

BOOK REVIEWS

How Solar Energy Became Cheap: A Model for Low-Carbon Innovation, by Gregory F. Nemet (Routledge, 2019). 260 pages, ISBN13: 978-0367136598.

The precipitous and persistent declines in solar photovoltaic (PV) costs have been one of the most notable developments in the energy landscape. Now one of the cheapest ways to generate electricity, solar's costs have fallen from \$300,000/MWh in its first commercial use in 1957 to about \$20/MWh today. Almost as remarkable as solar's technological success are the failures to forecast the pace and extent of these developments over the last decade. For instance, prices for solar contracts signed in 2017 are already below optimistic expert forecasts for 2030 in elicitations conducted between 2008 and 2015, which illustrates not only the tendency to overestimate solar costs but also the limits of forecasting (Reed, et al., 2019; Creutzig, et al., 2017; Craig, et al., 2002).

Despite these striking trends, questions about how solar became inexpensive have remained largely unanswered. There has been disagreement about the relative importance of scale economies, learning-by-doing, policy support, and R&D in cost declines. Since solar is only 1–2% of global electricity supply, understanding the drivers of its historical development could shed light on solar's future. These lessons could also help to direct and accelerate the technological progress of other low-carbon options, because addressing climate change requires significant transformations in the energy system.

Gregory F. Nemet's book *How Solar Energy Became Cheap: A Model for Low-Carbon Innovation* provides a comprehensive assessment of solar's cost declines and synthesizes a wide range of scholarship. The book aims not only to provide an answer to how solar became inexpensive but also to explain why it took so long and how PV could serve as a model for other technologies. The research is based on over 70 personal interviews and quantitative work in peer-reviewed publications by Nemet and others. Familiarity with this literature is not required for readers of the book, but the additional detail complements Nemet's summaries and the well-referenced text points motivated readers to further material.

The book's core argument is that inexpensive solar evolved from a "...sequence of disparate activities over the past 70 years that involved strong global links, important local activities, and the participation of multiple governments, firms, and influential individuals. It included both technology-push and demand-pull policy instruments. Diverse national systems of innovation complemented each other, sometimes concurrently but mostly sequentially" (p. 17). Nemet demonstrates how solar's technological frontier moved through incremental improvements in efficiency, manufacturing, supply chains, and automation with feedbacks between stages of innovation rather than through breakthroughs. Solar's flexible scale, i.e., its capability of being deployed in 100s of MW projects as well as wristwatch cells less than one watt, kept the industry afloat during lean times by allowing it to expand into niche markets such as space applications, consumer electronics, military, and offshore oil rigs. Nemet shows that the relative importance of economies of scale, learning-by-doing, and R&D have shifted over time, which suggests that tidy narratives about prospective technological change should likely be viewed with skepticism. Given how prevailing discourse often emphasizes learning from experience as the primary mechanism of technical change for wind and solar, the book could emphasize more strongly that the empirical literature—including the seminal Nemet (2006) paper—complicates this picture. Applying simple learning-by-doing extrapolations for other technologies would be to learn the wrong lesson from solar's experience.

Nemet organizes the book into four parts that follow the timeline of solar's development and deployment, and individual chapters trace the knowledge flows and learning in particular countries. This structure reflects the book's theoretical framework of national innovation systems to geo-

graphically bound the analysis while also highlighting global linkages. The first section (“Creating a Technology”) follows the scientific underpinnings of PV and early efforts to demonstrate and deploy the technology in the United States. The second section (“Building a Market”) describes Japanese electronic conglomerates’ forays into niche PV markets and government activities like the first major rooftop subsidy program with a declining rebate schedule. A second chapter in the section details Germany’s feed-in tariff that invested over \$200 billion to encourage deployment and catalyzed the development of PV-specific production equipment to automate manufacturing and lower costs globally. The third section (“Making It Cheap”) describes China’s massive scaling of PV production and installations in the past two decades and focuses on the pioneering company Suntech and its founder Shi Zhengrong. A second chapter in Part 3 centers on local learning and soft cost reductions in the 2010s. The fourth section (“Doing It Again”) looks at how the drivers of success for PV could accelerate innovation for analogous technologies (with examples of direct air capture and small modular reactors) that could scale to “gigatons worth of removal or of avoided emissions” (p. 190).

One theme that emerges is that solar’s success has been propelled both by intentional efforts and by happenstance. In addition to government support and entrepreneurial efforts, “serendipity also affected progress, including chance visits as well as the co-evolution of the semi-conductor industry and the spillovers to PV it provided” (p. 212). Nemet emphasizes that there is “nothing inevitable about the rapid development and widespread adoption” (p. 213) of technologies like PV, which is simultaneously a sober reflection on the many chance events that sustained PV as well as a reminder of what is possible with purposeful policy and investments over many years.

Another recurring motif is the importance of global mobility on innovation. Booms and busts characterize solar’s history, and the volatility of each country’s interest in supporting PV research, production, and deployment as they ceded leadership provide cautionary tales about the political economy of innovation, even for technologies with significant public support. However, the public and private knowledge generated by PV investments flowed across countries and firms, and global dissemination of “ideas, people, and goods enabled countries to focus on parts of the PV value chain that were most competitive” (p. 187) and continued solar’s development momentum. For instance, Chinese entrepreneurs like Shi Zhengrong brought their training and expert networks from Australia to scale up lower-cost production quickly using elite technology, which allowed them to serve expanding demand in German markets in the 2000s and to produce 70% of the world’s PV by 2017.

How Solar Energy Became Cheap is filled with important research that will make it essential reading for many energy professionals. The book offers concrete insights for economists and policy analysts in particular. For instance, solar presents a stark case study of the gap between static and dynamic policy assessment (i.e., where a static analysis would undervalue innovation) but also underscores how poor track records of long-run forecasting complicates prospective analysis. However, the book largely omits guidance on how governments and investors should navigate tradeoffs and allocate scarce resources, including political capital, across portfolios of potentially promising technologies in different stages of development (not to mention other social objectives). Solar’s circuitous development trajectory and systematic underestimation serve as reminders to the energy modeling community of the importance of transparency, extensive sensitivity analysis, and robust decision making under deep uncertainty with diverse preferences.

The book provides a useful starting point for thinking about how solar could be a guide for other low-carbon technologies. The country-specific case studies suggest that policy innovation and diffusion are nearly as important as their technological counterparts. Although the book quite rightly advises the use of proven ideas from two decades’ worth of policy experimentation across jurisdictions (e.g., research funding, tax credits, feed-in tariffs, portfolio standards), the large menu of policy choices and technologies asking for support combined with diverse stakeholder interests make it difficult to determine *ex ante* which strategies to pursue across different timeframes. Some of the recommendations might also be sharpened by applying lessons not only from innovation suc-

cess stories like solar, where selection bias could limit the generalizability of insights, but also from research efforts with more mixed outcomes (e.g., *The Technology Pork Barrel* by Cohen and Noll is a useful counterpart). On the whole, the chapters on accelerating innovation give a valuable summary of best practices but also illustrate the sizable gap between current actions and future needs at national and global levels. On one hand, it is encouraging to see so many opportunities, but on the other, it is an unpromising signal of disengagement that the provision of high-value public goods (e.g., R&D for low-carbon technologies) is not being sufficiently pursued, which raises questions about the institutional capacity to manage future scale ups.

This backdrop makes Nemet's book a timely contribution distilling extensive research into a well-organized narrative that a range of audiences should hear and heed. With so many causes for concern about the rate of progress in addressing issues like climate change and energy access in light of their scale and urgency, it is helpful to be reminded of reasons for optimism, and the cost and performance progress of PV are encouraging.

John Bistline
Electric Power Research Institute

REFERENCES

- Cohen, L. and R. Noll (1991). *The Technology Pork Barrel*, Brookings Institution Press (Washington, DC).
- Craig, P., A. Gadgil, and J. Koomey (2002). "What Can History Teach Us? A Retrospective Examination of Long-Term Energy Forecasts for the United States." *Annual Review of Energy and the Environment* 27: 83–118. <https://doi.org/10.1146/annurev.energy.27.122001.083425>.
- Creutzig, F., P. Agoston, J.C. Goldschmidt, G. Luderer, G. Nemet, and R. Pietzcker (2017). "The Underestimated Potential of Solar Energy to Mitigate Climate Change." *Nature Energy* 2: 17140. <https://doi.org/10.1038/nenergy.2017.140>.
- Nemet, G. (2006). "Beyond the Learning Curve: Factors Influencing Cost Reductions in Photovoltaics," *Energy Policy* 34(17): 3218–3232. <https://doi.org/10.1016/j.enpol.2005.06.020>.
- Reed, A., S. Ericson, M. Bazilian, J. Logan, K. Doran, and C. Nelder (2019). "Interrogating Uncertainty in Energy Forecasts: The Case of the Shale Gas Boom." *Energy Transitions* 1–11. <https://doi.org/10.1007/s41825-019-00015-9>.

* * *

Policy, Regulation, and Innovation in China's Electricity and Telecom Industries, edited by Loren Brandt and Thomas G. Rawski (Cambridge University Press, 2019) 529 pages. ISBN13: 978-1108480994.

Since China's electricity system is the largest in the world, by far, this edited volume is a great read for anyone interested in the electricity system in China. In spite of its title, of the nine chapters that follow the introduction no less than seven discuss energy. The other two—on telecoms and semiconductors—contain much of interest to the energy economist. It is written by a well-qualified team of authors.

One of the main themes of the book is the contrasts that Chinese policy gives rise to: excellence and failure. China is both to be feared for the awesome scale at which success is possible when it gets things right and to be pitied for its apparent inability to replicate the open competitive ecosystems that require market based liberal democracies to flourish. Thus, China leads the world in ultra-high voltage (UHV) power grid design and building, but in spite of decades of effort has struggled to make much headway on semi-conductors.

Chapter 1 (by Brandt and Rawski, the editors) sets the scene looking at the policy, regulation, and innovation in China's electricity and telecoms industries. As they nicely comment 'China's industrial policy is routinely viewed as both ineffectual and threatening, sometimes on the same page' (p.1). They suggest that the book is about: how the upgrading of these two sectors is being promoted; what the regulatory, institutional and structural barriers to upgrading are; what is hap-

pening to productivity; and what the innovation prospects are. A key observation is that in spite of huge progress in catching up, only Huawei (in telecoms) has reached a position of such innovative leadership that it is now suing OECD firms for infringement of its intellectual property. Overall, within the huge increase in R+D in China, expenditure is heavily focused on development, and shows continuing weakness in fundamental research. It also appears that—looking across generation equipment, transmission equipment, wires and cables, telecom equipment, solar materials and equipment, and wind turbines—total factor productivity (TFP) has fallen in recent years. The chapter makes the point that the fall in TFP was largely—apparently—the result of reallocation of output away from incumbents to low productivity entrants, with the suggestion that this is possibly a result of politically motivated favouritism of inefficient public sector entrants.

In Chapter 2 (by Wu) the evolution of electricity and communications regulation is examined. In spite of strong evidence that independent regulation is key to balancing incentives and the public interest in electricity and telecoms, China has not been able to create well-funded independent regulators in these sectors. The story around broadband is particularly well told. China's limitation of access to the global internet, as part of its state censorship, together with weak regulation has resulted in slow *and* expensive internet access. China has therefore failed to rationalise communications and telecoms regulation as has happened in many leading countries. In electricity, State Grid Company of China (SGCC) has been free to pursue an expensive strategy of overinvestment in UHV power grids while having very high industrial electricity prices. This chapter paints a picture where other regulatory objectives—which result in high cost and low quality—prevent the implementation of the sort of pro-competitive, incentive-based regulation that has developed so powerfully in many OECD countries.

Chapter 3 (by Pearson) turns the attention to local government and its role in promoting innovation in the clean energy sector. China's unique structure—which is not federal—has limited the capacity for impact. Local officials are promoted on the basis of delivering central government objectives and have a tenure of 2-3 years. This has limited innovative long term thinking of the sort that has been very beneficial in other parts of the world. Indeed, the chapter offers some good evidence that much local government support for clean energy causes a misdirection of effort and lots of competition for subsidies. One example of this would appear to be electric vehicle (EV) policy, which has led to most EV sales being subsidised local fleet sales, with limited encouragement of the sorts of imported technology which might kick start a private EV ecosystem.

Chapter 4 (by Davidson) goes on to discuss the conflicts between central government policy and the local challenges faced by the electricity system. China is characterised by 'fragmented authoritarianism' with different bits of government competing with each other to take a lead in various policy areas. The recent 2015 reform of the electricity sector to introduce competitive wholesale power markets is discussed. The system has inherent problems to address such as the reform of dispatch of power plants and the reduction of the curtailment rates of renewables. The responses to these problems include decentralisation and the use of mainly provincial wholesale power markets—putting the emphasis on provincial level implementation. The paper nicely discusses how China did successfully develop super-critical coal fired power plants as a centralised effort, but points out that the problem now is how to make them more flexible in the face of the current, more local, challenges.

Chapter 5 (by Thun and Sturgeon) focuses on China's communications sector policy. It points out that while all governments have sought to have some control over their leading communications infrastructure companies, their ability to do this has been compromised by the move towards a global value chain model and global platforms in the sector. This has created a global and interdependent sector. China's attempts to take a separate path in mobile communications with its own technology standard (TD-SCDMA for 3G) largely failed. Instead global—non-Chinese—standards have emerged in mobile platforms. 'The Great Firewall of China' has limited Chinese involvement in global telecommunications platform technology but did help the Chinese firm Tencent to develop

WeChat as a superapp, which if anything is more pervasive than any app seen in the OECD. The chapter discusses whether the expensive attempt to create TD-SCDMA was actually an example of 'successful failure' given its role in helping develop indigenous Chinese firms, such as Huawei, who have gone on to develop leading technology for 5G. However, OECD firms dominate mobile operating systems, processors, modems, memory and integrated circuits for both Apple and Samsung products (and even for Huawei products).

Chapter 6 (by Yi-chong) examines the State Grid Company of China and its rise to global prominence. This chapter gives a very positive account of SGCC and its success (it was the 2nd largest firm by sales in the world recently). The chapter emphasises SGCC's success in open innovation particularly in the area of UHV transmission, which has allowed it to promote a plan for global energy interconnection (powering the whole world via a global supergrid). SGCC argued for a huge expansion in transmission capability, exploiting its position as the advocate for grids, following its separation from generation in 2002. SGCC successfully mobilised its massive R+D to create the technology required for 1000kV+ lines. When Siemens and ABB refused to share R+D output with SGCC, it invested in R+D itself and successfully developed some of the missing technology required for the UHV lines it wished to build. SGCC has expanded into transformer manufacturing and, since 2009, has begun expanding globally. The unanswered question—raised in the chapter—is whether anywhere else in the world will want the UHV lines that SGCC can now deliver.

Chapter 7 (by Fuller) looks at Chinese industrial policy towards the semi-conductor industry. The integrated circuit value chain is divided into design, fabrication and assembly and testing. These are increasingly specialized activities, with design and fabrication requiring significant knowhow. China has basically failed to break through in these parts of the value chain in spite of decades of trying and its firms remain some distance behind the global leaders (such as Qualcomm, Intel and AMD). The reasons for this are partly to do with the use of public firms to supply public sector contracts (e.g. for smart cards), the lack of trust shown towards China by multinational firms worried about copying, and the lack of skilled staff. However, since 2014 more effort has been made to acquire technology directly through purchase of overseas firms, which may eventually see more catch-up than previously.

Chapter 8 (by Rawski) focuses on excess costs in the electricity sector. This chapter presents a wealth of data about the costs in the Chinese electricity sector with some interesting comparisons with the US. Rawski puts a figure of at least 30% on the excess cost in the Chinese electricity sector. The reasons for this are various and there is some fascinating detail on these excess costs. China has five times the total number of workers per kWh as the US. An analysis of managers alone shows that 18% of all electricity employees in China are managers against around 7% for the US. Unit coal rail freight costs are 78% higher in China than in the US, with excess costs as high as 6.2% of the sales value of electricity! A substantial cost reduction is required just to meet comparable rates of return to the US sector.

Chapter 9 (by Brandt and Wang) focusses in on the solar and wind sectors. China has quickly established itself as the world's major manufacturer of solar panels. It did this because of initially low entry barriers and through exploiting its strengths in mass-manufacturing. Over time, it has been able to massively cut costs and expand the efficiency and international competitiveness of supply chains within China. It also successfully responded to the need to meet international performance standards (e.g. 25 year guarantees). The chapter argues that because it was an export oriented market, the industry was able to establish itself quickly by using foreign components where necessary, as these were for re-export. Had the industry been reliant on domestic sales this would not have been so easy, a point they then illustrate with reference to the wind manufacturing sector whose growth has relied on sales within China. Chinese wind turbines appear to be of significantly lower quality compared to their overseas competitors, when looking at their actual output. This is in addition to problems of wind curtailment. An overall lesson is that international collaboration is key to success in a global manufacturing sector.

Chapter 10 (by Madhavan, Rawski, and Tian) looks at capability upgrading and catch up in the Chinese nuclear sector. China is expanding its nuclear power station fleet substantially at a time when the leading nuclear firms of Westinghouse, Toshiba and Areva have all been struggling (to put it mildly!). This chapter discusses the significant progress China has made in civil nuclear power, to the point where its companies—CNNC and CNG—are in a position to expand significantly overseas. The chapter documents how China has embraced international standards and improved its safety culture since Fukushima (in 2011). It has also developed its own reactor technology (CAP1000 and CAP1400) in collaboration with overseas firms, and expanded its domestic nuclear manufacturing capability. However, issues remain: lack of qualified staff, weak regulatory authorities and competing internal reactor designs. It remains to be seen whether China (or anyone else) can capitalise on a nuclear renaissance given the likely weak global demand for reactors. China's own nuclear expansion could itself be derailed by problems arising from weak regulation, lack of media scrutiny, and corruption.

This book is incredibly stimulating and thought provoking. However, I thought it was rather uncritical of conventional economic wisdom and somewhat lacking in advice for Chinese policy makers. I was left wondering at several points how to move beyond 'a just do what we do' conclusion towards something that Chinese policy makers might want to do.

TFP is a controversial measure of performance and only weakly related to income per head. It has been declining or negative in many countries' energy sectors. China's economic success challenges the universal applicability of much textbook economic wisdom (as did Japan and South Korea before it). While China may have plenty of problems, OECD countries hardly have successful energy policies and their telecoms regulation has itself struggled to keep pace with new technology.

Much of the tone of the book seemed rooted in a competitive market driven network industry paradigm that is itself coming under increasing challenge in Europe, not least from regulators concerned with the failures of self-regulation. Rather surprisingly, the book did not consistently discuss the sheer scale of the Chinese home market and the fact that a 'local' market in China is equivalent to a national market in the rest of the world. However, these more critical reflections are prompted by the stimulation this book provided.

*Michael G. Pollitt
Judge Business School
University of Cambridge*