A Model for Clean Energy Innovation

How Corporate Buyers Can Accelerate the Development and Commercialization of Technologies Needed for Net Zero

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Future Requires Innovation + Cost-Competitive Deployment

Key Messages:

- Future: Affordable, Reliable, Resilient, Net Zero GHG Energy with Large-Scale Electrification
- Requires innovation to improve pre-commercial[1] technologies needed to balance wind & solar[2]
- Buying not yet cost-competitive technologies at scale is inadequate & often counterproductive

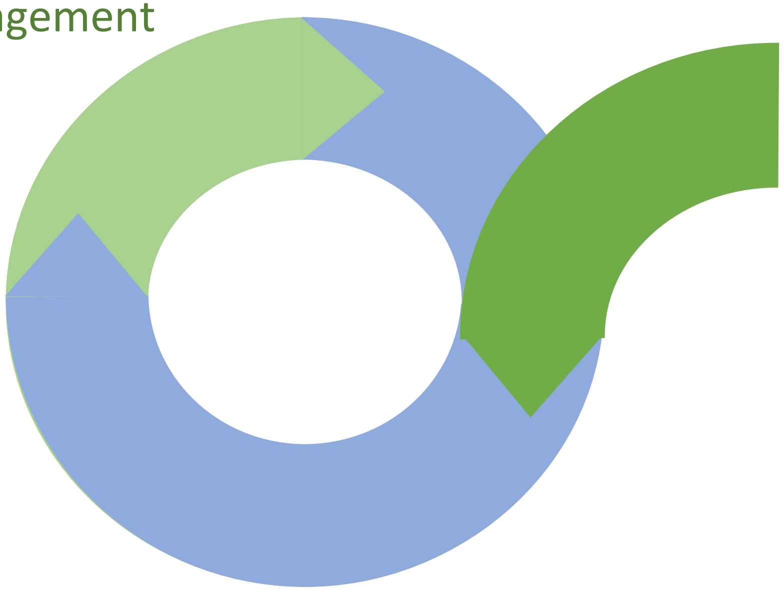
Learning Curves & Model Based Forecasts

- Learning curves are based on past statistical relationships, typically between cumulative deployed capacity and a technology's cost or price, but *are not proof of causation*[3]
  - Time (Moore's Law) explains energy technology cost reductions almost as well as deployment (Wright's Law)[4]
- By omitting variables, learning curves overstate the impact of deployment & Learning by Doing[5]
  - Omitted variable bias occurs if omitted variables have non-zero coefficients & are correlated with modeled variables
  - Most learning curves calculate a progress rate using one variable, cumulative deployment, to explain cost reductions
  - Multi-factor curves may include R&D (that often has a greater impact on costs) &/or a limited set of input costs[6]
- Detailed bottom-up studies often find Learning by Doing plays limited or no role in reducing costs[7]
- Model-based forecasts are projecting a continuation of trends using historical data
  - Given sufficient technology-specific data, probabilistic model-based forecasts tend to outperform expert elicitation[8]

Learning Mechanisms: *Opportunities for Acceleration*

Learning by Doing / Using
- Tacit Knowledge Acquisition
- Organizational Knowledge Management

Learning by Feedback
- Testing
- Demonstrations
- *Advanced Simulation*
- *Sensor Networks*
- *Operational Data Integration*



Learning by Searching
- Basic & Applied Research

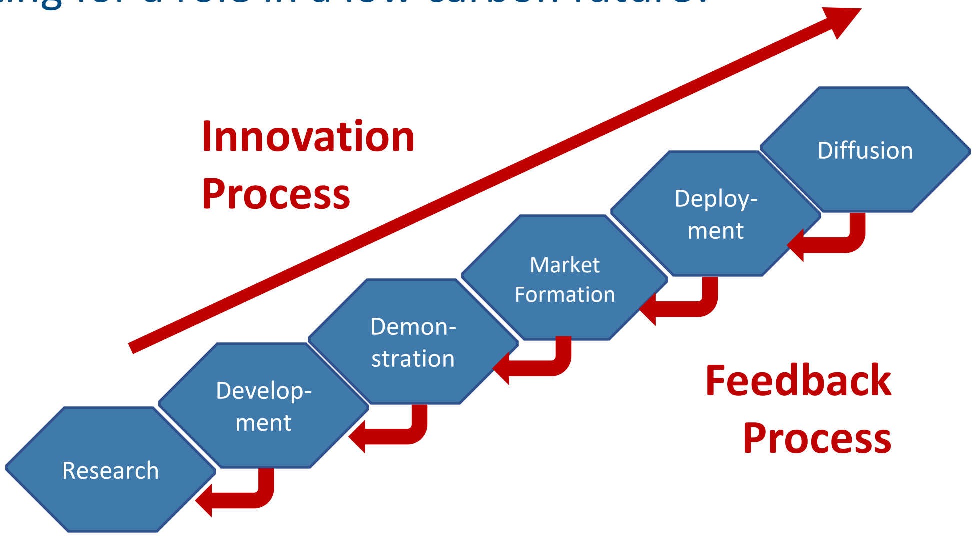
Learning by Interacting
- Clusters
- Alliances
- Imported / Shared IP
- Vertical Integration
- Communities of Practice
- Manufacturing Equipment

Innovation: Primarily by Recombination
- Analysis
- Experimental Design
- *Virtualization*
- *Generative AI*

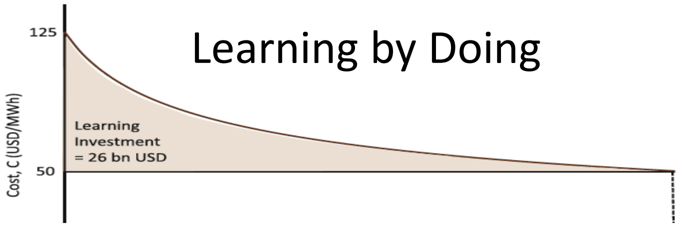
Opportunities for Acceleration:
Advances in Learning by Interacting
Keys to Chinese PV development

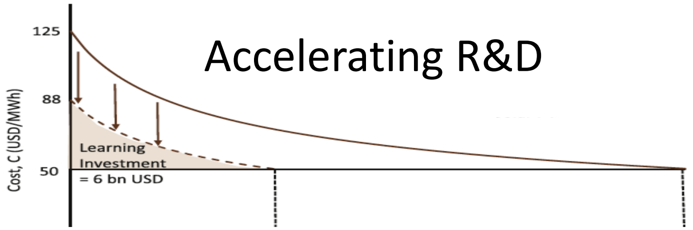
How Best to Accelerate Innovation: Key Questions

- What is the probability of the technology successfully competing for a role in a low carbon future?
- How can buyers help accelerate innovation:
  - Innovation is a product of knowledge discovery, exchange, analysis, learning, and application
  - Acceleration is a function of the tempo at which knowledge cycles through innovation and feedback loops to produce improvement
  - Are opportunities for accelerating the tempo innovation being effectively utilized?
  - Can the tempo increase yet remain consistent with the capabilities of the emerging industry?



- When technologies are not close to being economically competitive, aggressive premature deployment may increase costs and be counterproductive.[9] How can corporates act earlier to accelerate technology development?





Based on: Shayegh et al. 2017

- As technologies become cost-competitive, accelerating deployment may enable economies of scale and reduce costs. However, social and institutional factors, including incumbent opposition, may impede the extent and pace of adoption. How can corporate buyers eliminate barriers and enable deployment of competitive technologies?

Acceleration Potential: Innovation Patterns & Paths

Technology and component characteristics will affect the likely pattern of innovation and the available opportunities for accelerating the tempo of innovation.

Relevant Technology Characteristics	Typical Innovation Patterns	Paths to Accelerating Innovation
Modular – encouraging component innovation, **Granular** – allowing rapid low-cost experimentation, and **Mass-Produced** – enabling economies of scale and knowledge embedded in production equipment, e.g., PV modules, LED lighting	**Rapid:** Innovation occurs through: • Integration of scientific advances in system architecture • Independent component innovation • Supply chain coordination and design standardization • Manufacturing process improvements • Economies of scale enabled by embedding knowledge in production equipment[10]	• Researchers help OEMs apply new science • Supply chain coordinates on standardization • OEMs & engineers help equipment suppliers embody knowledge in equipment design • Operating data provides researchers and OEMS the ability to monitor performance • Installers give OEMs tips to simplify install
Moderately complex standard platforms – Many components, integration of key elements required to enable control. Performance often improved by increasing unit scale, e.g., wind & gas turbines	**Moderate:** Innovations introduced in new models: • Basic design persists, e.g., 3 blade, upwind facing turbine • Integration of component innovations enables upscaling • Standard platform is adapted for varying conditions	• Operating data provides researchers and OEMS the ability to improve and adapt • Developers give OEMs tips on how to simplify deployment & improve operations
Customization of construction or installation – affects cost components and processes for different technologies, e.g., construction of large nuclear, wind farm site work, installation of residential rooftop PV	**Variable:** Differing conditions limit the relevant transferable knowledge and can retard the diffusion of innovation • Equipment can be modified to simplify installation • Workforce Development	• Providing OEMs information on how to simplify adaptation to varying conditions • Knowledge Management: e.g., Communities of practice that share tacit knowledge
High design complexity requiring tight integration of critical components and system level design, e.g., nuclear power, commercial aircraft	**Long:** Innovation introduced in new standard designs: • Significant innovations require lengthy periods of design, testing, and systems integration	• Researchers, engineers, & material scientists contribute to new standard designs • Advanced design tools and test beds
High regulatory complexity – environmental, safety, and other regulatory issues may affect design, deployment, and / or the ability to make changes, e.g., nuclear, potentially hydrogen storage at scale	**Impeded:** Designs & deployment plans subject to detailed regulatory requirements, agency review, and litigation • Designs & deployment plans are completed up front • Regulators may have access to design &/or testing	• Agency staff observation of testing & early regulator consultation on deployment plans • Enhanced consultation with potentially affected communities and stakeholders

Accelerating the Development of Pre-Commercial Technology

- Is the pre-commercial technology (pre-TRL 9) on a path that will enable it to compete successfully for a role in a low carbon future?
- What risks are associated with subsidizing premature deployment?
  - Support may prove to be costly and unsustainable, e.g., CA Wind Rush, early Japanese rooftop PV rebates
  - If the industry supply chain is constrained, rapidly increasing deployment may raise input prices and disrupt markets, e.g., 2008 silicon price spike
  - Subsidized deployment may be counterproductive diverting limited industry talent and resources from more important R&D[13]
  - Early deployment may lock the industry in to an arguably inferior technology, e.g., light water reactors
- Pre-commercial technologies may benefit from:
  - Niche applications that financially support R&D without distorting the developer’s priorities and can be used in testing technological advances
  - Prizes with well defined criteria and timelines that catalyze investment
  - R&D collaborations with established firms that have complementary capabilities, e.g., accelerators, testbeds, join development agreements[12]
  - Advanced purchase or market commitments that include early financial support based on meeting specified conditions and milestones

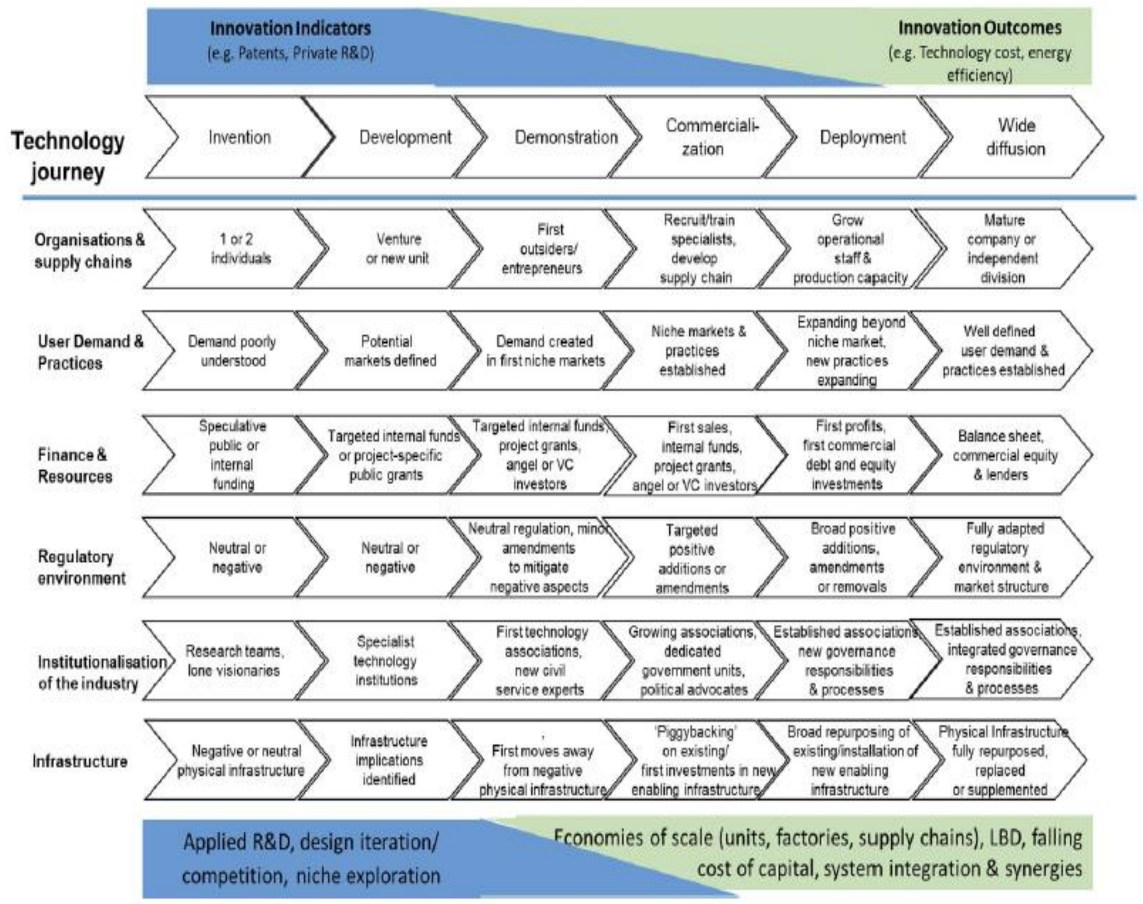
Prize → R&D Collaboration → Purchase Commitment

IEA / Traditional TRL Classification	TRL	Description[11]
Concept / Research	1	Idea: Principles Observed
	2	Application Formulated
	3	Experimental Proof
	4	Validation in Lab Conditions
Large Prototype / Development	5	Components Proven in Relevant Conditions
	6	Full Prototype Proven at Scale
Demonstration	7	Pre-commercial Demonstration
	8	Commercial Demonstration at Scale
Early Adoption / Deployment	9	Commercial Operation in Relevant Conditions
	10	Integration at Scale
Mature / Diffusion	11	Stability & Predictable Growth

Accelerating Deployment: Evaluating Opportunities and Risks

- As a technology achieves commercial operation and starts to become cost-competitive, accelerating deployment may:
  - Create manufacturing & firm level economies of scale
  - Induce entrepreneurs to invest in additional R&D
  - Reduce financing costs by attracting new investors and demonstrating a track record of performance[14]
- Paying a premium requires buyers to assume risks and costs that the technology's investors would assume in an efficient market
- Larger investments involve greater risk:
  - Market dynamics may change the relative advantages of different technologies, e.g., costs associated with efforts to onshore clean energy supply chains[15]
- Accelerating deployment requires alignment with organizational, user, financial, regulatory, institutional, & infrastructure considerations[16]
  - For example, accelerating siting and permitting

Expanded Innovation Framework



Source: Grubb et al. 2021

Case Studies

Case Study 1: Solar Photovoltaics

- **PV is a modular, granular, mass-produced technology capable of rapid technological and process improvements**
- **For much of its history PV was was a niche technology, too expensive to directly compete in the power generation market**

1954 — **Bell Labs develops PV technology**

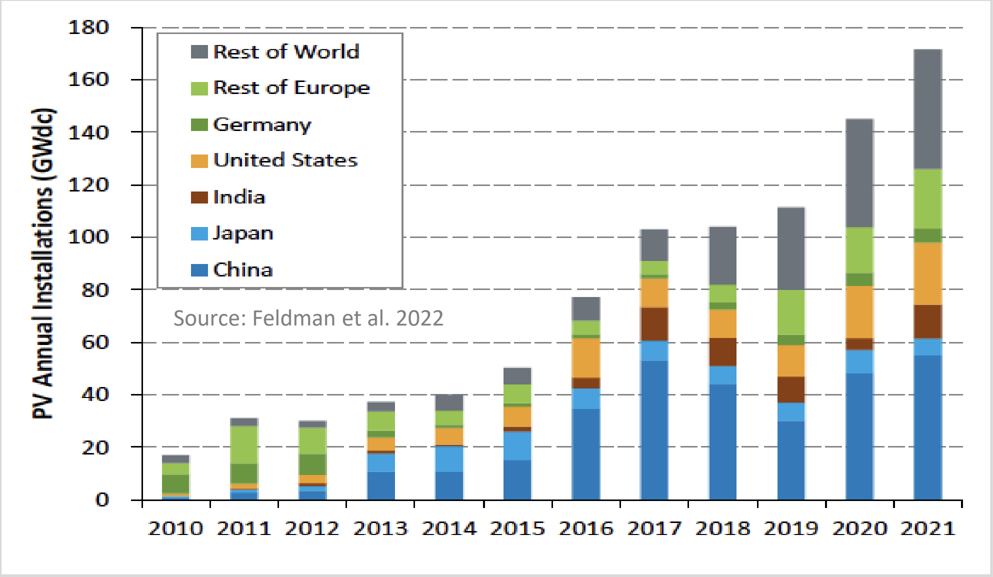
1993 — **Japan launches a million-roof rebate program, which was terminated due to high PV costs having met only 20% of its goal**

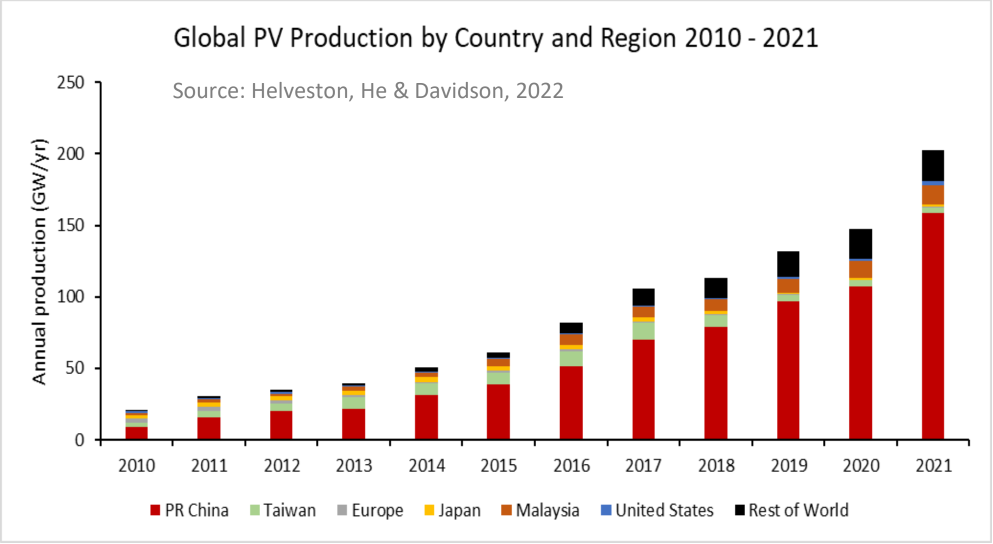
2000 — **Germany begins offering 20-yr. Feed-in-Tariff contracts at nearly 2X electricity prices, leading to:**
  - 30GW PV being installed by 2012, supported by 200 Billion € in subsidies at a direct cost to ratepayers equal to ~1/4 average household electricity prices
  - A rapid increase in demand that produced a 10X spike in silicon prices and major losses for German and Japanese PV companies

2010s — **Manufacturing moves to China, costs decline >15%/yr. on average**
  - In the 1990s, Chinese firms imported technical expertise, equipment, and western capital and were prepared for the growth in the European market
  - Since 2010, Chinese manufacturers have reduced costs with the implementation of a series of advances in crystalline silicon technology and the sharing of knowledge across a cluster of vertically integrated companies
  - Today Chinese companies have over an 80% market share at each stage of the PV production process, which has raised concerns in the US and EU

- **Learning by Doing had little if any impact on PV costs**
  - **Detailed bottom-up studies found Learning by Doing did not have a significant effect on costs, once other factors were taken into account**

PV Capacity Additions by Country





Case Study 2: Onshore Wind

- **Wind turbines are a moderately complex technology with many components and a significant level of design integration – design changes generally require engineering a new turbine platform**
- **Deployment has not always correlated with decreasing costs. Instead, specific technological factors and exogenous economic conditions seem to be the main driver**

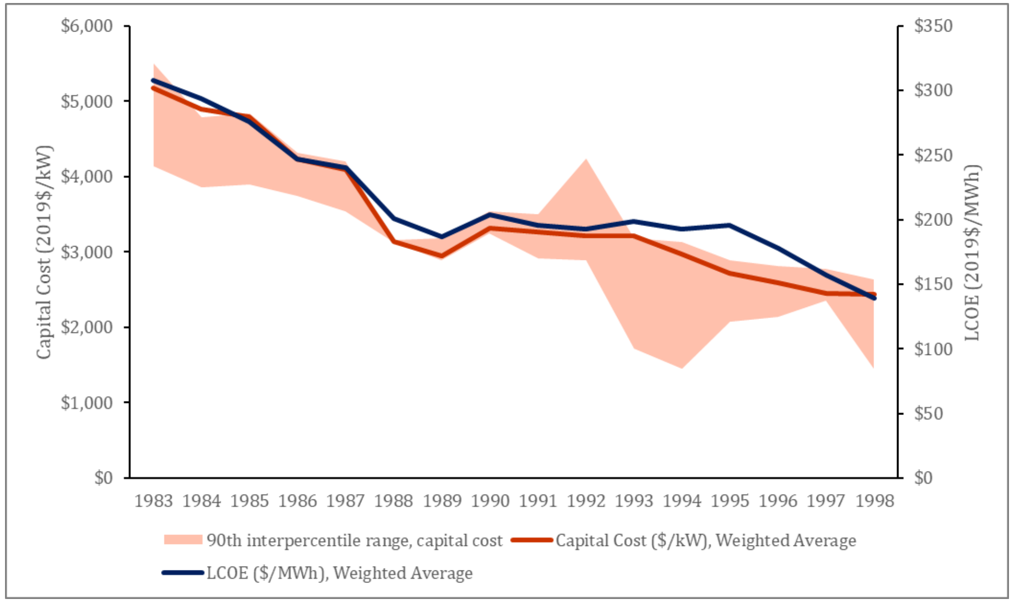
1980s Early deployment in the 1980s, supported by government programs such as California's standard offer contracts, gave wind turbine manufacturers the resources to improve components, rapidly scale up turbine size, and build efficient supply chains, reducing capital costs and LCOE through the 1980s and early 1990s

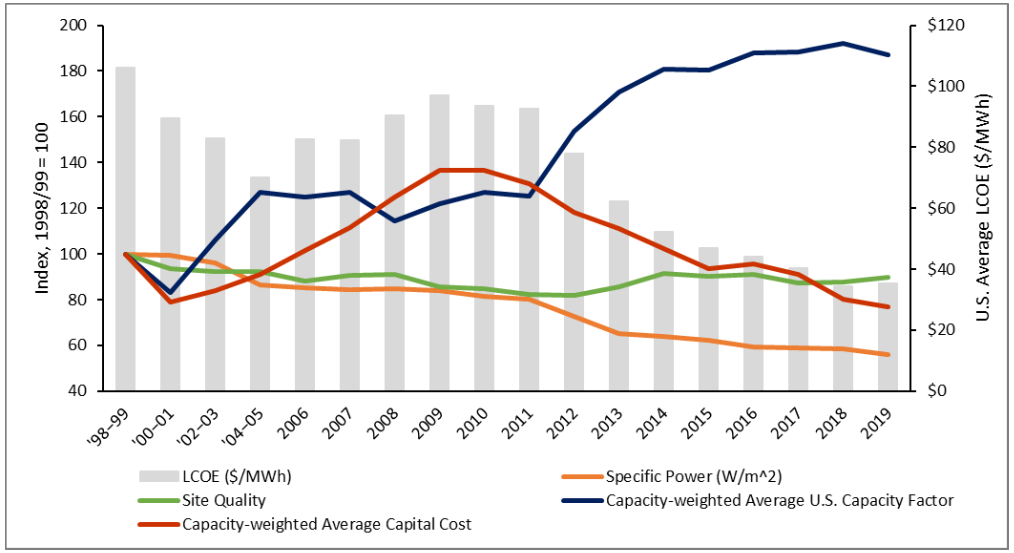
Supply-side subsidies and market economics spurred an increase in global wind capacity from 7.6 GW in 1997 to 58 GW in 2005. LCOE dropped – driven primarily by increased capacity factors – but capital costs per kW did not decline

Annual additions to wind capacity grew rapidly from 2005 to 2009. LCOE and capital costs per kW rose despite the rapid deployment. High demand stressed supply chains, and exogenous economic factors such as currency movements and high commodity prices increased costs. Technological progress and growth in turbine size stagnated

2010s Since 2012, renewed growth in turbine size and advanced nacelle technology has dropped LCOE to record lows, mostly due to higher capacity factors. However, average LCOE has stabilized in recent years and the future direction of technological progress is not clear

- **Corporate procurement of renewable generation did not begin in earnest until the late 2010s, after LCOE had already dropped to levels competitive with other forms of power generation**

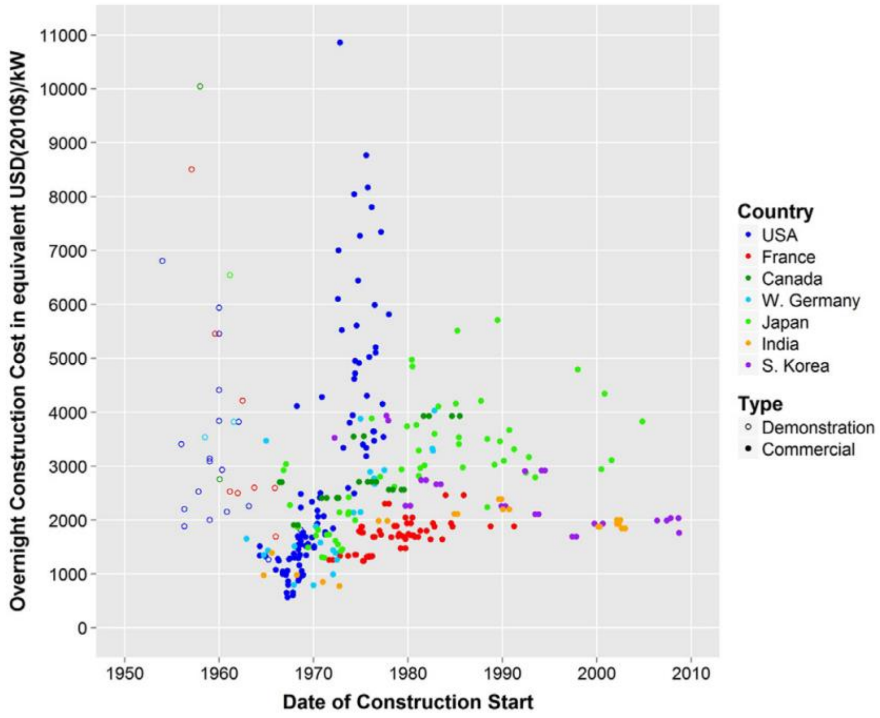




Case Study 3: Nuclear Fission Reactors

- **Highly complex technology, not manufactured – constructed on-site over multiple years, subject to significant regulatory oversight**
  - High design complexity, requiring tight integration of critical components, increases implementation risk (e.g., construction delays)
  - Site customization and long construction time limits transferable knowledge and ability to iterate
  - Need for regulatory approval of new designs impedes innovation
- **Deployment has not brought down costs**
  - Costs have varied by country and time period but have generally ***increased*** over time as more reactors have been deployed
    - The U.S. experienced rapid cost escalation beginning in the mid- to late-1960s
    - Most other countries with large reactor fleets, including France, experienced more moderate cost increases than the U.S.
    - Under "best case" conditions (i.e., a single utility building a standardized design) South Korea achieved modest cost declines – but recently adopted a new design, doubling construction time and likely resulting in increased costs compared to historical levels
  - Events at Three Mile Island, Chernobyl, and Fukushima impacted construction starts on new reactors and early retirements but do not fully explain cost increases
  - Cost increases stem from the inherent difficulty of executing an extremely complex infrastructure project and added requirements imposed to ensure safe operation of the plant
  - (Extremely) high capital costs and long construction durations make projects sensitive to construction delays and susceptible to cost overruns
- **Advanced nuclear reactor designs, including SMRs, represent an attempt to control costs and risk but are unproven in practice and remain subject to rigid regulatory oversight**

Source: Lovering et al. 2016



*Overnight Construction Cost includes costs related to design/engineering, licensing, procurement, and construction but does not include the costs to finance the project. The total cost of constructing a nuclear reactor will also depend on the financing terms and construction time; as construction duration increases, interest can add a significant amount to the total cost of the project.

References

1. International Energy Agency. (2020). Energy Technology Perspectives: Special Report on Clean Energy Innovation. IEA. Retrieved from https://www.iea.org/reports/clean-energy-innovation. Shifting to the IEA 'sustainable path" requires that 35% of cumulative CO_2 reductions come from prototype or demonstration stage technologies and an additional 40% from technologies that are not widely deployed.
2. Davis, S., N. Lewis, and M. Shaner. 2018. Net Zero Emission Systems, *Science* 360, 1419 (Jun2 2018).
3. Grubb, M., P. Drummond, A. Poncia, W. McDowall, D. Popp, S. Samadi, C. Penasco, K. Gillingham, S. Smulders, M. Glachant, G. Hassall, E. Mizumo, E. Rubin, A. Dechezleprêtre, and G. Pavan. 2021. Induced innovation in energy technologies and systems: a review of evidence and potential implications for CO_2 mitigation, *Environmental Research Letters* 16, 403007.
4. Meng, J., R. Way, E. Verdolini, and L. Diaz Anadon. *(2021).* Comparing expert elicitation and model-based probabilistic technology cost forecasts for the energy transition. *Proceedings of the National Academy of Sciences*, 118(27); See also: Nagy, B., J. Farmer, Q. Bui, and J. Trancik. (2012) Statistical Basis for Predicting Technological Progress. PLoS ONE. 8(2); and Lafond, F., A. Bailey, J. Bakker, D. Rebois, R. Zadourian, P. McSharry, and J. Farmer. (2017). How well do experience curves predict technological progress? A method for making distributional forecasts. *Technological Forecasting and Social Change.* 128, 104-107. Time related improvement would likely be insufficient to achieve emission reduction objectives. Compare: PV cells were first developed in 1954. Wind has been used in power generation since the 19th century, and 3-blade upwind turbines have been used since the late 1970s.
5. Samadi, S. (2018). The experience curve theory and its application in the field of electricity generation technologies. *Renewable & Sustainable Energy Reviews*.
6. National Academy of Sciences, Engineering, and Medicine. (2016). *The Power of Change: Innovation for Development and Deployment of Increasingly Clean Electric Power Technologies;* Jamasb, T. (2007). Technical Change Theory and Learning Curves: Patterns of Progress in Electricity Generation Technologies. *The Energy Journal, 28*(3), 51-72; Rubin, E. S., Azevedo, I. M., Jaramillo, P., & Yeh, S. (2015). A review of learning rates for electricity supply technologies. *Energy Policy, 86*, 198-218. See also: Zhou, Y. and A. Gu. (2019). Learning Curve Analysis of Wind Power and Photovoltaics Technology in US: Cost Reduction and the Importance of Research, Development, and Demonstration, *Sustainability*, 11, 2310; Louwen, A., Nemet, G. F., Husmann, D., & van Sark, W. (2022). Historical and Future Cost Dynamics of Photovoltaic Technology. *Reference Module in Earth Systems and Environmental Sciences.*
7. Pillai, U. (2015). Drivers of cost reduction in solar photovoltaics. *Energy Economics, 50*, 286-293; Nemet, G. F. (2005). Beyond the learning curve: factors influencing cost reductions in photovoltaics. *Energy Policy, 34*, 3218-3232; Kavlak, G., McNerney, J., & Trancik, J. E. (2018). Evaluating the causes of cost reduction in photovoltaic modules. *Energy Policy, 123*, 700-710; Trancik, J. E., Kavlak, G., Klemun, M. M., & Kamat, A. S. (2020). *Modeling Photovoltaics Innovation and Deployment Dynamics.* Massachusetts Institute of Technology. U.S. Department of Energy; Zeigler, M., J. Song, and J. Trancik. 2021. Determinants of lithium-ion battery technology cost decline. *Energy Environ. Sci.*, 14, 6074.
8. Diaz Anadon, L. (2023). Forecasting the Cost of Clean Energy Technologies. Appendix to TCR. (2023) *A Model for Clean Energy Innovation, How Corporate Buyers Can Accelerate the Development and Commercialization of Technologies Needed for Net Zero.*
9. Shayegh, S., D. Sanchez, and K. Caldeira. (2017). Evaluating relative benefits of different types of R&D for Clean Energy Technologies. *Energy Policy.* 107, 532-538.
10. Wilson, C., Grubler, A., Bento, N., Healey, S., De Stercke, S., & Zimm, C. (2020). Granular Technologies to Accelerate Decarbonization. *Science, 368*(6486), 36-39; Sweerts, B., Detz, R. J., & van der Zwaan, B. (2020). Evaluating the Role of Unit Size in Learning-by-Doing of Energy Technologies. *Joule*, 967-974; Dahlgren, E., Göçmen, C., Lackner, K., & van Ryzin, G. (2013). Small Modular Infrastructure. *The Engineering Economist, 58*(4), 231-264.
11. The table on this slide reflects both the traditional 9 step TRLs developed by NASA in the 1970s and an extension and modification of the traditional TRLs used by the International Energy Agency. International Energy Agency. (2020). See also: https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide?selectedVCStep=Generation&selectedSector=Power
12. Collaborations could open or expand a path for accelerating innovation. For example, a company with information technology and engineering capabilities might offer a start-up technology modeling and virtualization capabilities.
13. Böhringer, C., Cuntz, A., Harhoff, D., and Asane-Otoo, E. (2017). The impact of the German feed-in tariff scheme on innovation: Evidence based on patent filings in renewable energy technologies. *Energy Economics,* Volume 67, pages 545-553; Böhringer, C., Cuntz, A., Harhoff, D., and Asane-Otoo, E. (2014). The Impacts of Feed-in Tariffs on Innovation: Empirical Evidence from Germany. *Oldenburg Discussion Papers in Economics, No. V-363-14*; Nemet, G. (2009) Interim monitoring of cost dynamics for publicly supported energy technologies, *Energy Policy* 37, 825-835. See also: Hoppmann, J., M. Peters, M. Schneider, and V. Hoffmann. (2013). The Two Faces of Market Support – How Deployment Policies Affect Technological Exploration and Exploitation in the Solar Photovoltaic Industry. ETH Zurich, Department of Management, Technology, and Economics; Jamasb, T. (2007). Technical Change Theory and Learning Curves: Patterns of Progress in Electricity Generation Technologies. *The Energy Journal, 28*(3), 51-72.
14. Egli, F., S. Bjame, and T. Schmidt. (2018). A dynamic analysis if financing conditions for renewable energy technologies. *Nature Energy* 3(12).
15. See for example: U.S. Department of Energy. (2022). *Solar Photovoltaics Supply Chain Deep Dive Assessment.* U.S. DOE; International Energy Agency. (2022). *Special Report on Solar PV Global Supply Chains.* IEA.
16. Grubb et al. (2021); Geels, F., B. Sovacool, T. Schwanen, and S. Sorrell. (2017). The Socio-Technical Dynamics of Low-Carbon Transitions. *Joule.* 1(463-479) (November 15, 2017).

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