golden Sun programme for distributed solar PV between 2009 and 2011, launched by the Ministry of Finance, the Ministry of Science and Technology (MOST) and the National Energy Administration (NEA) of NDRC [7]. The Golden Sun Programme came under heavy criticism from China's PV industry and experts due to in-transparent project approval, alleged fraud and delays in subsidy payments [37]. This resulted in an even greater overcapacity of solar panel manufacturing by 2012, when Chinese production equalled 55 GW, representing about 150% of annual global consumption [37].

The consequent global decline in solar PV system prices caused several US and EU manufacturers to go bankrupt: Solyndra (USA), Q-Cells (Germany), BP Solar (British) and others pulled out of the solar PV industry and others downscaled their operations, including Sharp (Japan) and First Solar (USA) [47]. This decline in the industry resulted in anti-dumping and anti-subsidy investigations by the USA and the EU, which had impacts on the Chinese solar PV industry [38], including Suntech defaulting on its debt, failing to pay US$541 million worth of bonds [7]. In contrary to its US competitor Solyndra, Suntech survived the crisis, and although weakened, still exists today. Mazzucato [36] suggests that the strong government support and state-backed financing Suntech received is in stark contrast to that of Solyndra, which was an entirely private company, which does not exist today. The two companies both scaled up too rapidly, depended too much on export demand and were hit by the sharp decline in the price of polysilicon. Yet, thanks to the favourable politics of solar PV in China Suntech survived.

In 2014 new goals on distributed solar generation were introduced, just to be abolished again in 2015 by the National Energy Administration. Distributed generation was favoured by central government as the energy infrastructure in Western China is under-developed, there are high transmission and distribution losses from long-distance transportation of electricity and low energy demand. However, far more ground-mounted utility scale, centralised PV capacity is being added in China than distributed PV capacity based on roof-top installations or smaller ground-mounted installations. Nevertheless, the new 2015 targets of adding nearly 18 GW to the existing capacity encourage local governments to prioritize small-scale projects up to 20 MW. The new target also includes the aim to install a further 1.5 GW solar PV as poverty alleviation pilot projects in six poorer provinces. Qualifying local authorities need to have at least 200 households with a disposable income lower than RMB 3000/year who are eligible for a 3 kW solar home system [45]. In early 2015, less than an additional 8 GW were installed and significant capacity was standing idle, unconnected to the grid in predominantly rural provinces such as Gansu and Xinjiang [46]. However, by late 2015 the national target of 35 GW installed capacity had been reached.

4.3. Solar water heaters

4.3.1. Solar water heaters: status and prospects

China is the world's largest solar hot water market worldwide, and SWH are being described by Annini et al. [49] as the "undiscussed protagonist" of a low carbon transition. SWH were first developed in the 1970s in China. In the 1980s, China started manufacturing flat plate solar water heaters that were acquired through technology transfer from a Canadian firm and were similar to the predominant SWH design used in Europe today. Nevertheless, the production was expensive and several technical problems occurred. In the 1990s, Chinese scientists at the Beijing Solar Energy Research Institute at Tsinghua University had a breakthrough by developing and patenting their own, low-cost, indigenous innovation: the evacuated tube design also called the vacuum tube. Similar to other renewable energy industries in China, most importantly the wind energy industry, university-led R&D that was promoted by the national government was key to developing the evacuated tube technology.

The evacuated tube SWH technology was heavily supported by the national government until it was commercialised in 1998. Himin Solar Energy Group, known as Huanming in China and the country's leader in SWH, was the key player for commercialising the product and scaling up the business. Today leading firms, such as Himin, still cooperate with renowned universities and the Chinese Academy of Sciences (CAS) for R&D in solar water heaters. This needs two prerequisites: first, a skilled work force with excellent engineers for developing cutting-edge innovation, and second a low-cost work force for mass manufacturing of solar water heaters [49]. Today it is reported that about 95% of all solar water heaters in China are of the evacuated tube design [50]. Even more strikingly, Chinese firms are estimated to hold about 95% of the patents for core technologies of SWH worldwide [51]. Zhao et al. (2015) report that the number of solar patents has increased rapidly in recent years in China and about 86% of all patents for solar thermal energy technologies are related to SWH [70]. While key Chinese solar water heating technologies, such as the evacuated tube design, have been dominant for many years (compare Xiao et al., 2004 [75]), major improvements have been made in quality, installation rates and mass commercialisation. Fig. 9 shows the share of the total installed capacity of SWH globally, indicating the large dominance of China [7].

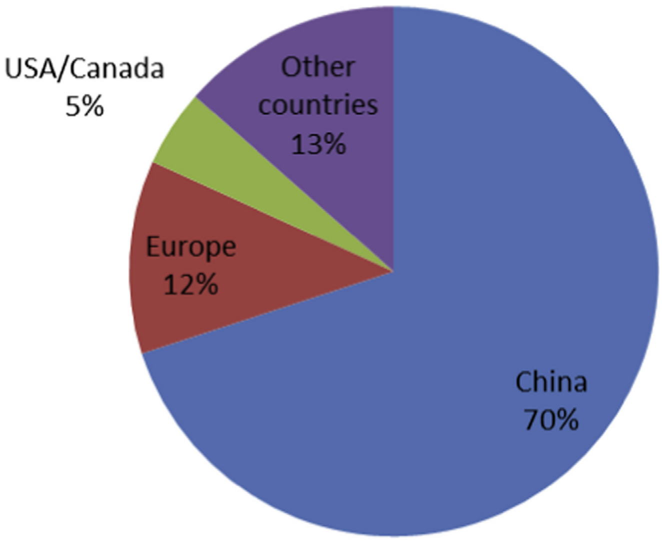

Fig. 9. Share of the total installed capacity of solar water heating in operation by economic region at the end of 2014. Data from [10].

Table 2
Latest solar thermal technology in China and its status. Based on [70].

Solar thermal technology	Status of technology
Evacuated tube SWH system	Commercialised for mass market, cost-effective prices
Flat-plate thermal SWH system	Not widely used or produced in China
Thermodynamic solar panels	Early stage R&D
Solar thermal air heaters	Early stage R&D
Solar cooling systems	Early stage R&D
Concentrated Solar Power (CSP), including parabolic, Fresnel, enclosed through and solar tower	Early stage R&D
Solar desalination plants	Early stage R&D

Table 2 shows the prevailing solar thermal technologies and their relevance for the Chinese market.

SWH in China are mainly produced for the domestic market, and have a large uptake particularly in rural areas. Up to 70% of the global installed SWH capacity is located in China [10,11] (see also Fig. 6). By 2014 a total of 374,660,000 m^2 of solar water heaters had been installed in China [10]. More than 80% of the new installed global capacity in the last years has been in China [10,11]. It has been reported that more than 30 million households used solar water heaters in 2009 [51], while estimates suggest that today over 85 million solar water heating systems are being used in China [10]. It is estimated that more than 260 GW of solar thermal heating capacity was installed in China by late 2015, which is reported to save about 75,690,000 t CO_2 per annum [10]. The literature in unanimous in suggesting that the potential market for solar water heaters in China is huge. About one million solar water heaters are being manufactured every year [49]. Nevertheless regional variations exist with Shandong province having the highest penetration rate of solar water heaters, with about 20% of all households owning water heaters [51]. Shandong province is also home to a SWH innovation cluster, housing the world's largest SWH firms. This cluster has developed due to several reasons, including strong provincial government support offering incentives for the solar water heater industry, networks among innovative firms, good infrastructure links (such as port links) and a lack of cheap provincial fossil fuel resources [7,49].

The sector has seen a rapid increase over the last 15 years [53]. It is estimated that the annual output growth rates of SWH increased at about 20–25% per year between 2000 and 2010 [50]. Fig. 10 shows the accumulated installation of solar water heaters and their growth rate.

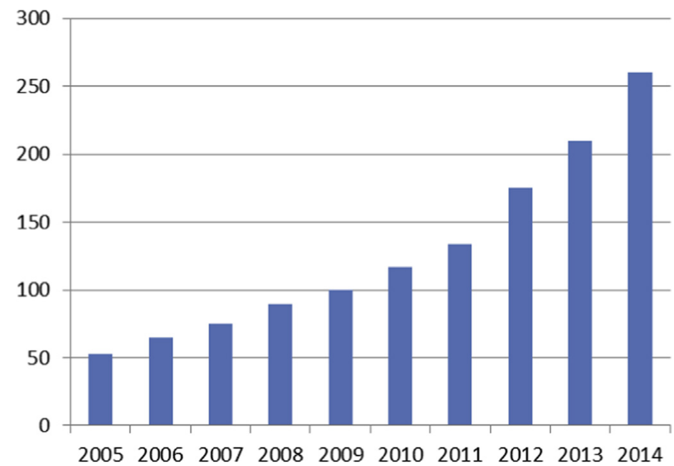

Fig. 10. Accumulated installation of solar water heaters between 2005 and 2014, measured in GW.
Source: [10].

About 3000 solar water firms are said to be based in China, of which about 1800 are solar water heater manufacturers and the remaining 1200 firms are component suppliers. Of these 3000 firms, the top 10 firms make up more than a quarter of the Chinese solar water heater industry [50]. Four firms are recording an annual sales volume of approximately 2 billion yuan (around US$326 million), two firms are reported to have an annual sales volume of approximately 0.5–1 billion yuan ($81–$162 million) and more than 20 firms have an annual sales volume of about 100–500 million yuan ($16–$81 million) [49]. The SWH industry includes both private and state-owned firms (SOEs) [7].

Top Chinese SWH firms include: Himin Solar Energy, Shandong Long Guang Tian Xu Solar Energy, Shandong Linuo New Material, Jiangsu Sunrain New Energy Group, Shandong Sangle Solar Energy, Shandong Linuo Paradigma Solar Energy, Jiangsu Huayang Solar Energy, Beijing Tianpu Solar Energy Industry, Beijing Huaye Solar New Energy, Guangdong Fivestar Solar Energy.

Leading innovation clusters in the SWH industry are based in Shandong province, Jiangsu province and Beijing [50]. The quality of SWH is paramount; hence China introduced several national standards to guarantee quality and made the Chinese Committee for the Standardization of Solar Energy in charge to oversee this quality procedure. Three product-testing centres are operating in Beijing, Hubei and Yunnan, although some leading firms have their own testing centres. The State Administration of Quality Supervision, sub-division Inspection and Quarantine, oversees the testing. It is estimated that about 80–93% of the tested SWH pass the standards test. In addition, voluntary certification centres exist that certify the quality of the SWH and/or their impact on the environment through ISO 14001-type certifications. A small number of small and medium enterprises (SMEs), particularly in rural areas, pose continuous problems as they seem to have sub-standard production systems and products [7,50,54].

The SWH supply chain is complex, including manufacturing firms, component suppliers, service providers, sales agents, as well as energy providers. The sector has increasingly become more efficient, and economies of scale have led to decreasing costs per unit. Currently a solar hot water heater costs a few thousand RMB (a few hundred US$), depending on quality and size.

Compared to electric hot water boilers or natural gas hot water boilers, the initial investment costs for solar water heaters may be higher in China (depending on the quality and brand of the boiler), however, SWH have minimal annual maintenance costs and as no fuel is needed they have lower annual costs than other hot water heaters [50]. The economic break-even point for solar water heaters compared to electric water heaters is usually at around 3 years; afterwards electric heaters are far more expensive than solar heaters and similar figures apply for gas boilers in China [52].

Most SWH are used on a small scale and for individual uses, yet they are increasingly being used on larger scales, for example by industries such as the Zhejiang Shaoxing Dyeing and Weaving Mill, the Kaida Dyeing and Weaving Mill and the Oriental Dyeing and Weaving Mill in Changshu, Jiangsu [7,50].

4.3.2. Solar water heaters: politics

Solar water heaters make an interesting case: before the evacuated tube design was patented and commercialised by Chinese innovators in 1998, there was national-level support for R&D; however after its commercialisation solar water heater firms have received relatively little stable national financing incentives. Central government initiatives played a key role for developing the cutting-edge evacuated tube design in the 1970s, 1980s and 1990s [49,52]. Today there are only few formal subsidies at the national level and there is a limited amount of industrial policy that supports the growth of the solar water heater industry. However there is strong support at the provincial and municipal level for solar water heaters and they have become ubiquitous in China, driven by a strong local demand and affordable prices. Unlike solar PV and wind energy, SWH have been developed mainly at the local level after their commercialisation, driven by local supply-side policies and subsidies, without much central government support [7]. There is an ongoing discussion among scholars and technical experts as to whether SWH are indeed a mature technology that does not need as many subsidies and financial incentives as solar PV or wind energy.

Nevertheless, since the introduction of the Renewable Energy Law in January 2006, there has been a rapid expansion of SWH installations across China. This is driven forward by two key policy incentives: First, some provincial and municipal governments including Hainan, Fujian, Jiangsu, Hebei, Henan, Shandong and Ningxia and cities like Shenzhen, Jinan, Rizhao, Yantai, Zibo, Qingdao, Xingtai, Qinhuangdao, Zhengzhou, Sanmenxia, Huhhot, Nanjing and Wuhan have introduced a mandatory requirement since 2007 which requires installing solar water heaters as part of every new building. Second, the 2009 policy on "household appliances going to the countryside" introduces a subsidy for SWH, equivalent to a reduction of 13% of the wholesale price that aims at increasing the availability and use of SWH in rural areas [50]. Different incentives for SWH firms at the local level include free or low-cost loans, tax rebates, research grants, cheap land provided by municipal or provincial governments. As solar resources vary significantly in different regions in China a local approach may be adequate as mandatory requirements by the central government may not be suitable for all regions [7].

In official national policy documents in the early 2000s, targets for SWH are still mentioned. For example, the National Development and Reform Commission NDRC's Medium and Long-Term Plan for Renewable Energy in China, which was issued in 2007 and covers plans up to the year 2020, mentions targets for solar water heaters: a total heat collecting area of 150 million square metres to be installed by 2010 and 300 million square metres to be installed by 2020, replacing 30 million tons of coal equivalent (tce) and 60 million tce respectively. By 2014 a total of 374,660,000 m^2 of solar water heaters had been installed in China [10], thereby easily exceeding the initial targets for 2020. The 10th Five Year Plan for 2001-2005 set national targets for installing 64 million square meters of solar water heaters by 2005 [49]. In more recent national policy documents however, solar water heaters are mentioned less than solar PV or other renewables in more recent national policy documents. The 12th Five Year Plan, covering the period 2011–2015, does not seem to focus on SWH. In terms of solar power, the 12th FYP lays out plans for large-scale solar power plants (including Concentrated Solar Power (CSP)) and PV, but less for solar water heaters [30]. This might be due to the assumption that Chinese solar water heaters are already at the cutting-edge of innovation, have widely been commercialised and deployed for two decades, and have become a socially-accepted and economically-viable Chinese technology.

A further issue related to politics and the political economy of solar energy is the career opportunities for provincial bureaucrats who contribute to building up a successful SWH industry at the provincial level. Local bureaucrats who manage to attract solar energy firms to their province and/or municipality and contribute to the success of the firms tend to be likely to have improved chances for promotion. Successful local firms can lead to local employment, tax revenues, economic growth and increased competitiveness for the province and/or municipality. These successes may reflect back positively on the leading bureaucrat who may get an opportunity to be promoted into a more senior and more influential role in the future [7].

Strikingly, neither the SWH firms nor the industry as a whole enjoys fiscal or taxation incentives in China, yet SWH installations and sales have increased rapidly in recent years, mainly driven by a large and rapidly expanding local demand, particularly in the rural areas and in smaller towns. Hu et al. [50] argue that SWH meet the demand of millions of Chinese customers by offering good quality, high performance, but at a low cost. Li et al. [52] add that SWH are also based on China's natural endowments for solar energy, which is abundant in China, whereas for fossil fuels there is a mismatch between demand centres (in the East) and production centres (in the West) and long-distance transport of fossil fuels and electricity is a challenge. Solar energy reduces pressure during peak load, is generated and used locally, and thereby contributes to energy security and opportunities for economic growth at the local level. At the grassroots level end-users in China tend to have a very positive attitude and there is a high level of public acceptance towards low carbon energy due to the general awareness of China's resource scarcity and the fact that solar energy provides employment in many regions in China [52]. Another driver that facilitates China's rapid rise in solar water heaters is its relaxed building codes that enable setting up solar water heaters on roofs without planning permission or other bureaucratic rules. Yet, there is very little available roof space in urban areas, hence SWH are more prevalent in rural areas where more people own their own houses. However experts suggest that the most important argument for SWH is their low cost. As socio-technical preferences have changed in the last decade with regards to hot water provision in China, a transition has been observed from the conventional high carbon pathway to the alternative low carbon pathway.

Han et al. [54] however argue that further incentives need to be introduced by the Chinese government to reduce costs of SWH to enable poorer families to purchase them. They also argue that the energy efficiency of the evacuated tube design is rather low and therefore argue that China should introduce a higher share of flat plate SWH [54]. This suggestion raises major concerns as flat plate SWH are more costly and would depend on technology transfer and the acquisition of foreign licences rather than being based on Chinese indigenous innovation and Chinese patents. It seems that in practice, the evacuated tube solar water heater is a dominant Chinese innovation that has already changed socio-technical preferences for millions of Chinese households. Yuan (2011) stresses the high level of social acceptance and public awareness for solar water heaters in China [69]. It is a technology that is low cost, abundantly available everywhere in China and it has become the 'standard' way of heating water in rural areas in China, although far less common in urban areas. Social practices in China, at least in the rural areas, have adopted SWHs as a mainstream way of heating water.

5. Discussion

In the sections above we discussed the pathways for low carbon innovation in China by taking solar energy as a case study. We found that China's approach to solar energy is two-fold:

On one side there is the high tech, export-oriented, large-scale / industrial-scale of solar PV. This is still rather expensive, top-down, driven by national firms and strongly supported by the central government. On the other side there is the frugal technology of solar water heaters which is largely domestically-oriented, indigenous technology, small-scale/individual-scale. It is relatively cheap, bottom-up, driven by local government, local firms and a strong local demand.

Solar PV is of high national importance, with about 60% of the total global solar PV production coming from China, and having an export value of US$20.2 billion [35,38]. Six of the global top 10 solar PV firms are Chinese. Solar PV is embedded in major recent policy plans such as the NDRC targets and the Five Year Plans. MOST drives forward R&D in solar PV, with an average annual investment of about 500 million yuan (about US$81 million) [44]. There is also the feed-in-tariff at national level in addition to support from local governments that provide free or low-cost loans, tax rebates, research grants, cheap land [47]. At the same time there is the paradox of the large-scale development of the PV industry without complementary policy support for creating a domestic market [58]. In addition, there is the twin challenge of the export of PV systems, but the import of purified silicon [47] and the industry being vulnerable to the financial crisis and anti-dumping laws in the US and Europe [36].

Shen and Luo (2015) resonate some of these findings by confirming that the renewable energy industry in China still suffers from several problems, despite strong policy support and increased subsidies. The main problems are high costs of technologies such as solar PV, grid connection as a major bottleneck, challenges in applying the feed-in-tariff and trade disputes due to its strong reliance on the export market [71].

On the other side are solar water heaters, the “undiscussed protagonist” of a transition from fossil fuels to low carbon energy [49:152]. Solar water heaters have received relatively little stable national financing incentives in the years since 1998, when the evacuated tube design was commercialised. This is partly because Chinese firms are reported to hold up to 95% of the patents for core technologies of SWH worldwide [51]. There are few national level formal subsidies and limited national-level supportive industrial policies for manufacturers. Policy and financial support is more focused at the local level with provincial governments creating incentives that help to build up the solar water heater industry in certain provinces, although they are fragmented and uncoordinated initiatives [50]. Nonetheless, SWH installations and sales have increased rapidly in recent years, particularly in rural areas and smaller towns [1,52].

Meanwhile, China's central government and its policies continue to focus on large-scale, still-expensive solar installations, fostering large-scale PV projects and CSP plants. The success story of solar water heaters seems detached from the central government approach, following its own localised, bottom-up, decentralised dynamics, fuelled by the demand of tens of millions of households for cheap water heating all over China.

Despite its often untold story, this humble technology is cutting CO_2 emissions and contributes to increasing the share of non-fossil fuels in primary energy consumption, thereby feeding into China's official climate and energy targets and indirectly playing a role it the country's Five Year Plans. Still, this technology and these dynamics are less formally addressed in key policy documents. The unusual expansion of SWH may be a signal that Chinese citizens may be ready for actively pursuing a low carbon transition by making solar their first energy choice.

The ‘hidden champion’ of solar water heaters is flourishing at the provincial level, largely uninfluenced by central government, domestically developed technology, driven by affordable prices and large local demand. Bringing solar water heaters back into China's energy and climate policies, helping to popularise them in urban areas, and including them in official targets could bridge the gap between the large-scale, top-down renewable energy policies relevant to the UNFCCC negotiations and its small-scale, bottom-up, citizen-led approach to solar water heaters that has led to 85 million solar water heaters already installed in China.

While this paper only examines solar energy, similar trends for low carbon transitions can be seen in transport and agriculture, with cheaper, localised, bottom-up approaches such as electric two-wheelers and organic agriculture being favoured over more centrally-supported innovations like electric cars and genetically modified crops [54,56,57]. There are therefore signs that alternative, decentralised, citizen-led, cheaper, bottom-up low carbon transitions can be powerful tools to mitigate climate change in China and beyond.

This discussion needs to be placed in the context of the “new normal”, a term that China's President Xi Jinping introduced to describe the next phase of China's economic growth. While economic growth is currently significantly lower than in recent decades (around 7% in 2014 and 2015, compared to double digits before [4]), China's political elite aims to use this as an opportunity to rebalance the country to diversifying its economy, continuing a more sustainable level of economic growth and distributing the benefits more equally. This is aimed at improving the affluence and well-being of Chinese citizens. For the low carbon economy this may mean that China is likely to invest more in low carbon energy as a way of diversifying its energy portfolio, taking investments away from coal and investing further in renewable energy. This is likely to be accompanied by attempts to distribute the benefits of a transition to a low carbon economy more equally amongst different strata of society, particularly poorer people and provinces, such as China's Western provinces. This initiative has already been started by the new 2015 scheme to add 1.5 GW of solar PV capacity in poorer areas by subsidising solar home systems and similar subsidy schemes such as the 2009 policy “household appliances going to the countryside” which encourages solar water heater purchases in rural areas.

Both SWH and PV come together in the building sector [72], which is manifested in the Chinese government's aim to increase the share of renewable energy in building energy consumption to 12% in 2020. Yet, this target is challenging [73]. While SWH have been taken up by the masses in China, PV remains an expensive and industrial-scale energy technology that is largely shunned by individual consumers. At the industrial-scale however, there is also significant potential for using both solar PV and solar thermal technologies for industrial use in China, for example to generate electricity, provide heating and cooling, process chemicals. It can be used in food, non-metallic, textile, building, chemical industries and the service industry. Solar-powered electricity is already widely used in telecommunication, agricultural, water desalination and building industry to operate lights, pumps, engines, fans, refrigerators and water heaters [74].

6. Conclusion

This paper reviewed pathways towards solar energy in China by examining two different solar energy technologies, namely solar photovoltaic (PV) and solar water heaters. It assessed the status, prospects and politics of China's low carbon transitions in solar energy and how it is associated with different models of innovation. It thereby looked beyond existing technology-focused approaches and rather focussed on socio-political perspectives of innovation.

The paper found two very different approaches to solar energy. Chinese solar PV is predominantly produced for the export market, relies on IP-intensive technology and has received much financial and political support from the central and provincial governments. On the other side, solar water heaters are an indigenous Chinese technology that is found everywhere across China, especially in rural areas. They have developed from grass-roots levels to mass products with very little central government support since their commercialisation. Although being largely absent from recent high-level discussions and policies, solar water heaters could contribute a lot to China's low carbon transitions that are driven at the local level.

With regards to low carbon transitions in solar energy, the solar PV industry and PV policy could benefit from learning how the solar water heater industry grew rapidly and continuously in recent years in the domestic market, how domestic demand was created and how this could be supported and improved in the solar PV sector. The solar water heater sector on the other hand could learn from the solar PV sector how to expand to the export market and how to attract further national-level support and financing. Both technologies come with different sets of barriers, for PV the main inhibiting factor is cost. Nevertheless lessons can be learned from both technologies and their politics and practices to increase the chances for larger-scale, successful low carbon transitions in China's energy sector.

Further research in this field should involve fieldwork to identify in which form transitions towards low carbon energy are emerging and what role solar PV and solar hot water heaters play, how potential transitions in solar energy relate to broader processes of decarbonisation, what socio-political changes are emerging in China with implications for changes in the energy system and what lessons China's approach to innovation for low carbon energy provides for other countries' industrial policies. These questions are currently being analysed by the authors through in-depth empirical work in China.

Acknowledgements

The authors would like to thank the UK Economics and Social Research Council ESRC for funding the project “Low carbon innovation in China: Prospects, Politics and Practice”, reference ES/K006002/1. We would like to thank two anonymous reviewers for their helpful comments on an earlier version of this paper.

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