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APPENDIX 2

SOLAR PV IN GERMANY AND CHINA

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Global trends

Installed capacity of solar PV electricity generation and, to a lesser extent, concentrated solar has tripled in the last six years, amounting to a staggering 35% annual growth rate. This growth might be explained by the continued exponential decline in costs of solar PV, as shown in Figure 1[1], which essentially halved over this same period (2015 to 2020) from US$0.117/kWh to US$0.057/kWh.

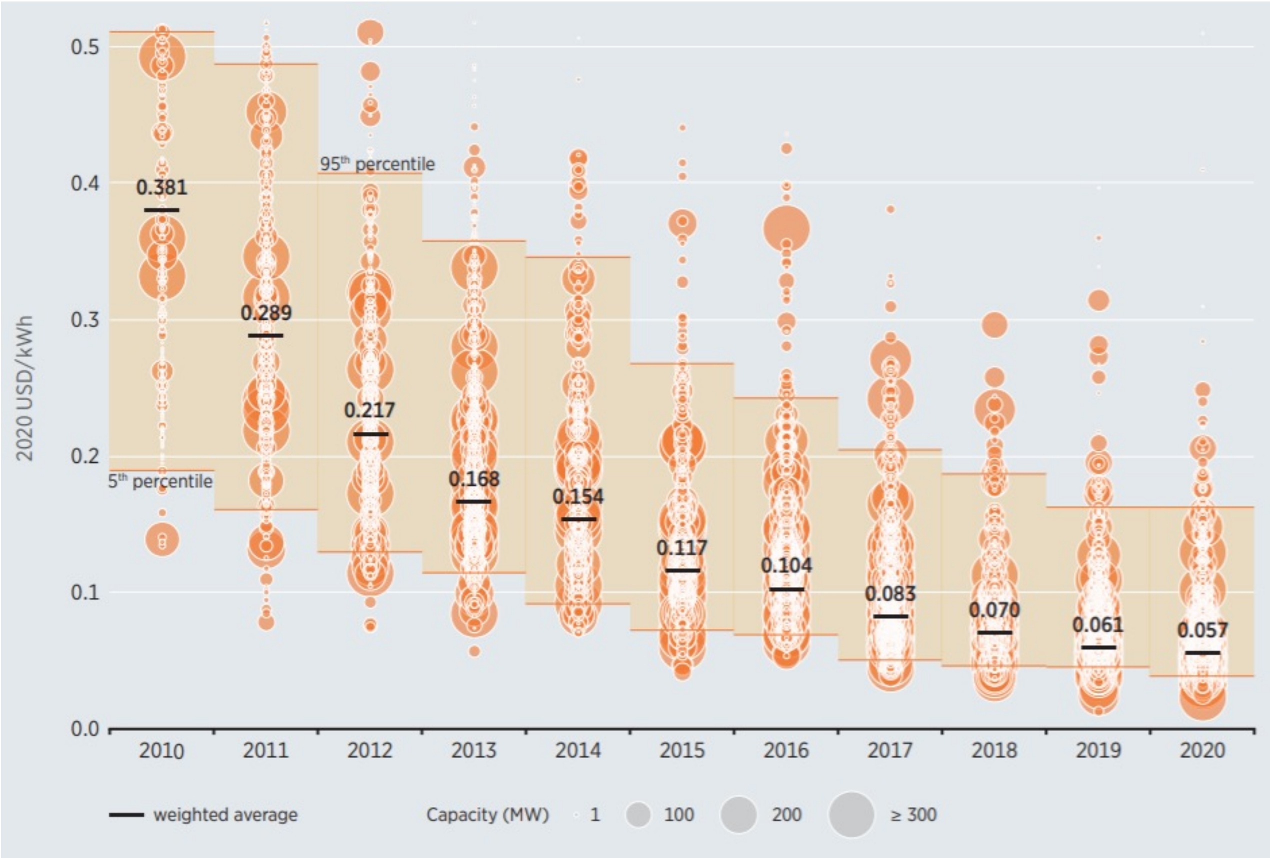

Figure 1 – Levelized cost of electricity (LCOE) and range for global utility-scale solar PV projects, with global weighted average (black line), 2010-2020 (Source: IRENA, 2021a)

Solar and wind capacity has continued to grow at relatively high rates in recent years, together accounting for 90% of the world's new renewable capacity in 2019 and 72% of total capacity additions in 2019 (IRENA 2020).

Even during the COVID-19 pandemic capacity for solar increased from 590 GW in 2019 to 720 GW in 2020 – a leap of 21%. Only 1% of this growth was in concentrated solar, and the majority of solar PV was utility scale.

[1] Levelized cost of electricity is a metric that allows the comparison of the combination of capital costs, operating and maintenance, performance, and fuel costs across energy sources. It applies a discount rate and spreads the total cost of electricity generation over the lifetime of the generating asset and expresses that cost in terms of the amount of electricity generated by the asset over that lifetime. Areas with higher solar intensity will have higher capacity factors and hence lower LCOE per kWh.

The greatest growth in capacity in the last five years has occurred in China, the US, India, Japan, Germany and, most recently, Vietnam. China has deployed more than three times the amount of solar PV than its nearest rival, the US, over the last five years[2]. As shown in Figure 2, it has some of the lowest total installed costs by country. It would seem logical to assume that the levels of installed capacity in each country is related to the relative costs. However, this relationship is quite complicated given that the countries currently with the lowest installed solar PV costs do not necessarily have the best access to solar potential, or irradiance levels. Germany is a particularly good example of this, being ranked 197th in terms of average practical photovoltaic potential[3]. The answer might lie in the history of utility-scale solar PV installations, which essentially were born out of Germany's energy transition or *Energiewende*.

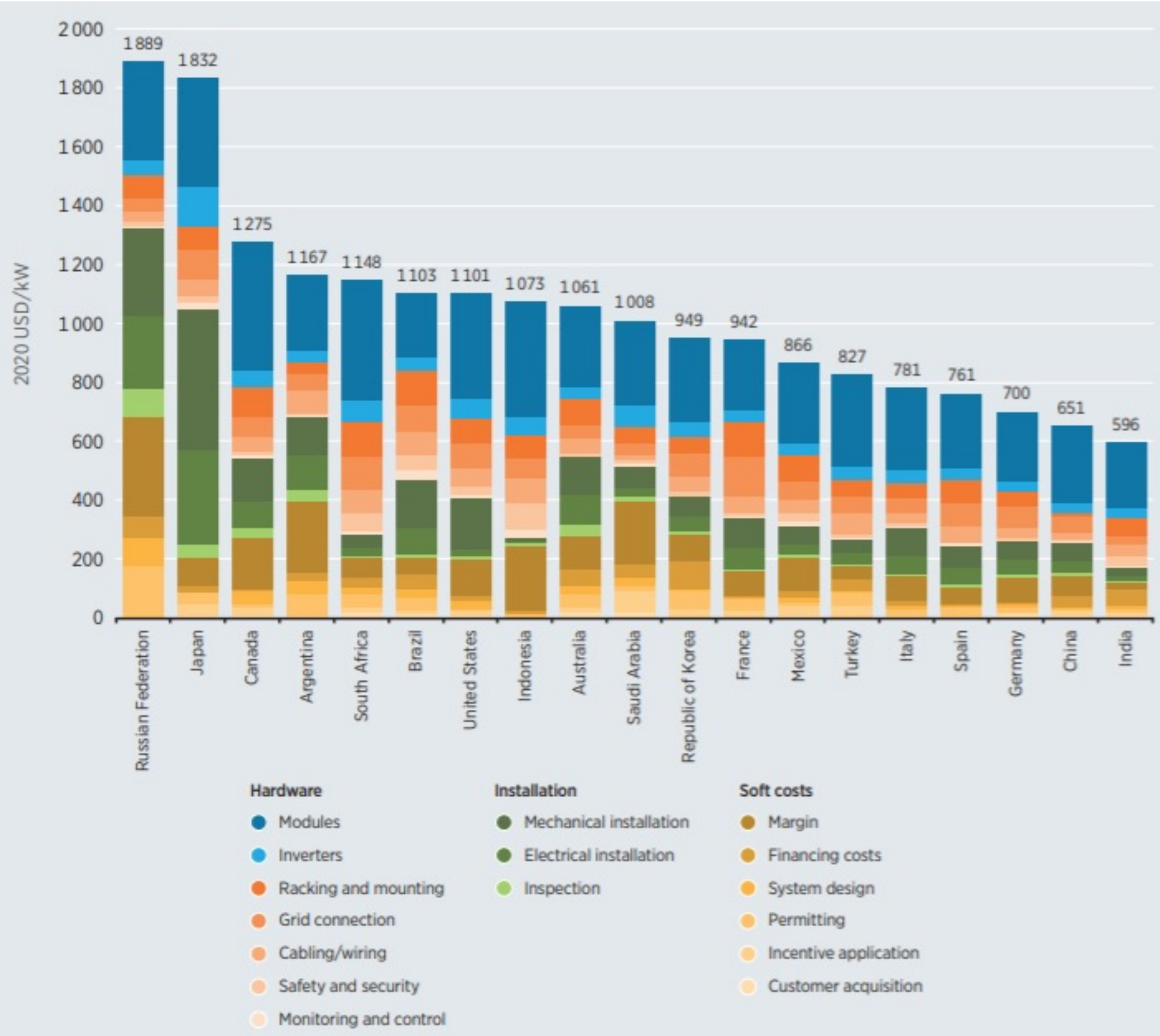

Figure 2 – A detailed breakdown of utility-scale solar PV installed costs by country, 2020. Source: (Source: IRENA, 2021a)

[2] Capacity estimates sourced from IRENA's IRENASTAT Online Data Query Tool, http://pxweb.irena.org/, Accessed 16/12/2021

[3] Source: Global Solar Atlas 2.0, a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalsolaratlas.info

Germany: Jump-starting grid-scale solar PV for the world

Alex Clark, Oxford University

> Germans seem to be proud of the *Energiewende* as a model that the rest of the world can learn from […] [B]ut we're only going to know if it is successful two or three decades from now.
>
> **Dieter Rucht, WZB Berlin Social Science Centre, 2015**

> For projects with low-cost financing that tap high-quality resources, solar PV is now the cheapest source of electricity in history.
>
> **IEA, 2020**

With political roots reaching back to the 1970s and beyond, Germany's '*Energiewende*' – or 'energy transition' – became best known by its current moniker following the Fukushima nuclear disaster in 2011 and the consequent commitment to phase out Germany's remaining nuclear reactors by 2022.

This long-term strategy has evolved to become the driving force behind Germany's political consensus on the transition to a renewable energy-based economic future. Its legislative foundations began in 1991 with generous feed-in tariffs (FiTs) for scaling up solar PV development, followed by priority dispatch for renewable energy sources in 2000, and eventually, the introduction of renewable power auctions in 2014.

The *Energiewende* has been credited not only with demonstrating the political and economic feasibility of building a distributed energy system based on renewable sources, but also with accelerating cost declines for solar PV technologies and bringing forward their mass commercialisation. Ex-post assessments broadly agree that the contribution of these policies to Germany's renewable energy industry has been decisive: renewable contributions to the German power mix rocketed from 6.5% in 2000 to 31.6% in 2015 (Arygyropoulos et al., 2016) and 42.7% in the first quarter of 2021 (Burger, 2021).

While the *Energiewende* has targeted a broad range of technologies, in practice it was largely a solar story from 2000, with a sustained boom in manufacturing and investment supporting 370,000 renewable energy jobs at its peak in 2013 (Pescia et al., 2015). Installed solar capacity in Germany rose from 1 GW in 2004 to 25 GW in 2011 (Buchan, 2012) and 56.4 GW – including biomass – in 2021 (Fraunhofer Institute for Solar Energy Systems, 2021).

Concurrently, the levelized cost of electricity (LCOE) from German solar PV systems reached US$0.03-0.07/kWh (utility scale), US$0.06-0.11/kWh (large rooftops), and US$0.07-0.12 (small rooftops) in 2020 – putting utility-scale solar in the lowest 5 percentile of global costs (Figure 1)[4]. This compares to US$0.11-0.23/kWh for coal, US$0.09-0.15/kWh for combined cycle and US$0.12-0.23/kWh for gas peaking plants, making utility-scale solar Germany's cheapest electricity source on an LCOE basis in 2020. Dispatchable PV-battery combinations are also increasingly competitive, cheaper than all fossil alternatives at the utility scale, and approximately on par with coal and CCGT at small scale (Kost et al., 2021; Kost et al., 2018).

The global average cost of solar PV modules themselves fell from around US$5 per watt in 2000 to US$2 in 2010, US$0.8 in 2015, and US$0.2 in 2020 (International Energy Agency, 2020). Germany, along with the US and Japan, was in a leading role in the industry at least for the first decade of this remarkable trajectory, with the 2000-2013 period being associated with at least a 60% decline in module costs, after which further declines are likely more attributable to a shift in production to Asia (manufacturing costs fell by as much as 30% in the 18 months to early 2012 as production began to relocate to China) (Buchan, 2012).

The political backdrop for the *Energiewende* is a long history of grassroots pro-renewable, anti-fossil and nuclear political activism, which broke into the mainstream at the Green Party's election to the Bundestag in 1983 and resulted in a series of bills, backed by an ever-broadening political constituency and ultimately resulting in the landmark 2010 'Energy Concept' strategy document (BMWi & BMU, 2010) laying out the key principles of what became branded as the *Energiewende*.

[4] Larger, utility-scale installations are generally cheaper per unit than smaller installations, though of course smaller installations may have some other offsetting advantages.

Setting the scene: Germany's socio-technical regime in the 1990s

Germany's energy system has historically been based on centralised coal and nuclear power, which remains largely under the control of four utility companies. The fossil-nuclear regime, under pressure from green politics' rise to prominence, broad popular support for the energy transition, and decentralisation-focused energy policies of the early 1990s, has found its position steadily eroding, overtaken by the rapid rise of renewable energy sources and the gradual 'democratisation of energy'. As of 2010, private citizens and community groups owned 40% of non-hydroelectric renewable capacity, with large companies only owning 13.5% of all renewable capacity, most of which was hydroelectric. Early nuclear phase-out is estimated to have further weakened the large utilities' position, by €100 billion in present value at the time (Buchan, 2012).

Early experimentation with renewable technologies was given new impetus by the 1973 oil crisis. The Green Party's election to the Bundestag in 1983 gave new weight to the anti-nuclear movement, with 1986 marking a turning point for political opposition to nuclear following the Chernobyl disaster and the more forceful introduction of climate concerns into political discourse. This political preoccupation became manifest in the expansion of technology-specific FiTs through the 1990s with the support of the influential Christian Democratic Union (CDU) Party, initially targeting small hydro projects before expanding to other technologies (Hockenos, 2015). A crucial precursor of the *Energiewende* was passed into law in December 1999 as the 'Renewable Energy Act [EEG] 2000'.

The law itself (Deutscher Bundestag, 1999) contained only a brief, qualitative impact assessment, and did not employ formal cost-benefit analysis (CBA) or any form of quantitative ex-ante analysis, which was mostly reserved for large investment projects and seldom introduced formally into the legislative process for policy appraisal purposes. This law paved the way for more legislation, ultimately leading to huge growth in the solar PV industry and a proliferation of small suppliers, complemented by the introduction of EU market liberalisation directives. Updated legislation in 2004 mandated different FiTs for different technologies, raising the renewable energy mix target to 20% by 2010. In 2009, curtailment was permitted to reduce grid congestion, and a 30% by 2020 target was introduced (Arygyropoulos et al., 2016).

Initially, Germany's approach more closely resembled a political and economic risk-opportunity analysis (ROA) than a traditional CBA.[5] The early documents make clear the strategic nature of Germany's renewable energy policymaking, which aimed to increase the short-term share of renewables using FiTs, and reap economies of scale and lower energy costs in the medium and long term. Prior to the introduction of FiTs in 1991, solar PV modules sat at roughly US$8 per watt, four times their cost 20 years later, when PV production began relocating to Asia. At the time, cumulative global solar capacity was negligible, at well below 100 MW across Europe. The prospects for the solar industry as a competitive energy source were deeply uncertain.

As German MP Nina Scheer observed, technology neutrality was a cornerstone of energy policy at the time, with "no master plan but rather a general direction and support scheme with priority access for renewable energies. No one knew in 2000 … that the cost of solar PV would sink so dramatically" (Hockenos, 2015).

Even so, Bundestag discussion documents from February 2000 demonstrate an awareness that significant technological progress had already been achieved, that a self-sustaining market was expected to develop in the long term, and further that Germany had an opportunity at the time to establish itself as a leader in the world market for renewable technologies (Deutscher Bundestag, 2000).

The *Energiewende* emerges: 2010 onwards

The 2010 *Energiewende* 'Energy Concept' inception document (BMWi & BMU, 2010) announced a series of core objectives: renewable energy growth, energy efficiency, competitive energy prices, energy security, climate goals, and medium-term industrial competitiveness (see also Pescia et al. (2015)), with implementation responsibilities divided between the ministries for the economy (BMWi, focused on power supplies and markets) and renewable energy and nuclear safety (BMU) (Buchan, 2012).

[5] For detailed discussion and rationale for Risk-Opportunity Analysis, and some of the inherent limitations of traditional cost-benefit assessment see main report, *The New Economics of Innovation and Transition*, www.eeist.co.uk.

Its foundational assumption was that rising energy demand would raise the long-term price of energy and lead to a deteriorating trade balance unless domestic technological alternatives were developed.

The document states that a radical supply-side transformation was needed to ensure long-term security and value, while also meeting climate goals and tapping potential for national industrial innovation and job creation. Its strategy for doing so is explicitly presented as a roadmap with built-in flexibility and regular opportunities to adapt to circumstances, intending to invest in renewables, efficiency, storage and grid expansion, with nuclear power acting as a bridging technology. As part of the policy process that resulted in the Energy Concept, external experts were commissioned to assess the costs and benefits of a renewable energy-powered future, concluding that the *Energiewende* was justifiable on a CBA basis subject to certain conditions, both within German control (efficient transition management, limiting renewable subsidies, expanding the grid) and beyond it (for instance, global carbon pricing) (Buchan, 2012). Exactly how these scenarios influenced the final policy is not fully clear, although they are presented as scenarios rather than forecasts; as signposts rather than definitive answers to lawmakers' questions.

The Energy Concept's self-proclaimed flexibility was almost immediately put to the test with the Fukushima disaster of 2011. The accident marked a major turning point, leading directly to the decision, with overwhelming parliamentary endorsement, to phase out the nuclear fleet by 2022 – 12 years earlier than planned. The strategic goals of the Energy Concept remained unchanged despite the significant new handicap, and it was decided to compensate for a smaller capacity base through greater grid expansion and investment in storage (Buchan, 2012). Subsequent legislation in 2012 raised the 2020 renewable target to 35%, adding an 80% target by 2050. Amid sharply falling PV prices, a flexible cap was introduced on capacity additions to limit costs to consumers.

From a 2012 vantage point, whether Germany had benefited from its solar PV investment was still uncertain. Germany rivalled China as a manufacturer and was recovering some of its initial investments in solar through technology exports. The subsequent peaking and collapse of domestic solar manufacturing as production moved at scale and speed to Asia, mostly to China, did not deter the implementation of the *Energiewende* agenda, with the energy security, trade balance and emissions benefits all remaining largely intact despite a sharp fall in domestic solar industry employment (Curry, 2019). Notwithstanding the production shift, German engineering firms had built robust comparative advantages and intellectual property value across a range of solar-related technologies from which they were able to benefit (Buchan, 2012).

It appears that the first of several components of an extensive CBA (both retrospective and forward-looking) for the expansion of renewable energy in the electricity and heating market was commissioned in 2010 by the BMU, the closest example of a 'traditional' CBA and a signal that as the *Energiewende* moved into the 2010s, a closer focus on CBA-based policy justification was considered useful (Breitschopf et al., 2010). The analysis explicitly considered distributional and employment effects. The retrospective analysis concludes that, on the basis of system costs, public investment in renewable energy yielded net benefits of €2.1 billion in 2007, and €2 billion in 2008, with benefits assessed solely on the basis of avoided environmental damage, suggesting that under a more complete analysis the policy would have performed even more strongly (Breitschopf et al., 2010).

In 2014, targets were raised again, and capacity additions reprioritised to focus on affordability, beginning a shift towards auctions for utility-scale installations. By 2016, German solar manufacturing was irretrievably below its 2013 peak and the locus of production had definitively settled in China. While insolvencies and firm closures did lead to significant job losses, the solar PV industry still employed 24,000 people in 2018; more than the 21,000 employed in lignite mines and power plants. German manufacturers also held substantial shares of world markets in inverter systems, silicon, silver paste, and PV production systems, and have maintained this strength to the present day (Wirth, 2021).

Notwithstanding this experience, the government approved a 45% increase in research funding towards complementary technologies required to facilitate the integration of solar and wind resources (notably in storage, distributed networks, industrial process efficiency, and hydrogen) in the form of the Kopernikus projects (Curry, 2019). In 2017 legislation, the move to auctions was completed, and medium-term targets introduced for 40-45% renewable energy by 2025, and 55-60% by 2035. By this point, most subsidised capacity additions were for wind (18 GW), comparing to just 2 GW of solar, which was largely expected to be small-scale (Arygyropoulos et al., 2016).

Public support for the *Energiewende* remained high throughout this process, even as energy bill surcharges to pay for renewable subsidies rose from 0.2US¢/kWh in 2000, to 4.1US¢ in 2012, with an expected peak at over 6.8US¢ in 2023 (roughly the same as solar LCOE in Germany today). Even by 2012, however, renewable energy prices were no longer driven by generous FiTs (the cost of which reached 0.5% of GDP in 2010), and had already begun to resemble wholesale electricity prices, with the high cost of subsidies primarily reflecting the high rate of capacity additions rather than high unit costs (Buchan, 2012).

Curry (2019) estimates the *Energiewende* was costing German consumers €25 billion annually, raising concerns that repeating the solar boom-bust experience with batteries and other renewable-enabling technologies may further raise the price tag. Kuittinen and Daniela (2018) observe that the less visible and distributional effects of the *Energiewende* partly explain consistently high public and political support for such an apparently expensive endeavour. This includes the democratisation of energy production, whereby a greater proportion of proceeds from electricity sales flow back into local economies than they otherwise would, potentially mitigating some of the costs and at least temporarily avoiding the likely counterfactual of deindustrialisation.

The *Energiewende* in retrospect, and a counterfactual perspective

While the 2010 Energy Concept 'scenarios' technically involved cost-benefit assessments of the *Energiewende* for Germany and under favourable assumptions would ostensibly have passed them, their influence on the document itself, and the scope and robustness of the analysis, is unclear. By the time the policy was introduced, FiTs had been in place for 20 years, the EEG was a decade old, and significant solar PV cost declines had already been achieved. The net effect this would have had on a CBA is not clear. However, a set of analyses starting in 2010 lay out detailed retrospective and forward-looking CBAs, covering macroeconomic and distributional costs and benefits, including avoided environmental costs, effects on employment, net effect on imports, and effects on the global market for renewable technologies.

It is also not obvious whether CBA played a formal part in the 2000 Act, but evidence from the law itself suggests that it did not. Instead, the initial policy appears to have been backed by a range of strategic judgements that, in policymakers' minds, left Germany with little long-term alternative but to develop alternative energy sources. Seen from this somewhat game-theoretical perspective, the only alternative strategy may have been even riskier: to hope that another country would make the required investments and further that Germany would have access to the resulting technologies at attractive prices and within its desired timeframe.

Even if the initial *Energiewende* decision had been based on a CBA, it would have struggled to accurately capture either the costs (given huge uncertainty on the projected costs of solar PV and other technologies, and the ability of other countries to free ride on potential gains) or the benefits (net trade balance gains from exports would also have been highly uncertain). The CBA conducted from 2010 onwards would probably not, in theory or practice, have accounted for citizens' preferences for avoided deindustrialisation, and potential reductions in price-setting for power by large utilities. It did assess the distributional effects and benefits of power system decentralisation, though the analysis does make clear that the nature of CBA means some of these costs and benefits cannot be directly aggregated, leaving policymakers to judge the relative importance of growth, distributive effects and respect for citizens' (partially) democratically revealed preferences. At the time, a CBA would also have struggled to incorporate climate, biodiversity, and human health impacts and counterfactuals (health and environmental benefits), as well as the effect of technology price declines on German and foreign abatement costs, level of abatement and resulting climate costs. It would also have had difficulty measuring the potential soft power benefits and costs to Germany of leadership on climate issues. Finally, it would have struggled to estimate the climate benefits and potential costs of pollution leakage to citizens of other countries. These practical difficulties would have rendered a CBA of limited use as a clear guide to decision-making.

The German Federal Ministry of Economics and Technology (BMWi) has commissioned a range of ex-post reviews to assess the net benefits of the Energiewende, although each looks at a different angle and the Ministry's integrated report explicitly acknowledges the existence of hard-to-quantify benefits beyond growth and employment (BMWi, 2018). Even with the benefit of hindsight on solar PV cost declines, the results of these evaluations, notably that of the German Council of Economic Experts (2016), are broadly sceptical – suggesting that an ex-ante equivalent, with more modest cost decline expectations, would likely have failed the test.

In any case, as discussed above, the German approach, even in 2000, resembled ROA more closely than CBA in its explicit acknowledgement of uncertainty and openness to adapting policies to accommodate change. The fact these principles have been followed even through Fukushima and the solar industry collapse suggests an implicit judgement that the opportunities outweigh the risks, although it is not obvious from that whether the resulting decisions were made in the interest of the public or for tactical/strategic political gain. The steadfastness of public support in the face of salient costs and less obvious benefits, however, suggests citizens' preferences play a major role.

As Kuittinen and Daniela (2018) note, “What is remarkable about this is that established politics has embarked on this emphatically decentralised path on the basis of a cross-party initiative, possibly without being fully aware of the numerous socially positive implications.”

If a formal ROA had been conducted, it may well have justified what occurred in practice, albeit facing many of the same quantitative challenges also confronted by CBA. Other issues ROA cannot address, being fundamentally a generalisation of CBA unconcerned with equity weighting, include how to value benefits to Germans versus foreign citizens (beyond the knock-on effects of foreign benefits on German citizens), and how to account for citizens' preferences, which the evidence presented here suggests were, and are, central to the argument for initiating and sustaining the Energiewende.

Reflections

The *Energiewende* has played a central role in the story of solar PV technology since at least the turn of the century. The decisions taken to implement both the 2010 Energy Concept and its predecessors do not appear to have been based on CBA in any meaningful way, more closely resembling – in principle, at least – the ROA approach discussed in this report. If an ROA had been formally conducted, it may well have concluded that the *Energiewende* was justified. This does not, however address key equity-weighting and citizen preference issues, both of which if included in such an assessment would likely have only strengthened the case.

Some economists have claimed that the incentivising of renewables was not the most cost-effective means of reducing emissions (Schmalensee 2011) and that Germany was not a good place to pioneer solar, due to its solar resources being much lower than other countries. However, a contrary argument is that a technological and industrial revolution was needed to drive the renewables revolution that has ensued – and that is best driven by a country that has a combination of strong industrial and engineering capability, strong financial capacity (including low interest rates and a good network of local banks supporting local industry/implementing companies) and a clear, stable, and broadly bipartisan directional commitment. In this regard, Germany was uniquely appropriate.

Thanks in no small part to Germany's investments, solar PV has become one of the cheapest sources of electricity on an LCOE basis under certain conditions (IEA, 2020). Over 60% of solar PV capacity additions in 2020 provided cheaper electricity than the most competitive fossil alternative (IRENA, 2021), underpinning and reinforcing the global developments noted in the Introduction. Kost et al. (2021) found that solar PV with battery storage is already cost competitive with fossil options on an LCOE basis in Germany and expect PV-only LCOE to fall further to €0.02-0.035/kWh by 2040.

The development of China's solar PV industry

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Following 20 years of erratic development, the solar PV manufacturing and generation industry in China has become a global leader, contributing significantly to the dramatic decline of solar PV costs and to the progress of low-carbon electrification around the world (Temple 2020), particularly in the past decade. However, the story behind this development and the policies chosen to promote it is complex and deeply linked to Germany's *Energiewende* and the shifts in the international terrain it generated (Annex 2a). It illuminates how strategic choices in response to global shifts took China beyond the recommendations and forecasts of conventional marginal-based analysis methods and towards its position as a global leader in solar PV manufacturing and generation.

China's PV cell manufacturing and solar power generation started in the late 1990s as a solution to the problem of electricity access in remote rural areas. To begin with, the government provided full subsidies to cover the installation and operation costs (e.g., the Brightness Programme, 2001) in order to promote deployment when the cost of PV modules was much higher (over CNY40 per watt compared to just CNY2 per watt today). International cooperation, like the Renewable Energy Development Program (REDP) supported by the Global Environment Facility (GEF), also contributed notably to the initial development of solar PV. By the end of 2003, the cumulative installed capacity of PV cells in China was 55 MW and its manufacturing capacity had reached 10 MW – almost 10 times the country's capacity in 1995.

During this period (1995-2003) the central government was reluctant to invest in an emerging technology. It set up no state-owned enterprises (SOEs) and distributed limited investment to solar generation and manufacturing. However, private capital investors and transnational corporations (e.g., BP, Siemens, Shell) saw the emerging shifts in the international PV market promoted by, among others, Germany's Energiewende, and began injecting investment into China's manufacturing capacity. This led to the establishment of SunTech Ltd, founded in Wuxi, Jiangsu Province in 2003. Together with other companies established at a similar time (e.g., Yingli, Solarfun and Trina), these private entrepreneurs established the first wave of modernised PV manufacturing factories in China.

Due to the continuous expansion of international PV demand, SunTech successfully raised funds through its Initial Public Offering (IPO) on the New York Stock Exchange in 2005, stirring up a big wave of investment into PV manufacturing from the whole country. Much of China viewed the industry as a leading emerging technology and a significant growth opportunity, with favourable conditions and preferential treatment in export markets, with SOEs also competing intensely for funds. The period between 2005 and 2010 saw the exponential growth of PV module production, in which 15 companies successfully collected money through overseas IPOs, taking China to the top-ranked PV module producer in 2008.

However, in contrast to manufacturing, solar power generation in China received little from the PV industry boom before 2009. Although the Renewable Energy Act was passed in 2005 the priority was given to wind power, which was cheaper than solar PV at the time (Zhang et al., 2014). In 2008, the accumulated installed capacity of solar PV was only 300 MW, corresponding to one medium-size coal-fired plant. That means 80% of the PV cells produced in China were exported overseas, with European countries as the main destination. In short, between 2004 and 2008, the development of PV in China was guided by export-oriented policies. This resulted in a "two-end-abroad" dynamic, which meant both technology and market heavily depended on other countries.

The rapid expansion of PV production helped decrease the technology's overall cost globally, but nevertheless, an over-capacity crisis had negative impacts on the development of the PV industry in China. In 2008, the financial crisis caused the decline of overseas demand, which led to severe adverse impacts on China's big, but vulnerable, PV manufacturing industry. Meanwhile, China announced its National Appropriate Mitigation Actions (NAMAs) in the lead up to the Copenhagen Climate Conference of 2009, one of which was to increase the share of non-fossil fuel generation to 15% by 2020. In 2011-2012, trade policy in the United States and Europe also changed dramatically, shifting towards 'antidumping' and 'anti-subsidy' policies. All these factors triggered a pivot shift in China's PV policy in order to advance its industry's place in the world economy.

The development of domestic PV power generation therefore began in earnest in 2009. Two concession bidding programmes for large-scale PV stations were opened in 2009 and 2010, and the Golden Sun Demonstration Project was initiated in 2009. Although the reaction to these initiatives was mixed, the opportunities they created should not be overlooked. In 2011 the concession bidding programmes had established a benchmark price for on-grid solar PV, and the government set an FiT accordingly to secure the revenue of generators against future price uncertainty. The Golden Sun Demonstration Project, in which subsidies were based on installed capacity rather than power generated, stimulated a rapid expansion of both on-grid and off-grid PV projects. It had offered 50% installation subsidies for grid-connected PV systems, and 70% installation subsidies for rural independent systems, which acted as a significant draw for investment from both the public and private sector. By the end of 2012, the installed PV generation capacity had reached 6.5 GW (20 times that in 2009) and the cost had dropped to CNY5.5/W for on-grid systems, and CNY7/W for off-grid systems – significantly cheaper than the CNY40/W in 2001 (Lo, 2014).

In 2011, the FiTs for solar PV power were set uniformly across the country, ensuring sustained and consistent market incentives. After that, the prices were adjusted regularly to take account of the diverse and variable solar resources and the technology's rapidly reducing cost, as well as the heavy up-front financial burden introduced by the FiT system. Besides the FiTs, other policy instruments also contributed to the fast growth in the PV generation industry. For example, a renewable electricity surcharge started in 2006 and evolved throughout the same period; a green electricity certification was implemented; and a regional target-responsibility scheme was also developed.

Further rapid expansion in PV capacity and manufacturing followed from 2013, when the report *Opinions on Encouraging the Healthy Development of the Solar Photovoltaic Industry* was released by the State Council – a trend which has continued. Almost a hundred favourable policies and sectoral regulations from various state authorities were put in place, covering all aspects of the PV industry (module manufacturing, market expansion, tax, pricing, subsidies, land management, etc). Among these, the mission (or goal)-oriented planning system played an important role (Zhao et al. 2020). The 12th Five Year Plan (FYP), for the period of 2011-2015 initially had a solar PV power generation development target of only 5 GW. However, this was revised upwards to 10, 15 and finally 21 GW – an unusual development as the FYP is usually locked in. In reality, the ultimate target was 40 GW. Although this was not announced formally, it was discussed intensely (e.g. CSP Plaza, 2013). By the end of 2015, the overall capacity had reached 43 GW, placing China top in the world in both manufacturing and generation. The 13th FYP then set an initial target of 110 GW for 2016-2020, which was even more significantly overachieved, with the sector eventually more than doubling that figure, at 253 GW (on-grid).

Reflections

That the reduction in the subsidies provided through FiTs has since been accelerated reflects the substantial competitive progress of the country's solar power market, as well the strong political will. In addition, China's manufacturers have used automation and other innovations to make photovoltaic modules cheaper. These systemic shifts have brought solar PV to the forefront of China's energy system. Not only has PV generation become one of the most important technologies for the low-carbon transition, but it has also been widely implemented in rural development programmes to alleviate poverty (Geall et al., 2018) and is used in resource-exhausted cities to enable land reuse.

Thus, PV's climb was international in its scope, stimulated as it was by the European market and international finance to start with, but has been very much centred on China. The gains in China's manufacturing expertise may yet spill over into other developing countries, with enormous growth in solar taking place in Vietnam and Myanmar, accelerating the global low-carbon energy transition for lower-income countries. The warnings from traditional economic analysis against the use of such substantial subsidies to create the Chinese solar PV dominance, such as over-capacity and eventual losses, have not materialised and the subsidies may very well have already been paid back through energy cost declines and the creation of a new industry that has benefited China both domestically and globally.

Solar energy and the global energy transition: recent lessons and future prospects

The initial discovery of selenium's ability to convert light into an electric current was in the 1860s, but it wasn't until the 1950s that Bell Laboratories in the US managed to turn solar PV modules into a proven technology. However, the solar cells they developed were so expensive that a homeowner would have had to pay over US$1.4 million to have a sufficiently large array to power the average house (Perlin, 1999). The rise of photovoltaics from this far distant point is an interesting case study of sensitive intervention points (Farmer et al. 2019), each contributing to the exponential rise in global PV capacity and fall in costs over the last 70 years. From the 'space race' between the US and Russia, via various niche markets including offshore oil rigs and remote locations, novel applications in small electronics, and eventually significant investments in the USA, Japan, and Australia (Perlin, 1999), we finally got to the *Energiewende* in Germany at the turn of the century. This bold policy programme provided the world with its first national-scale investment in utility solar PV, and the necessary assurances of global market demand to incentivise major new PV manufacturers, specifically in China, to enter the market with aggressive pricing strategies supported by healthy manufacturing subsidies. The economies of scale and learning achieved have resulted in PV prices falling a staggering 85% (IRENA 2021).

The role of these two economic giants in the solar story does not appear to be over[6]. Despite possessing a comparatively low solar intensity[7], both countries have capitalised on their technological, manufacturing, labour, or finance advantages, as well as political will, to reach ambitious renewable energy goals.

Although the solar intensity in these two countries is comparatively low, solar still represents their largest renewable resource in pure physical terms, and so for such countries solar has absolutely made sense given the goals they established and the technological, manufacturing, labour, or financial advantages they possessed. A fact that could apply to many other countries, regardless of whether they are particularly sunny.

Furthermore, China and Germany now have some of the lowest solar installation costs in the world, demonstrating the clear gains available to countries through learning-by-doing (Farmer & Lafond 2016, Way et al. 2021). This applies for more local cost components such as policy design, system design, installation, maintenance, and finance, but also in terms of exports, with China and Germany also ranked 1st and 2nd in exports of renewable energy related products[8]. With both also enjoying high rankings in green exports in general (Mealy and Teytelboym 2020), they appear to have strategically gained leading positions in what appears to be a strong and rapidly growing global green market.

[6] In the last five years (2016-2020) China funded the largest share of growth in installed capacity of solar, deploying some 177 GW, which is three times its nearest rival, the US. Germany also still ranks seventh in solar investment over this time, with installed capacity of 13 GW - 20 times its capacity additions of fossil fuels. Sources: IRENA's IRENASTAT Online Data Query Tool, http://pxweb.irena.org/, Accessed 16/12/2021
[7] China and Germany are ranked 161st and 197th of all countries in terms of average practical solar potential. Source: Global Solar Atlas 2.0, a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalsolaratlas.info
[8] Green Transition Navigator, www.green-transition-navigator.org, accessed 16/12/2021

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