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U.S. POLICY FOR CLEAN ENERGY INNOVATION:

Create Novel Technologies, Enable Knowledge Flows, and Build Markets

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March 2021

As U.S. federal agencies consider adopting a more comprehensive approach to supporting innovation in clean technologies, they should take note of what has worked well in the recent past. Solar provides a successful example. Policies and investments should focus on technology creation, knowledge flows, and market support.

Key Takeaways

- Solar became cheap through a sequence of policies deployed by five countries.
- Design of industrial policy should focus on robust support for technology creation, knowledge flows, and building markets.Other small-scale technologies with millions of units can use the same drivers.
- U.S. energy policy can benefit by applying nine innovation accelerators emerging from the solar case.
- Government policy should support the creation of new technology, facilitate knowledge flows, and build markets, all in support of private sector efforts to develop technologies, find markets for them, and make them affordable.

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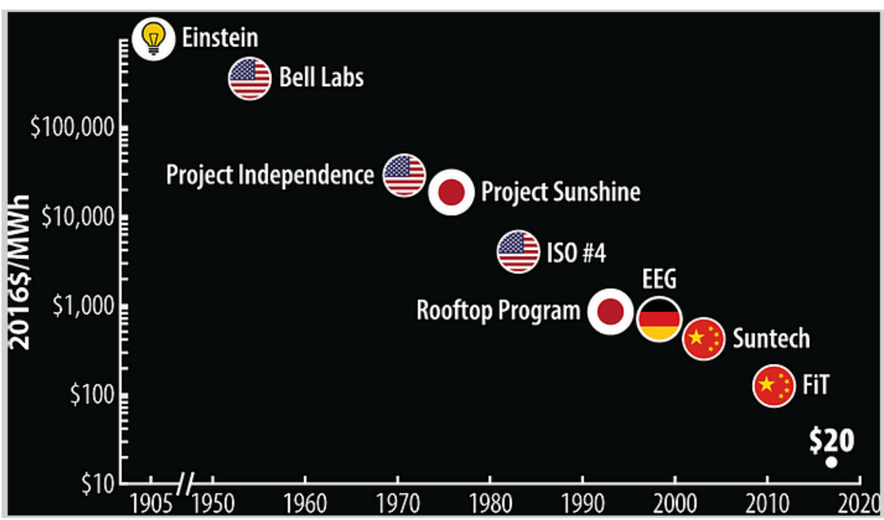
Solar provides a model for clean energy innovation

The development of low-cost solar photovoltaics (PV) provides an important case study to inform the array of industrial policies we need to address climate change. Costs have fallen by a factor of 10,000 since the first commercial application in 1958.[1] Adoption has been growing 30 percent per year for 30 years.[2] Solar power today is the cheapest way that humans have ever produced electricity at scale, and it continues to fall in cost. I studied this progress for 15 years and wrote a book about how it happened and how we can apply those lessons to other technologies. Here's what I found and why it matters for designing industrial policy to address climate change.

Solar cost reductions and timeline of international contributions[3]



1. G.F. Nemet, *How Solar Energy Became Cheap: A Model for Low-Carbon Innovation* (Routledge, 2019).

2. International Renewable Energy Agency, *Renewable Energy Statistics 2020* <https://www.irena.org/publications/2020/Jul/Renewable-energy-statistics-2020>.

3. https://www.howsolargotcheap.com/

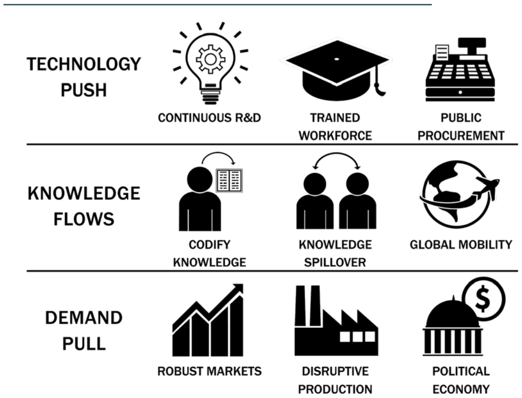
PV's evolution can be summarized as the result of distinct contributions by the U.S., Japan, Germany, Australia, and China — in that sequence, with each illustrating an aspect of industrial policy. PV improved as a result of the following steps:

1. Basic science in Europe and the U.S. provided understanding on how light interacts with molecular structures;
2. A U.S. corporate lab used that science to develop the first solar cell in 1954, licensed it to defense contractors, and sold it to the U.S. Navy in 1958 for early satellites;
3. The U.S. launched a major federal R&D and public procurement effort in the 1970s, motivated by the oil crises;
4. Japanese industrial policy, after coordinating electronic conglomerates to serve niche markets in the 1980s and in the 1990s, launched the world's first major residential rooftop subsidy program, with a declining rebate schedule;
5. Germany passed a law in 2000 providing generous 20-year fixed-price contracts to solar installers. This quadrupled the market for PV and stimulated efforts by firms to develop production equipment that automated and scaled PV manufacturing;
6. Chinese entrepreneurs, almost all trained in Australia, built factories of gigawatt scale in the 2000s. After 2009 central government industrial policy provided low-cost loans and created the world's largest market for PV from 2013 onward; and
7. A cohort of residential adopters emerged with high willingness to pay, accessing information from neighbors and installer firms that were rapidly learning to lower installation costs.

Solar innovation followed a sequence of activities in **technology creation, market development, and cost reductions**. The U.S. created the technology, the Japanese and then the Germans built a market, and the Chinese made it cheap. That sequence provides a model for industrial policy to follow in supporting analogous technologies. Indeed, lithium-ion battery packs are following a cost and adoption trajectory shaped by strikingly similar mechanisms.

Policy insights to advance clean energy: Technology, knowledge, and markets

Nine components of industrial policy



A key challenge in applying the solar model is to adapt it to move through the innovation process much faster. The sequence of policies above succeeded in delivering low-cost solar, but they took decades, which is too long for combating climate change. Through the solar case study, I identified nine industrial policy components, sorted into three areas, that can accelerate innovation:

Government support for **technology creation**, sometimes known as "technology push," includes: 1) public *R&D* investment that shifts its emphasis to reflect the changing needs for technology along its life cycle; 2) support for *education*, both for technical as well as for implementation skills; and 3) *public procurement* to expose nascent firms and technologies to real-world conditions, but accommodating their novelty with higher purchase prices.

Support for **knowledge flows** includes 1) *codifying knowledge*, for example in accessible reports and data sets; 2) facilitating *knowledge spillovers* across technologies, companies, and countries by connecting actors; and 3) enabling *global mobility* by taking advantage of the distinct contributions of diverse national innovation systems around the world.

Building markets for new technologies, by creating expectations of large and growing demand, sometimes called "demand pull," includes: 1) creating market signals that are *robust* to changes in the political environment; 2) facilitating *disruptive production*, for example by compromising on attributes that consumers value only weakly to provide them with attributes they value highly, such as convenience; and 3) taking *political economy* concerns seriously, for example by addressing parties in a position to impede innovation and considering the longer-term implications of who becomes powerful as a result of innovation.

Policy changes in the U.S. to accelerate clean energy innovation

The federal government should apply these nine innovation accelerators:

Technology push

1. *Continuous and evolving R&D*. Boosting federal energy R&D clearly is needed and fits previous commitments, such as the multilateral Mission Innovation agreement to double clean energy R&D. But R&D priorities also need to shift over time, for example to address new bottlenecks that arise in commercialization. R&D thus also includes policy innovations such as ARPA-e, the energy-innovation agency modeled on DARPA, as well as shifts such as the Office of Fossil Energy's new focus on carbon removal.
2. *Trained workforce*: The pace of innovation is typically constrained by the availability of trained scientists and engineers as well as broader sets of skills that are crucial for making technology commercially viable. Key priorities including boosting support for education and enhancing technical capacity within the federal workforce.
3. *Public procurement*. Federal purchases of nascent technologies have enabled scale-up, performance improvements, and cost reductions in the past. A key consideration is to measure and align goals of purchasing so that they target learning and innovation, not just low cost or pollution reduction.

Knowledge flows

4. *Codify knowledge*. Technology experimentation, development, demonstrations, and early adoption generate ample data with high social value. The policy priority here is to make those data transparent and accessible. Open access should be standard; proprietary claims on data are outdated and misaligned with the public purpose of the overall effort.

5. *Knowledge spillovers*. Novel techniques, designs, and applications build on the innovations of others. The U.S. should take full advantage of this, as multinational companies already do massively. U.S.-China collaborations are promising and could be expanded. Immigration of knowledge workers is perhaps the most effective channel for benefiting from knowledge spillovers.

6. *Global mobility*. People, parts, finance, and goods moving around the world have been crucial to successes with wind, solar, and batteries. The U.S. needs to focus on enhancing these collaborations and flows. Restricting knowledge flows to within the U.S. will slow innovation and prevents the U.S. from taking advantage of the distinct innovation capabilities that have developed elsewhere.

Demand pull

7. *Robust markets*: Investment depends on clear expectations of growing demand for clean energy technologies. Policies that are vulnerable to elections and changes in public priorities do not create credible expectations. A federal clean energy standard should complement state efforts but not replace them. Retain the experimental governance that federalism provides. See what works best and allow local variation to reflect distinct implementation contexts. Demand created by policy in other countries also makes expectations robust to policy changes.

8. *Disruptive production*. Support for advanced manufacturing is clearly crucial to accelerating innovation. But the U.S. should not only focus on being at the technical frontier in manufacturing. Successful disruptive innovations make compromises on performance to target actual consumer preferences, such as costs and convenience, which can change over time.

9. *Political economy*. Durable policies stimulate private investment, and part of making policies durable involves acknowledging that there will be winners and losers from innovation. A political science perspective on innovation makes clear that clean energy policies can create new winners, who can use their growing influence to support even more stringent policy later, for example, on a carbon price. Sequencing policies should thus be a part of the overall strategy. Policies are also needed to support those adversely affected by innovation, such as communities whose economies depend on fossil fuels.

Many technologies can learn from solar

Many technologies would benefit from solar's lessons. The ones most amenable to emulating solar's success are those with *small scale*, *modularity*, and *massively iterative production*, such that manufacturing millions or billions of units is the relevant scale of production. Batteries certainly fit, as do a wide variety of energy-efficient end-use products like lighting, heat pumps, and connected devices. Another example, low-temperature direct air capture, also seems well-suited to benefit from these same policies.

Not all technologies are configured to respond to the same industrial policy tools that improved solar. Large-scale technologies, such as advanced nuclear fission, nuclear fusion, and carbon capture for power and industry, require learning from different models. They are more likely to benefit from lessons from large technological systems, like refineries and chemical plants, where system integration is the dominant challenge. A set of meso-scale technologies, such as small-scale nuclear reactors, including small-modular and micro, has the potential to benefit from both small-scale and large-scale examples. Small-scale nuclear aims to attain some of the benefits of many iterations while retaining some economies of scale, and still needing to manage system integration complexity. Still other technologies work on an even smaller scale for which the manufacturing component is minor. For example, soil carbon sequestration practices stand to benefit from lessons drawn more from highly distributed adoption contexts, such as the Green Revolution.

Emerging empirical research on innovation is indicating that small-scale technologies like solar get cheaper faster and are adopted more quickly than larger-scale technologies.[4] This is because their small scale makes them lower risk, adaptable to a variety of adoption contexts, and modularly suited to a larger set of niche markets. Perhaps counterintuitively, small-scale technologies seem to be more scalable than large ones. The policy implication here is that learning from solar is even more important. It is not just that we should apply solar's lessons to small-scale technologies, but also that we should expect more innovation from them than from large-scale technologies and perhaps focus more effort on them.

The success of technologies like solar, as well as wind and batteries has given us a playbook to use for other technologies that share the same essential technological characteristics: modular scale, high technology, and massive iterations. Government policy should support the creation of new technology, facilitate knowledge flows, and build markets, all in support of private sector efforts to develop technologies, find markets for them, and make them affordable.

4. C. Wilson et al. "Granular technologies to accelerate decarbonization," *Science* 368, no. 6486 (April 2020): 36–39 <https://doi.org/10.1126/science.aaz8060>.