The Coalition of Finance Ministers for Climate Action

How government actions have accelerated clean energy innovation: lessons for economic analysis and modeling by Ministries of Finance

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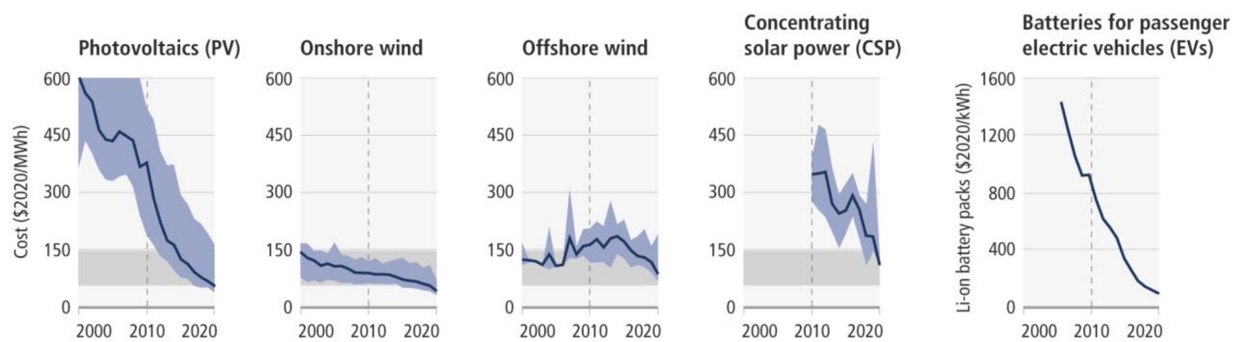
Over the last 10 years, the transition to a clean global economy has become much more feasible and affordable because of the dramatic cost reductions in multiple clean technologies. For example, the costs of solar panels have declined by 85%, onshore wind power by 56%, and batteries by over 90% (IPCC, 2022) (Figure 1). The historical evidence and analysis of drivers of change make clear that governments, including Ministries of Finance, have played a central role in accelerating innovation for these and other clean technologies. The apparently sudden arrival of low-cost clean energy should be viewed not as a serendipitous development but as the accumulation of purposive public investment by multiple governments over decades. Examples include wind power by Denmark (Johansen, 2021), solar power by Germany (Haelg et al., 2018), and batteries by China (Helveston and Nahm, 2019). Government interventions at particular moments played especially important roles.

The modeling of future costs and adoption of clean technologies would benefit from explicit characterization of the key drivers for solar: learning curves and S-shaped adoption. For example, recent work found that integrated assessment models tend to favor inefficient large-unit-scale technologies and compared with real world data, do not accurately represent the rapid adoption of small-scale granular technologies, such as renewable energy and efficient end-use devices (Creutzig et al., 2023; Wilson et al., 2020). Two key improvements in modeling would be to use up-to-date information on technologies, particularly on costs, as well as characterizing how technology costs change. Both changes would help models inform decision-making by bringing them closer to real working conditions.

Figure 1. Levelized costs of energy for clean energy technologies



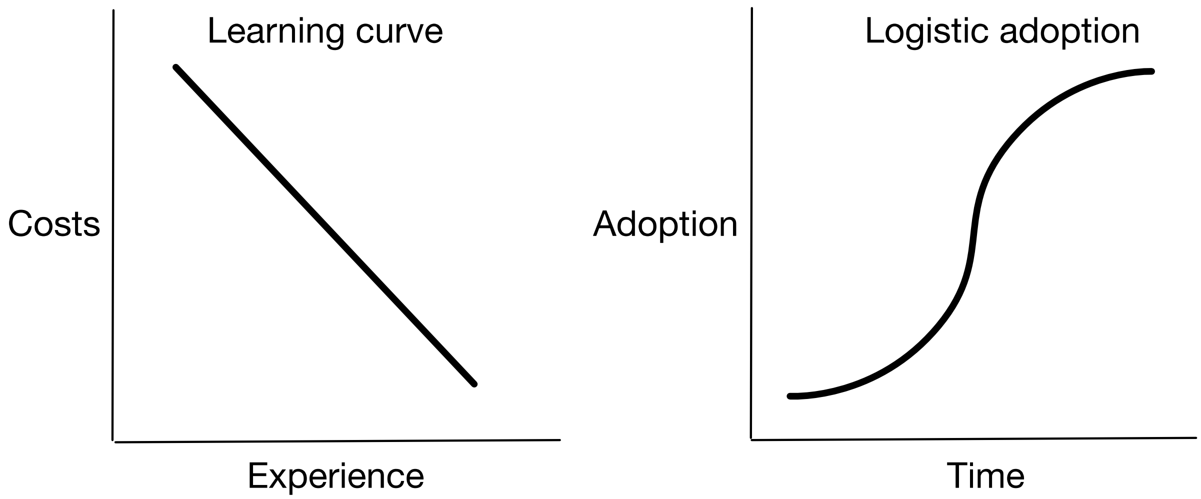
Note: The black line is the median, and the blue shading around it is the 5th to 95th percentile range. The gray box is the same range for the cost of fossil fuel electric generation in 2020.
Source: IPCC (2022)

The patterns observed for these technologies align closely with the broader set of empirical results from the literature on economics of innovation as well as the theory explaining them.

First, since the observations of telegraph operators in the 19th century, we know that technologies can improve via a process of learning-by-doing, in which performance improves as producers accumulate experience. This has been formalized into the learning curve in which a power function describes the relationship between costs and experience, where costs include the installation, capital, operations, and maintenance costs per MWh of electricity produced (Figure 2). Experience is typically calculated as the cumulative capacity (in watts) of installed solar panels. Globally, since the early 2020s solar panels have fallen in cost by 24% for every doubling in experience, wind by 15%, and batteries by 20% (IPCC, 2022; IRENA, 2023).

Second, observations of a wide range of technologies, beginning with farmers deciding to use new seed varieties, show that their adoption follows an S-shaped (logistic) curve. Early technology diffusion proceeds slowly among a limited number of adopters, while the technology is seen as risky and expensive. At some point a much broader set of actors finds the technology attractive and growth takes off—perhaps due to peer effects or cost competitiveness with alternatives—before approaching market saturation. We see these patterns both at country level and when aggregated to the global level.

Figure 2. Representations of two key dynamics for clean energy innovation: the learning curve (left) and S-shaped logistic adoption curve (right)



Note: In general, the learning curve implies that costs come down as experience in production is accumulated. Experience correlates with cumulative adoption, which grows according to an S-shaped (logistic) curve: slow at first, then acceleration before approaching saturation.
Source: Author

The consistency of learning curves for costs and S-curves for adoption is striking and central to understanding the development of the clean technologies making an impact now. One important implication is that these technologies will likely make a much bigger impact later. The most direct policy implication is that cost reductions move technologies up the S-curve, which in turn generates experience, creates opportunities for learning-by-doing, reduces costs, and thus appeals to a broader set of adopters with lower willingness to pay. The initial conditions are thus crucial and create a strong role for governments to implement policies that incentivize early adoption.

A deeper analysis of the sources of these cost-reducing activities in solar (Nemet, 2019) has elevated the importance of the roles governments have played over the past seven decades, during which the costs of solar have fallen by a factor of 10,000. In summary, the governments of five countries each made a distinct contribution to the technology—no single national government persisted in developing solar photovoltaics (PV). Each lead country relinquished its lead, and no single company ever led global manufacturing for more than a few years. The free flow of ideas, people, machines, finance, and products across countries played a major role in explaining the success of solar PV. One important implication is that barriers to knowledge flow would have delayed innovation for solar.

Further, a series of incremental innovations, supported by governments, accumulated; no single breakthrough explains observed cost reductions. In short: 1) the US created a technology, 2) Germany created a market, and 3) China made it cheap. Japan played a crucial role in phases 1 and 2, and Australia in phases 1 and 3. The key Government actions in the development of low cost solar were the following (Nemet, 2019):

- The US Navy made the first commercial purchase of solar cells, for the Vanguard II satellite, launched in 1957. In the 1970s billions of US dollars in federal appropriations for R&D and a public procurement program entrained skilled scientists and engineers into the R&D effort and stimulated the first commercial production lines (Laird, 2001; Christensen, 1985; Blieden, 1999).
- Coordinated by Japan's Ministry of International Trade and Industry's industrial policy, Japanese electronic conglomerates served niche markets in the 1980s, and in 1994 the Japanese Government launched the world's first major rooftop subsidy program, with a

declining rebate schedule, demonstrating there was substantial consumer demand for PV (Kimura and Suzuki, 2006).

- Germany passed a feed-in tariff law in 2000 that quadrupled the market for PV, catalyzing the development of PV-specific production equipment that automated and scaled PV manufacturing (RESA, 2001; Lauber and Jacobsson, 2016).
- Chinese entrepreneurs, almost all trained in Australia, built supply chains and factories on a gigawatt scale in the 2000s catalyzed by a reform of China's tax system They survived during the 2007–2009 global financial crisis through extension of low-cost loans from the MoF. China became the world's installer of PV from 2013 onward, once it had adopted its own feed-in-tariff (Helveston and Nahm, 2019; Quitzow, 2015).

Governments' support for developing solar has been effective in part because of the technology's characteristics. Central to PV's development has been its modularity, which provided two distinct advantages: access to niche markets, and iterative improvement. Solar has been deployed as a commercial technology across nine orders of magnitude: from a 1W cell in a calculator to a 1GW plant in the Egyptian desert, and at almost every scale in between. This modular scale enabled PV to serve a sequence of policy-independent niche markets (such as satellites and telecom applications), which generally increased in size and decreased in willingness to pay, in line with the technology's progress in cost reductions.

Many of the same dynamics and the role of government in accelerating innovation can be seen for other technologies, such as electric vehicles, offshore wind power and heat pumps, further advanced geothermal, small nuclear reactors, and clean hydrogen production. A preponderance of evidence shows that Government actions have been central to generating cost reductions and accelerating adoption in clean technologies (Bistline et al., 2023; Grubb et al., 2021; Neij and Nemet, 2022; Nemet et al., 2018). Effective policy in clean energy has taken a wide variety of forms in that governments fund innovation directly, such as through R&D; derisk novel technologies by co-funding technology demonstrations; create early markets via advanced market commitments; stimulate broader adoption through subsidies; use price pollution to improve competitiveness of clean energy; and coordinate international cooperation. All of these actions are only possible with investments of public funds raised by MoFs.

Above all, the combination of these diverse policy instruments creates expectations of large and growing markets. Their variety, and the fact they are not correlated, makes the expectations these policies create robust to political changes, business cycles, and changing social priorities. Government policy is thus central to creating an environment for long-term investment in the energy transition.

As climate policy moves forward, governments, and MoFs in particular, will confront an array of decisions related to climate change. Those decisions depend on the improved modeling of policy possibilities and their outcomes. The effects of policy on innovation in clean energy have been a central dynamic over the past 20 years and will likely continue to be so. Recent work finds that models would benefit from up-to-date information on technology costs, explicit characterization of the adoption of small-scale end-use technologies, linkages across sectors of the economy, and a more realistic treatment of the potential for demand-side solutions (Creutzig et al., 2023). An instructive recent example is a paper looking at the marginal value of public funds for climate policies, which finds that subsidies for solar have the highest return, in part because of the inclusion of learning-by-doing in their analytical framework (Hahn et al., 2024).

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