Coming Clean with Energy Cost Curves

An Interview with MIT's Jessika Trancik

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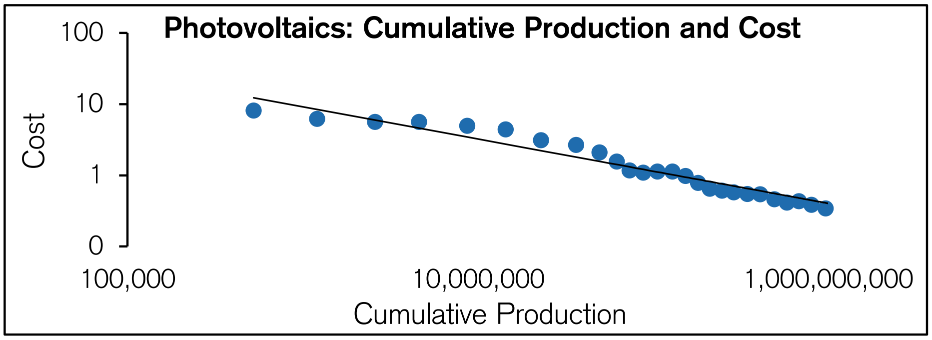

Source: pcdb.santafe.edu/process_view.php.
Note: "Photovoltaics 2" curve; Cost in 2005 U.S. Dollars per Kilowatt Hour; Production in Kilowatt Hours.

"I am interested in how we can support economic activity based on a fundamentally different infrastructure for providing commercial energy, one that doesn't emit greenhouse gases. There are limited financial resources and there's limited time to achieve this transition, and so it's important to invest our engineering, policy, and financial resources wisely."

Jessika Trancik

- Change in energy consumption behavior is not enough. To mitigate the release of greenhouse gases, we need to switch to energy sources that do not contain carbon. Over the next few decades, we may see a wholesale change in our energy infrastructure, which will create winners and losers.
- Moore's law and Wright's law. While most investors are familiar with Moore's law, which specifies the relationship between the cost of technology and time, fewer know Wright's law, which considers the relationship between the cost of technology and cumulative output. The laws often provide similar results, but Wright's law outperforms Moore's law for certain technologies. This is important because it means that output itself can drive costs down.
- Interaction between government, companies, and investors. The roles various stakeholders play will determine the rate of change in the sources and uses of energy. The government provided basic research for many technologies that we take for granted today, including the Internet and GPS. Further, policy-supported demand may be a crucial factor in spurring private sector innovation to further reduce unit costs for key technologies, including batteries and photovoltaics.

Introduction

The ability to harness energy has played a central role in driving living standards over the centuries. We are now at the point where human energy use has changed our world. For example, per capita carbon dioxide emissions have risen sharply in the last century and a half. The ultimate impact on the climate and human welfare is unknown. Governments, the scientific community, and investors seek cleaner forms of energy to slow the rate of carbon emissions.

Jessika Trancik is an Associate Professor in Energy Studies at the Massachusetts Institute of Technology (MIT) and an external professor at the Santa Fe Institute. Her research focuses on energy technologies, including their costs and impact on the environment. Professor Trancik's work sheds light on how our infrastructure for providing energy may change in upcoming decades. She combines theoretical models with empirical data to arrive at applied solutions. Here's a discussion with her about these and other issues:

Michael Mauboussin (MM): Hi, Jessika. Thanks for taking some time to share your thoughts with us. Many of the most pressing issues facing our global society relate to energy consumption and the effect it is having on our world. Your work focuses on predicting the future of energy technologies and ways to improve their development. Can you discuss how you approach the problem of forecasting technological improvement and how that work applies to current challenges?

Jessika Trancik (JT): Hi, Michael, thanks for the question. It's great to have the opportunity to discuss these issues with you.

First, let me give some background on why I'm interested in these topics, because it will help explain my research approach. Commercial energy has driven industrialization and increasing living standards in the developed world since the late 1800s, and more recently in emerging and developing economies. But, as is widely recognized, we now have a problem in that the energy sources we've relied on to build our economies release greenhouse gases when burned, which threaten to irreversibly change the climate and negatively affect human wellbeing. I am interested in whether we can support economic activity based on a fundamentally different infrastructure for providing commercial energy, one that doesn't emit greenhouse gases. There are limited financial resources and there's limited time to achieve this transition, and so it's important to invest our engineering, policy, and financial resources wisely. My research aims to understand the promise and limits of different technologies in order to increase the probability of success.

The reason technology is so important for addressing this problem is that changes to behavior won't be enough alone. Even with extreme improvements to how efficiently we consume energy, the source of energy has to change in order to meet climate goals. To meet these goals, we'll need to switch over to fuels that don't contain carbon, and we likely need to move toward conversion technologies that aren't based on combustion. This transformation in our energy supply infrastructure would have to happen within a few decades.

A transformation toward low-carbon energy is both a challenge and an opportunity for engineers, private investors, and governments. I am interested in uncovering opportunities that may otherwise be hidden, in order to accelerate a transition to low-carbon energy. Specifically, I ask: How should engineers, private investors, and policymakers invest limited time and money to make this happen? Can we use data and mathematical models to help direct and inform key areas of technology innovation to accelerate this transition? The approach is somewhat analogous to taking insights from epidemiology to inform drug development.

My methods include developing mathematical models informed by, and testable against, data to describe why the costs of a technology are changing over time, analyzing large data sets to understand how well various forecasting models perform, and developing computer simulations to model the emissions impacts of technology portfolios.

Many of the applied questions I am interested in require a new fundamental understanding of the features of technologies and human activity that influence rates of technological progress. So the work focuses on developing both basic and applied insights. In terms of specific technologies, I am particularly interested in solar energy and energy storage, and managing our use of natural gas, because of the key role these technologies will play if decarbonization is achieved.

MM: Let's delve into your research on evaluating the performance of technologies. First, how do you model this performance? Second, it'd be great to get your take on a handful of technologies. For example, will silicon-based photovoltaics (solar energy) costs continue to fall?

JT: Photovoltaics (PV) is a technology that I've been interested in for some time. This is a technology that has seen an unprecedented cost decline over the past four decades. The costs follow a remarkably regular trend. So this raises the following questions: Where does this regularity come from, and why are photovoltaics (dominated by crystalline silicon, or x-Si, modules) costs improving so quickly? Also, is there room for improvement? Answering these questions has taken a number of years and papers. We've shown the importance of certain design features—such as unit scale and the degree to which a technology's components can be changed without disturbing other components—in determining the rate of improvement, and how the regularities we observe in data could arise from a simple process of search.

More recently, my students and I have been studying which photovoltaics device features have improved most and the policies that supported these improvements—going from modeling the device physics to studying the public policies that spurred human efforts to improve PV. The results show clearly the important role that government policies played in incentivizing market growth, and in turn efforts by and competition among private firms in improving photovoltaics. This technology improvement didn't just come from governments investing in research. Government policies to support market growth were critically important. From this we can conclude, as we reported ahead of the Paris climate talks, that emissions reduction efforts and technology improvement can be mutually reinforcing. This was an important message to bring to the negotiations.

And, to answer your specific question—will x-Si costs continue to fall— yes, there is still room for improvement, particularly in the non-module costs. There is also room to scale up this technology, but it's important to pay attention to potential natural resource limitations. The scalability of x-Si looks quite good but some other cell designs, based on other semiconductor materials, might be more limited, which is something that we've created a tool to assess.

MM: Should we as a society invest in flow batteries[1] or lithium-ion for renewables integration? What battery energy density is required for widespread electrification and are we likely to get there?

JT: Flow batteries show promise but lithium-ion (Li-ion) batteries have a head start. I'd invest some in both technologies for stationary energy storage applications (Li-ion is better for mobile storage), and to track the improvement in flow batteries very carefully. What is interesting about flow batteries is that due to the design of the technology there is potential for reducing the energy capacity costs, or the cost of storing energy, which is critically important. In recent work, we've shown how the two dimensions of energy capacity costs and power capacity costs, or the cost of power conversion, should be optimally balanced to maximize the value of storage.[2] Reducing energy capacity costs is important because of certain emergent properties of electricity prices that turn out to be similar across locations. We're currently sharing our cost targets and technology assessments with storage technology developers in the lab, private investors, and policymakers that are designing incentives to stimulate the growth of storage markets.

Widespread electrification of transportation is already physically possible today, even with today's batteries, below average cost vehicles, and today's charging infrastructure. In a recent paper we found that across diverse cities in the U.S., from Houston to New York, almost 90 percent of vehicles on an average day could be replaced by a low-cost electric vehicle, which saves consumers money, even if only once-daily charging were possible, for example at home overnight.[3] This is based on a model that we built in my group over the past four years, called "TripEnergy," which reconstructs the second by second driving patterns of people across the U.S.

Battery improvement will increase this number but there is a heavy tail of high-energy days for which other engines or "power train" technologies are going to be needed for some time. And, of course, a person deciding to buy an electric car has to have his or her needs met on all days. One way to encourage the growth in battery electric vehicles would be to make vehicles with today's dominant engines, the internal combustion engine, easily accessible to drivers on their high-energy days. I'm thinking of, for example, shared internal combustion engine vehicles—even driverless ones in the future—that show up at the front door on demand. This would require being able to predict which days will exceed the battery capacity of the electric vehicle, which is something that we're developing an application to do.

MM: Can natural gas serve as an effective bridge fuel to lower carbon alternatives?

JT: In terms of carbon emissions, natural gas is an improvement over coal, but we do need to pay attention to methane emissions or natural gas leakage from current infrastructure. We've developed methods to account for methane in climate policies. This involves understanding how methane compares to carbon dioxide, and again some interesting dynamics in how these very different gases contribute to climate change. Based on this work, we are uncovering what methane emissions reductions need to be achieved alongside carbon dioxide focused policies for countries to meet their climate pledges.

MM: Many of our readers know about Moore's law, which states that the number of transistors on an integrated circuit doubles roughly every two years. They also know that Moore's law, or a variant, applies to other technology cost curves as well. Fewer are familiar with Wright's law, which expresses a reduction in cost based not on time but on cumulative output. Can you tell us a little about these models and how they inform your research?

JT: These models describe how technologies improve over time, and are "phenomenological" models that are based on observed trends in the empirical data. These models describe the rate of change in technology costs and other features as a function of time or another variable such as production.

Wright's law or the learning curve was proposed by T.P. Wright in 1936 as a way to relate the production quantity of a technology to its cost. This model says that for each one percent increase in cumulative production, there is a fixed percent decrease in cost. This means that to see cost improvement, a technology's production needs to increase, and it suggests that the technology cost improvement that results from increasing production may be somewhat predictable.

This model contrasts with Moore's law which relates technology improvement to time. If time is driving technological improvement, no amount of human effort can affect the rate.

So, conceptually, a worldview based on Moore's law is quite different from one based on Wright's. In the first case technologies follow inexorable trends, while in the second case the level of human effort determines rates of technological improvement.

Mathematically, however, there are conditions under which both Wright's law and Moore's law would hold. This happens when the rate at which production is growing is fixed in time. If production grows with time at a constant exponential rate and costs fall at an exponential rate with time (following Moore's curve), then Wright's law will describe technological costs. Or if production grows exponentially and costs fall with production following a power law functional form (Wright's curve), then Moore's law will describe the technology's cost decline.

Much of my work has focused on testing these laws and explaining the underlying mechanisms. The examples of my research that we touched on above deal with specific examples of technologies, but underlying these insights is a picture of how technologies improve and change more generally. This picture emerged from looking at many different examples of technologies, within and beyond the energy sector.

When we test these laws against the data we see that, in fact, both Wright's and Moore's curves do similarly well in describing the changes in technology costs. This similar performance has to do with the fact that production tends to grow exponentially at a constant rate within technologies or industries. This rate can differ substantially across technologies or industries.

However when we look at the mechanisms underlying these curves, the reason for technological improvement seems to come down to effort, or a Wright's curve worldview where production drives improvement, at least for the deterministic part of the process. In any industry there is a good deal of randomness in, for example, how prices of input materials fluctuate over time. These stochastic processes can contribute significantly to cost trends and fluctuations over time.

Furthermore there are limits to cost improvement over time, defined by the raw materials costs that go into making any technology. The floors in these raw material costs can change over time, for example if these materials become scarcer and prices increase.

Understanding the regularities and stochasticity in cost and other performance trends for energy technologies is critical to evaluating which technologies are most promising for climate change mitigation. My work has focused on developing an understanding of why technologies improve, and characterizing how regular or noisy these performance trends are for different technologies. I've focused quite a bit on how well we can do in forecasting technology cost changes and limits to improvement, and how we can quantify the uncertainty in those forecasts to arrive at robust conclusions.

MM: You mentioned that both government policies to incentivize market growth and competition among private firms are important to improve the competitiveness of photovoltaics (and other technologies as well, I would guess). Is there anything you would like to see out of government, or the investment community, to foster a more rapid transition to an alternative infrastructure for commercial energy?

JT: What I'd like to see is more intense, informed, and sustained effort over time, on the part of both government and businesses. The interface between policy decision making and insights from science has grown stronger in recent years, and it is important that this continues. Private companies have also become increasingly more informed about issues of climate change and energy, and we are starting to see this affect real decisions.

Government plays a critical role, of course, so long as the objective is to address an external cost to society, such as carbon emissions, that is not priced in the marketplace. These government policies can be structured in such a way as to directly support innovation through publicly-funded R&D, or to create incentives for the private sector to invest. Both approaches are important and not easily substitutable for one another.

To incentivize private sector efforts through government policy, many have written about why a carbon price can be an economically-efficient approach, assuming the right price can be determined and applied (which itself requires forecasting technological progress). In the United States, however, no price has been adopted and a variety of other mechanisms have been used instead, to incentivize the development and adoption of low-carbon technologies. As many have noted, the efforts on the part of government to support alternative energy have been uneven over time.[4] Simply sustaining efforts, even with a set of imperfect policy instruments, can go a long way.

But for government policy to really be effective, it should measure progress and use these data-informed insights to design more effective portfolios of policies and technologies. This approach is needed both for government R&D and incentives for market growth. In your writing you've discussed the balance of luck and skill involved in investing.[5] In the area of energy policy there is certainly room to further develop skill before we bump up against the limits imposed by randomness.

For example, one can use historical data to estimate limitations that different input materials could put on future growth, and use models to estimate limits to cost improvement. Historical data can be used to understand the degree to which a group of technologies or a specific industry tends to see slower or faster improvement, or experience steady or more erratic progress. There are certain design features of technology that are correlated with slower or faster development. We can use data-informed models in various ways to improve our forecasts and understand the degree of unpredictability. Developing technology portfolio models can point to risk mitigating policies and technologies.

It is also important to ask which technological capabilities are likely to be most impactful. While it is difficult to predict which specific technologies will succeed, it is possible to identify important functionalities.[6] Here too, modeling can help by shedding light on how people are consuming energy and which technologies are likely to take off in the marketplace and support emissions reductions.[7] Taking this approach we see, for example, the extent to which improved energy storage technologies and new business models for meeting transportation needs can support electrification and decarbonization of transportation.[8] Developing smarter home energy systems and managing intermittent renewables and distributed energy systems is likely to be important as well, and models of energy consuming behavior can shed light on priority areas for technology development and institutional innovation.

Private industry can use many of these same approaches to inform their decisions with data and models. Three kinds of tools can provide particularly useful insight: time-series analyses to measure and compare rates of technological progress; a combination of phenomenological and mechanistic models to identify the drivers of technology innovation; and portfolio models to inform specific decisions. There are some research challenges here to address, but we already have insight that can be used today. The more sophisticated that firms become, the better and faster the technological development trends can be.

It is inevitable that there will be false starts and failures in developing new technologies. Both government and industry would benefit by taking this into account and pursuing portfolios that can withstand a few failures.

In general, while much about the world isn't predictable, there is information to be gleaned from data-informed models that can help us understand technological innovation and accelerate a transition to clean energy.

Full Biography

Professor Jessika Trancik is an Associate Professor in the Institute for Data, Systems, and Society at MIT, and an external professor at the Santa Fe Institute. Professor Trancik's research centers on evaluating the environmental impacts and costs of energy systems over time and space. Her research aims to accelerate clean energy technology development by informing decisions made by engineers, policymakers, and private investors. This work involves assembling and analyzing expansive datasets, and developing new quantitative models and theory. Projects focus on electricity and transportation, with an emphasis on solar energy conversion and storage technologies.

Trancik was a postdoctoral fellow at the Santa Fe Institute and a fellow at Columbia University's Earth Institute. She earned a B.S. in materials science and engineering from Cornell University, and a PhD in materials science from Oxford University, where she studied as a Rhodes Scholar. She has also worked for the United Nations, and as an advisor to the private sector on investment in low-carbon energy technologies. She has published in journals such as *Nature Climate Change, Nature, Proceedings of the National Academy of Sciences, Nano Letters, and Environmental Science and Technology.* You can find more information at http://trancik.mit.edu/.

Appendix

Moore's law is a recognized way to forecast performance improvement in the semiconductor industry. In 1965, Gordon Moore, one of the founders of Intel, predicted that the number of transistors on an integrated circuit would double every year.[10] In 1975, he revised the time to double to two years.[11] Moore's law says that the production cost of an integrated circuit decreases as a function of time.

Over the last 50 years, the manufacturing cost per transistor has followed Moore's law with remarkable accuracy. Only now is it bumping into the limits of physics.

There's another law that predicts performance even better than Moore's law. Most people know that Orville and Wilbur Wright built the first airplane. But few know about the engineers, including Theodore Paul Wright, who made the plane a viable commercial product. Wright was a naval aircraft inspector during World War I who joined the Curtiss Aeroplane and Motor Company after the war. Although Theodore had no relation to the Wright brothers, two of his brothers rose to eminence in their respective fields.

Wright saw the potential of manufacturing airplanes for commercial use early but knew they would have to be cheaper. So he kept track of industrial capacity and labor efficiency. He published his findings in 1936 in a paper called "Factors Affecting the Cost of Airplanes." This paper provided a statistically rigorous case for the learning curve.[12] Wright's law says that the cost of a plane decreases as a function of cumulative production.

Wright's law goes well beyond aircraft manufacturing. Jessika Trancik, along with Béla Nagy, Doyne Farmer, and Quan Bui, examined how well various models, including Moore's law and Wright's law, predicted the change in cost per unit for various technologies.[13] They tested the models with cost and production data for 62 different technologies, including computer hardware, energy, and chemicals. (See http://pcdb.santafe.edu/process_view.php.)

Wright's law made the most accurate forecasts of technological progress of all of the models, with Moore's law close behind. They also found that their models had predictive power for both low- and high-technology products, which suggests that you can use a common forecasting method for disparate industries.

Moore's law and Wright's law did provide similar forecasts for technologies in the sample that had exponential increases in production.[14] Although Wright's law is not well known, economists and consultants have used it widely.

Wright's law not only predicted costs more accurately than Moore's law did for the overall sample, it beat Moore's law in forecasting the costs for the electronics industry. This raises a provocative idea: Maybe the belief in Moore's law spurred production, but it was Wright's law that explained the shape of the cost curve all along.

If Wright's law is accurate, it makes sense to focus on cumulative production. For example, the main drawback of alternative energy today is cost. If advances in clean energy depend more on cumulative production than on the passage of time, increasing production may be the best way to lower the costs for alternative energy sources. Indeed, a study led by Trancik suggests that increases in the production of clean energy technologies, such as solar and wind energy, could push costs low enough to make these alternative energy sources viable in the next few years.[15]

This research is important for a couple of reasons. First, you want to use the model that most accurately predicts the rate of technological change. This allows you to be effective at defining the range of possible outcomes. Second, a grasp of the driver of technological change is critical. If Wright's law is the best predictor of cost per unit, you can anticipate the move down the cost curve by understanding the amount of cumulative output.

The electric vehicle industry is a good example of Wright's law in action. In 2005, there were only 1,670 electric vehicles. The total expanded to12,480 in 2010 and soared to 1.5 million in early 2016.[16] The compound annual growth rate was 94 percent from 2005 to 2015, and 152 percent for the 5 years ended in 2015. Demand growth is expected to be in the range of 30-40 percent in the next 5 years.[17]

The battery is the main cost of an electric car. The future of the industry to some degree hinges on the capacity and cost improvement for lithium-ion batteries for the automobile industry. Global capacity was about 28 megawatt hours (MWh) at the end of 2014, but capacity utilization was below 40 percent. Demand is expected to double over the next five years, which will be accommodated by additional capacity and improved capacity utilization. Cumulative production, the key to Wright's law, is rising rapidly. Lower costs for batteries spur additional demand, which increases output and further reduces cost.

The cost of batteries for plug-in hybrid electric vehicles fell from approximately $1,000 per kilowatt hour (kWh) in 2008 to roughly $270 per kWh in 2015, a 17 percent annual decline. Automobile manufacturers and governments have set ambitious targets for battery costs. For example, General Motors hopes to reduce the cost of its electric batteries to below $100 per kWh by 2022 for the Chevrolet Bolt, and Tesla hopes to get under $100 per kWh by 2020.[18]

Moore's law and Wright's law have both effectively explained the reduction in costs for a host of technologies. But they have different drivers of performance. Moore's law relies on technological improvement, and hence the cost declines are a function of time. Wright's law is based on manufacturing experience, so cost declines are a function of cumulative output. Technology and experience are both important and are interrelated. To the degree to which Wright's law better explains the decline in the cost of a technology, investors are well served to focus on output and capacity as indicators for future costs.

Endnotes

[1] Per Wikipedia, “A flow battery, or redox flow battery (after *reduction–oxidation*), is a type of rechargeable battery where rechargeability is provided by two chemical components dissolved in liquids contained within the system and separated by a membrane.”
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[3] Zachary A. Needell, James McNerney, Michael T. Chang, and Jessika E. Trancik, “Potential for Widespread Electrification of Personal Vehicle Travel in the United States,” *Nature Energy*, 1, Article No. 16112, 2016. See carboncounter.com to compare the costs and emissions of 125 automobile models.
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[8] Needell, McNerney, Chang, and Trancik, 2016.
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[10] Gordon E. Moore, “Cramming More Components onto Integrated Circuits,” *Electronics*, Vol. 38, No. 8, April 19, 1965, 114-117.
[11] Gordon E. Moore, “Progress in Digital Integrated Electronics,” *Technical Digest: International Electron Devices Meeting*, 1975, 11-13.
[12] T.P. Wright, “Factors Affecting the Cost of Airplanes,” *Journal of the Aeronautical Sciences*, Vol. 3, No. 4, February 1936, 122-128.
[13] Béla Nagy, J. Doyne Farmer, Quan M. Bui, and Jessika E. Trancik, “Statistical Basis for Predicting Technological Progress,” *PLoS ONE*, Vol. 8, No. 2, February 2013.
[14] When cumulative production of a technology increases exponentially over time, it is increasing as a function of time. If cumulative production is increasing as a function of time, any cost reductions that result as a function of production (which is consistent with Wright’s law) can also be seen as resulting as a function of time (which is consistent with Moore’s law).
[15] Jessika E. Trancik, Patrick R. Brown, Joel Jean, Goksin Kavlak, Magdalena M. Klemun, Morgan R. Edwards, James McNerney, Marco Miotti, Joshua Mueller, and Zachary Needell, “Technology Improvement and Emissions Reductions as Mutually Reinforcing Efforts: Observations from the Global Development of Solar and Wind Energy,” *Institute for Data, Systems and Society, Massachusetts Institute of Technology*, November 13, 2015.
[16] “Global EV Outlook 2016: Beyond One Million Electric Cars,” *International Energy Agency OECD/IEA 2016,* 2016; Jeff Cobb, “Global Plug-in Car Sales Cruise Past 1.5 Million,” *HybridCars.com*, June 22, 2016.
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[18] “Global EV Outlook 2016: Beyond One Million Electric Cars.”

Important information