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The Tipping Point: How America Can Lead the Transition to a Prosperous Clean Energy Economy

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The Tipping Point: How America Can Lead the Transition to a Prosperous Clean Energy Economy

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The world is approaching a historic tipping point. Rapid advances in price and performance are bringing clean energy technologies ever closer to the point where they beat fossil fuel technologies on the merits; where they are quite simply cheaper and better. Solar and wind are already beating coal in a number of situations and locations. Once this tipping point is broadly reached, the full might of markets will come to bear and drive a wave of transformation that will replace the fossil fuel economy with a clean energy economy. Betting on coal at this point in history is about as smart as betting on typewriters in 1976—the year Apple released its first personal computer.

This paper will argue that it is almost inevitable that the U.S. and the world will reach this tipping point, but that it is not happening fast enough. Progress needs to be accelerated in the U.S. for three reasons: First, the sooner the tipping point is reached, the lower the risks of damaging climate change. Second, in the race to build and deploy clean energy technologies there are significant first-mover advantages; the next ten years will likely determine which nations lead and which nations follow. Third and finally, for those who believe that government intervention in the economy should be limited, the faster America reaches this tipping point, the faster it can scale back intervention in its energy markets. A relatively brief but forceful policy push over the next ten years can drive the U.S. rapidly to the tipping point where clean energy technologies win on the merits and free market forces take over. Citizens will then enjoy the benefits of cleaner, cheaper, more secure energy, and the job creating economic growth that will come from this transformation, for decades to come.

This paper will briefly discuss: (1) why clean energy technology has advanced so rapidly and why the tipping point is almost inevitable; (2) why the U.S. needs to actively accelerate its progress to this point; and (3) how smart policies can ensure U.S. leadership in the energy economy of the future.

1. Technologies Beat Commodities: Why Clean Energy Technologies Will Win

Many energy analysts have been surprised by the rapid growth in clean energy technologies such as solar, wind, and batteries. For example, the International Energy Agency (IEA) has consistently underestimated renewable capacity additions (*figure 1*).[1] This is because few foresaw that the levelized cost of wind energy would drop 50% since 2009, and the median price of U.S. installed residential solar would more than halve between 2007 and 2015.[2] Battery costs have also dropped 58% from 2007-2015, and the cost of LED lights dropped 80 percent from 2010-2015. [3] Many people have also been surprised by rapid performance increases. The efficiency of wind turbines, for example, has doubled from 2000-2017.[4] Likewise, as the cost of electric vehicles (EVs) has come down, their power and range has gone up. EVs a decade ago were limited to a range of around 100 miles, while the latest models today can achieve 335 miles.[5] And consumers have been delighted to learn that EVs accelerate faster, are quieter, and more readily integrate advanced digital technologies than fossil fueled cars.[6]

But to people who study technology, this acceleration of progress is not that surprising. In fact, it is quite predictable. Professor J. Doyne Farmer, an American physicist at the Institute for New Economic Thinking at the University of Oxford, and his colleagues, have looked at the progress rates of a large number of goods in the economy over long periods of time.[7] Farmer and his team have shown that one can divide those goods into two broad categories: commodities and technologies. Commodities are goods that are dug out of the ground or grown—for example coal, oil, gas, copper, and wheat. Technologies on the other hand are goods that are designed and embed human knowledge—for example transistors, aircraft, gene sequencing machines, solar panels, wind turbines, and batteries.

In analyzing their data, Farmer and his team observed a striking pattern (*figure 2*). The prices of commodities are quite volatile, but there is no long-term trend—they follow what statisticians call a random walk. For example, coal prices rise and fall with changes in the economy, technology, regulation, trade, and other factors. But despite major changes in mining technology and declines in transport costs, in inflation adjusted terms the price of delivered coal is about the same today as it was in the 1890s (*figure 3*).[8] This is not to say there hasn't been technology progress—coal mining today is a sophisticated, highly-automated, business. But, nonetheless, after an initial period of price declines from 1820 to 1900 when fossil fuels were first introduced, the real prices of coal, oil, and gas have fluctuated a lot, but not trended downward.[9] The reason is that technology innovation in commodities tends to result in supply-demand cycles rather than long-term price decreases.[10] The cycles work like this: current sources of supply begin to dry up, prices rise, companies invest in research and development (R&D), innovations then allow them to tap new sources of supply, prices come down, eventually the new sources begin to dry up, and the cycle starts over. For example, oil has gone from on-shore, to off-shore, deep off-shore, the arctic, horizontal drilling, tight oil, and tar sands, with prices cycling, but no long-term trend.

Technologies on the other hand exhibit fundamental, long-term downward price trends (*figure 4*) as well as improvements in performance. The best-known example is Moore's Law which predicts that the number of transistors in a computer chip will double every 2 years. We have seen Moore's Law revolutionize the world and it is still going. Farmer and his team found that it is not just semiconductors that follow Moore's Law, but a wide variety of technologies, from communications cables to gene sequencing. In fact, Farmer and his team found that most technologies follow a function similar to Moore's Law known as Wright's Law, named after Theodore Wright, an American engineer who discovered it in 1936 while working on the production of B-29 bombers. Under Wright's Law the rate of progress is dependent on the cumulative production volume of the technology rather than on time as in Moore's Law. Wright observed that as the cumulative volume of B-29 bombers produced increased, their cost dropped rapidly. Wright's Law curves are also known as experience or learning curves because it is believed that the price and performance improvements are a function of the knowledge accumulated from experience working with the technology.

Farmer and others have shown that key clean energy technologies such as solar, wind, batteries, and LED lights, are firmly established on Wright's Law curves. The recent rapid progress in solar prices, for example, can be attributed to major increases in cumulative production volumes, largely due to increased global solar demand driven by policies such as Germany's feed-in-tariffs* and China's major expansion of solar capacity. In short, the more solar, wind, batteries, and other clean energy technologies produced, the cheaper and better they have become, and will continue to become—something that is not true of fossil fuel commodities (*figure 5*).

This accelerating progress on renewable prices and performance does not take-away the challenges of integrating large-scale renewables into the grid. However, grid technologies are improving as well and utilities around the world are increasingly gaining experience with managing high levels of renewables. For example, on June 7th this year, the UK ran on over 50% renewable power for the day, and during the same month the entire region of Qinghai, China, with a population of five million, ran on 100% renewables for a week.

Some clean energy technologies, however, are not declining in price. Nuclear has seen its costs rise over time and coal-based carbon capture and storage (CCS) has yet to see significant cost declines. Safety and other regulations are certainly part of the story. But it may also be due to the fact that each nuclear or CCS plant is so large, expensive, and unique, that it is difficult for the experience curve effect to kick in.

2. Accelerating the Clean Energy Tipping Point

Work by Bloomberg New Energy Finance and others shows that based on these experience curves, solar and wind are on track to reach two tipping points (*figure 6*).[11] The first is when unsubsidized new-build solar and wind beat new-build coal and gas. This first tipping point has already been reached in Germany, is expected to be reached in China by 2019-2021, and in the U.S. by 2022-2023. The second tipping point is when unsubsidized new-build solar and wind beat *existing* fossil plants. This is when large scale replacement of the energy infrastructure will begin. This is expected in the late 2020s to early 2030s across the developed countries and China, depending on national policies.

While this is encouraging, progress needs to be accelerated in the U.S. for three reasons: (A) to minimize climate damage, (B) to maximize U.S. technological and industrial leadership, and (C) to limit government involvement in energy markets.

A. Minimizing Climate Change

Scientists estimate that in order to avoid the most dangerous and irreversible effects of climate change, global emissions of carbon and other greenhouse gases must drop to net-zero by around 2050.[12] By that point humankind will likely have used up its remaining "carbon budget" and any positive emissions beyond mid-century will cause global temperatures to rise above 2ºC degrees (3.6ºF) creating significant risks including extreme weather events, rising sea levels, more unreliable food supplies, droughts, flooding, species extinction, and other negative effects on planetary ecosystems and human society.[13]

While 2050 may sound comfortably far off, it isn't. Energy-using infrastructure has a long-lifetime: 30-60 years for power plants, 10-30 years for transport, and decades or even centuries for buildings. So, the infrastructure the U.S. is building and planning today will determine its emissions mid-century. Researchers at Oxford have calculated that the power generation infrastructure on the ground today already has enough "baked-in" future emissions to exceed the world's carbon budget and lead to warming over 2ºC.[14] This means that the world needs to get to tipping point 1—when

* A feed-in-tariff is a payment made by a utility (usually with government support) to a non-utility producer of low-carbon energy (e.g. a household or business with solar panels or wind turbines) to sell the power they produce but do not use themselves to the grid. The tariffs are designed to incentivize renewable energy adoption.

clean energy technologies are cheaper than new-build fossil—now. But the U.S. and other countries also need to accelerate progress to tipping point 2—when clean energy begins broadly substituting for existing fossil infrastructure – as soon as possible, but no later than a decade from now. If not, by 2030 the world may be locked into a path to temperatures higher than 2ºC with irreversible negative consequences that may be highly costly or impossible for humankind to adapt to.

B. Maximizing U.S. Technological Leadership

The second reason the U.S. should accelerate its clean energy progress is to maximize its chances of playing a leadership role in these technologies in the future. The U.S. has pioneered many key clean energy technologies (the first solar cells were developed by the U.S. space program) and numerous U.S. companies currently play leading roles in the industry. However, a consequence of Wright's Law is that knowledge and experience tend to build where production and demand are located, and it is a cumulative, accelerating process. This means that there are significant early-mover advantages, and catch-up may be difficult or impossible.

Thus, the countries that move aggressively to build a clean energy economy today will build the industrial ecosystems of talent, assets, infrastructure, and knowledge to dominate those businesses tomorrow. For example, China State Grid, which serves 1.1 billion customers, is investing $12 billion in R&D for smart grid technologies and is building the world's largest electric vehicle charging infrastructure.[15] Overall, China invested $103 billion in domestic renewable energy in 2015 versus $44 billion by the U.S.[16] If the U.S. steps back from clean energy leadership, there is a risk that America will be locked-out of this growing market, unable to catch-up, and dependent on imports for clean energy products and services from China, Japan, South Korea, Germany and other countries. It would also be a loss for American workers as we rapidly approach the tipping point where more jobs depend on the clean energy economy than on the fossil fuel economy.[17]

C. Limiting Government Intervention in Energy Markets

U.S. federal and state government has a long history of involvement in energy markets. Some of this is necessary and justified, for example state regulation of utility monopolies, safety and environmental standards, and government investments in energy R&D. However, the U.S. also provides large taxpayer funded subsidies and tax breaks to the energy industry—for example from fiscal years 2002-2008 the fossil fuel industry received subsidies and tax breaks of approximately $72 billion and the renewable energy industry received $29 billion.[18] Scaling back or eliminating these subsidies and tax breaks may be desirable both to reduce government spending as well as to limit government intervention in the energy market.

Somewhat counter-intuitively, the fastest way to achieve this may be to have a strong near-term policy push on clean energy technologies to accelerate them down the Wright's Law curve and get them over the tipping point to beating fossil fuels in unsubsidized free market competition.[19] At that point subsidies and tax incentives would no longer be needed for either the fossil or clean energy industries. The market could then decide which energy technologies are most efficient in which applications and locations. As with any major technology transition, some dislocation in labor markets is inevitable as jobs are created in one sector and lost in another. Some of the subsidies saved could thus be re-deployed to help workers in fossil fuel based industries make the transition. Once we have tipped to a clean energy economy, it may also be possible to unwind a number of government regulations. For example, the shift away from large monopolistic utilities to a more de-centralized system based on renewables may provide opportunities to substitute markets for regulation. In contrast, by continuing to provide major subsidies to fossil fuels and less (and inconsistent) support to clean energy, the U.S. is delaying the tipping point, requiring a longer period of government intervention and regulation, and harming U.S. competitiveness.

3. Smart Policies: Make Clean Energy Cheap

One of the primary goals of energy policy should therefore be to drive the cost of clean energy downward and its performance upward to reach the tipping point as quickly as possible. This strategy can be thought of as "make clean energy cheap." This is in contrast to the traditional approach which has been to "make fossil energy expensive" through regulation and putting a price on carbon emissions (i.e. cap-and-trade or a carbon tax). While there are strong economic arguments for carbon prices, they have been politically difficult as there are concerns about the near-term costs on consumers, many policymakers are skeptical of increasing taxes or regulation, and not surprisingly the fossil fuel industry strongly resists this. While policymakers should continue to look for avenues to create a price on carbon, they should also examine strategies for "making clean energy cheap."

The first lever is to significantly boost clean energy R&D. The U.S. government has a strong and successful track record in "mission driven innovation"—using public investments and the power of government to mobilize massive R&D on nationally important missions.[20] From Cold War military investments, to the space program, the fight against AIDS, missions to crack the human genome, and recent efforts to fight terrorism, U.S government agencies such the Defense Advanced Research Projects Agency (DARPA), National Aeronautics and Space Administration (NASA), National Institutes of Health (NIH), and Department of Energy (DOE), have played a critical role in driving progress in a wide range of technologies with massive positive spillover effects for the U.S. and the world.

Despite the urgency and opportunity of building a clean energy economy, the U.S. government invests relatively little on renewable technology R&D, just $1 billion in 2016. Research suggests that this should be increased to around $5 billion in order to have a meaningful impact on clean energy progress.[21] The private sector also has a role to play, for example in 2015 a group of 20 entrepreneurs and investors led by Bill Gates pledged $2 billion to the Breakthrough Energy Coalition to fund clean energy development.

The second lever the government has is to pursue policies that boost clean energy demand. This creates markets, drives up production volumes, pushes technologies down the Wright's Law curve, lowers prices, and increases performance. Much of the recent progress in clean energy technologies has been attributable to demand creation policies in Europe and China. There are a variety of policy tools that would have the impact of helping create large and stable markets for clean energy technologies in the U.S., including: carbon prices, public infrastructure investment (e.g. smart grid), feed-in tariffs, capacity auctions[†], removing fossil subsidies while boosting clean energy support, performance standards, regulatory reform, and government purchasing (e.g. energy, buildings, vehicles).[22] None of these policies is a silver bullet and each has pros and cons, but a smartly crafted package of such policies, implemented consistently and at scale over the next decade, would significantly boost U.S. clean energy demand, drive prices down further, and accelerate the U.S. to the tipping point.

[†] Many utilities and governments hold auctions where private sector companies bid to provide electricity generating capacity at the lowest cost for a given set of requirements. As clean energy costs have declined, clean energy sources have become increasingly successful in these auctions.

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Just as Moore's Law revolutionized the information world, Wright's Law is revolutionizing the energy world. Clean energy technologies are riding the Wright's Law curve and will out-innovate and out-compete fossil fuel commodities in the coming decades, and will replace fossil fuels as surely as personal computers replaced typewriters. The U.S. faces a choice: It can resist this transition but not stop it, spend taxpayer money on a declining industry, jeopardize its future competitiveness, and increase risks from the climate. Or it can, in America's proud tradition as the most dynamic, innovative, and forward-looking country in the world, choose to lead.

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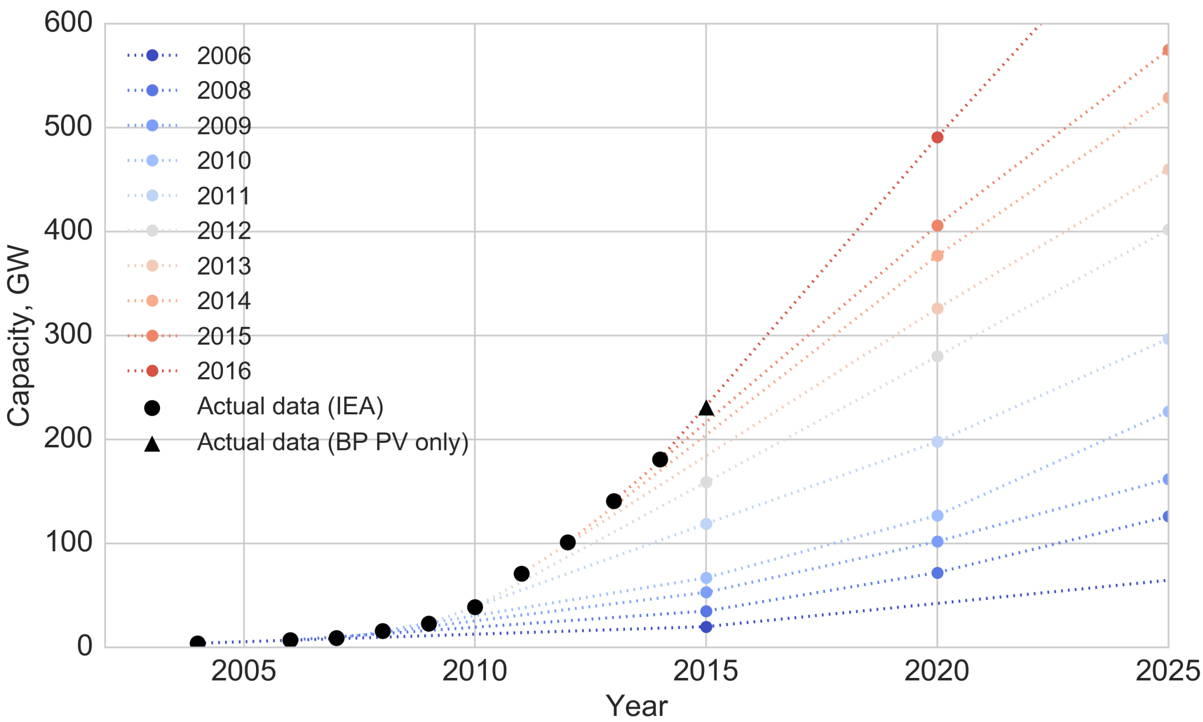
Endnotes:

[1] Also see U.S. Energy Information Administration (2016). Wind and Solar Data and Projections from the U.S. Energy Information Administration: Past Performance and Ongoing Enhancements, March 2016.
[2] Wind figure from Liebreich, M. (2016). Bloomberg New Energy Finance Summit, 5 April, 2016. Solar figure from U.S. Department of Energy, Lawrence Berkeley National Laboratory (2016). Tracking the Sun IX.
[3] Nyquist, S. (2015). Peering into energy's crystal ball. *McKinsey Quarterly*, July 2015.
[4] Henbest, S. (2017). Energy to 2040 – Faster Shift to Clean, Dynamic, Distributed. Bloomberg New Energy Finance, June 26, 2017.
[5] 2009 Nissan EV-11 (Leaf prototype) with 24 kWh Li-ion battery vs. 2016 Tesla Model S with 75 kWh battery.
[6] GM's all-electric Chevrolet Bolt was named *Motor Trend's* 2017 Car of the Year.
[7] Farmer, J.D., Lafond, F. (2016). How predictable is technological progress? *Research Policy*, 45, 647-665.
[8] McNerney, J., Farmer, J.D., Trancik, J.E. (2011). Historical costs of coal-fired electricity and implications for the future. *Energy Policy* 29 (6), 3042-3054.
[9] Fouquet, R. (2008). *Heat, Power and Light: Revolutions in Energy Services*. Edward Elgar Publications, Northampton, MA. And Fouquet, R. (2015). Lessons from energy history for climate policy. Centre for Climate Change, Economics and Policy, working paper no. 235.
[10] While the costs of fossil fuels has not trended down, the costs of fossil fuel electricity are driven by both fuel costs (a commodity) and generating costs (a technology). McNerney et. al. (2011) show that in the case of coal the technology costs of coal power (capital and O&M costs) declined in real terms 1900-1950, but as the technology matured, costs have fluctuated but not declined since. Thus, real total coal generated electricity costs (fuel plus capital and O&M) have fluctuated but not declined since the 1950s.
[11] Bloomberg New Energy Finance *New Energy Outlook 2017*, Henbest (2017), Farmer & Lafond (2016).
[12] Rogelj., Schaeffer, M., Meinshausen, M., Knutti, R., Alcamo, J., Riahi, K., & Hare, W. (2015). Zero emissions targets as long-term global goals for climate protection. *Environmental Research Letters*, 10(10): 105007.
[13] Intergovernmental Panel on Climate Change (2014), Fifth Assessment Report.

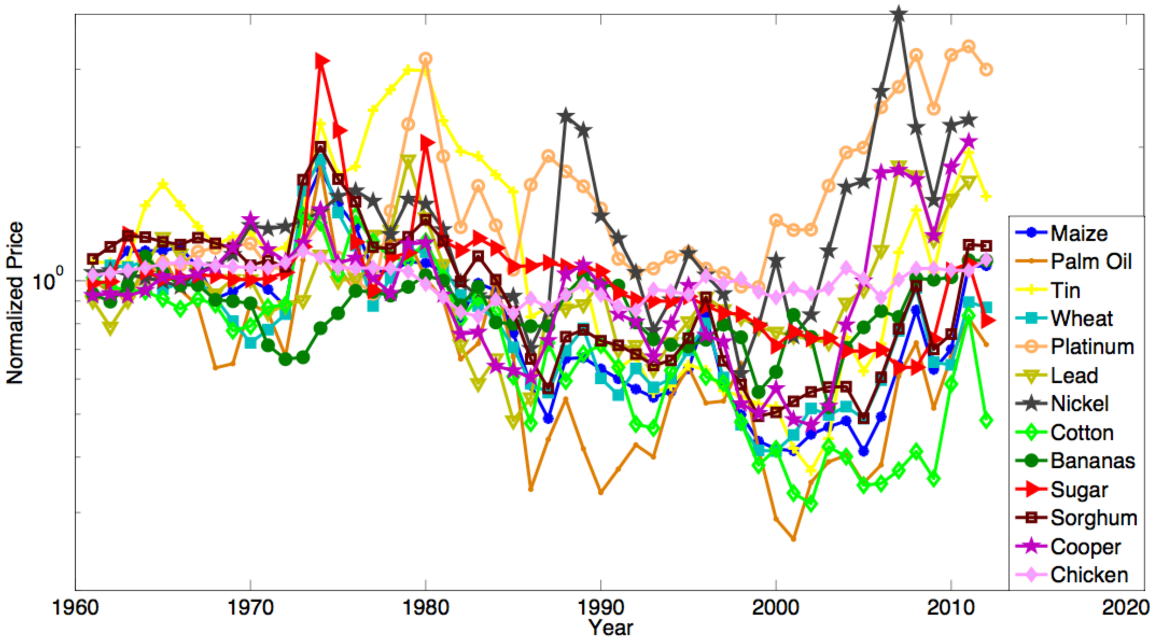
[14] Pfeiffer, A., Millar, R., Hepburn, C., Beinhocker, E. (2016). The '2ºC capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity sector and the transition to a green economy. *Applied Energy*, 179, 1395-1408.
[15] Speech by Dr. Yinbiao Shu, Chairman, State Grid Corporation of China, at the Blavatnik School of Government, University of Oxford, June 19, 2017.
[16] Bloomberg New Energy Finance, *New Energy Outlook 2016*.
[17] We may already be at this point – according to the U.S. Department of Energy, U.S. Energy Employment Report (January 2017) in 2016 1.1 million Americans worked in coal, oil, and gas while 800,000 were employed in low carbon electricity production, 2.2 million in energy efficiency products and services, and 259,00 in alternative fuel vehicles.
[18] Environmental Law Institute (2009). Estimating U.S. Government Subsidies to Energy Sources: 2002-2008. September 2009.
[19] Acemoglu D., Aghion P., Bursztyn L., and Hemous D., (2012). The environment and directed technical change. *American Economic Review,* 102(1): 131-166. And Acemoglu D., Akcigit U., Hanley D., and W. Kerr, (2016). Transition to clean technology, *Journal of Political Economy*, 124(1): 52-104.
[20] Mazzucato, M. (2015). *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*. Revised edition. Public Affairs, New York.
[21] Pless,J., Hepburn, C., Rhys, J., Farrell, N. (2017). Inducing and Accelerating Clean Energy Innovation with 'Mission Innovation'. INET Oxford working paper.
[22] Energy Innovation: Policy & Technology LLC, Policies That Work, December 2015.

Figure 1. IEA solar capacity forecasts vs. actual



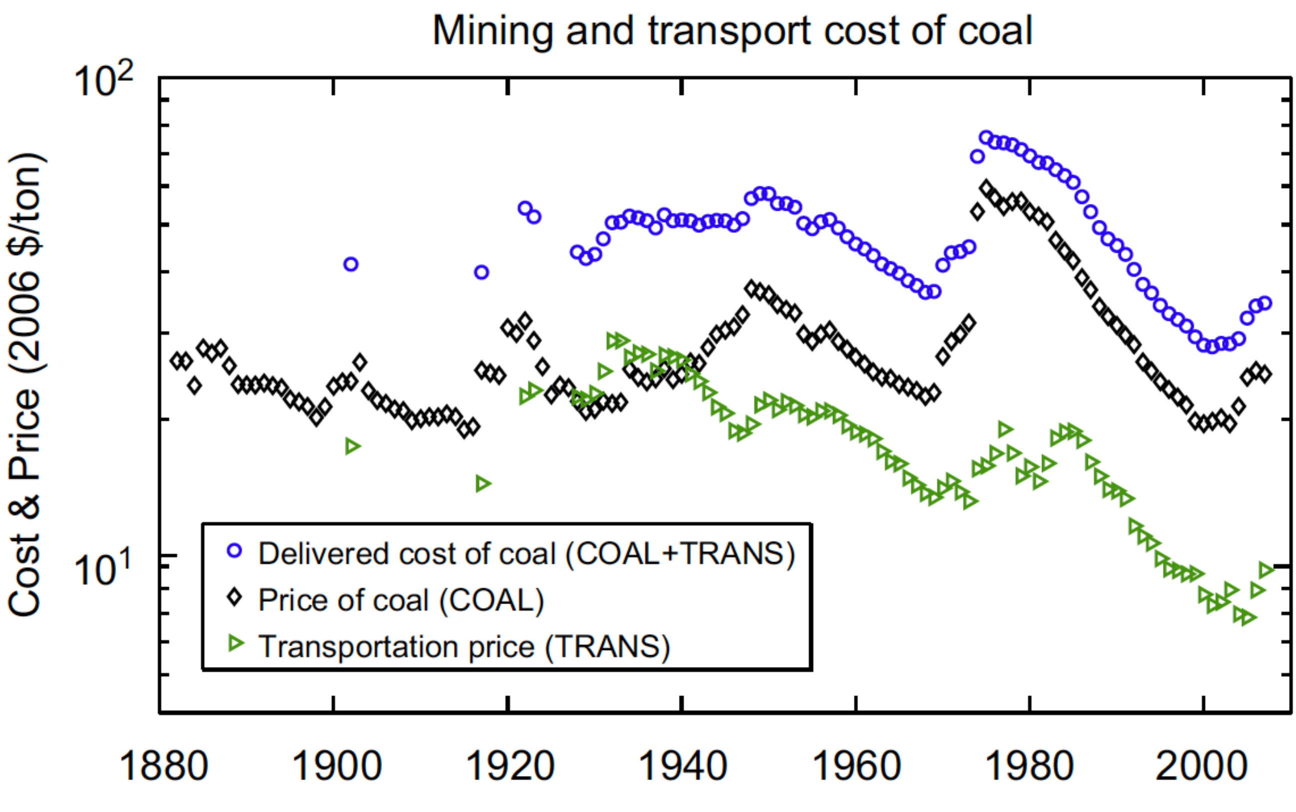
Sources: Forecasts for cumulative installed solar capacity (PV and CSP combined) from the International Energy Agency (IEA) *World Energy Outlook* (WEO) 2006-2016. Actual data from IEA except 2015 which is PV data from the 2016 BP *Statistical Review of World Energy*.

Figure 2. Commodity prices follow a random walk



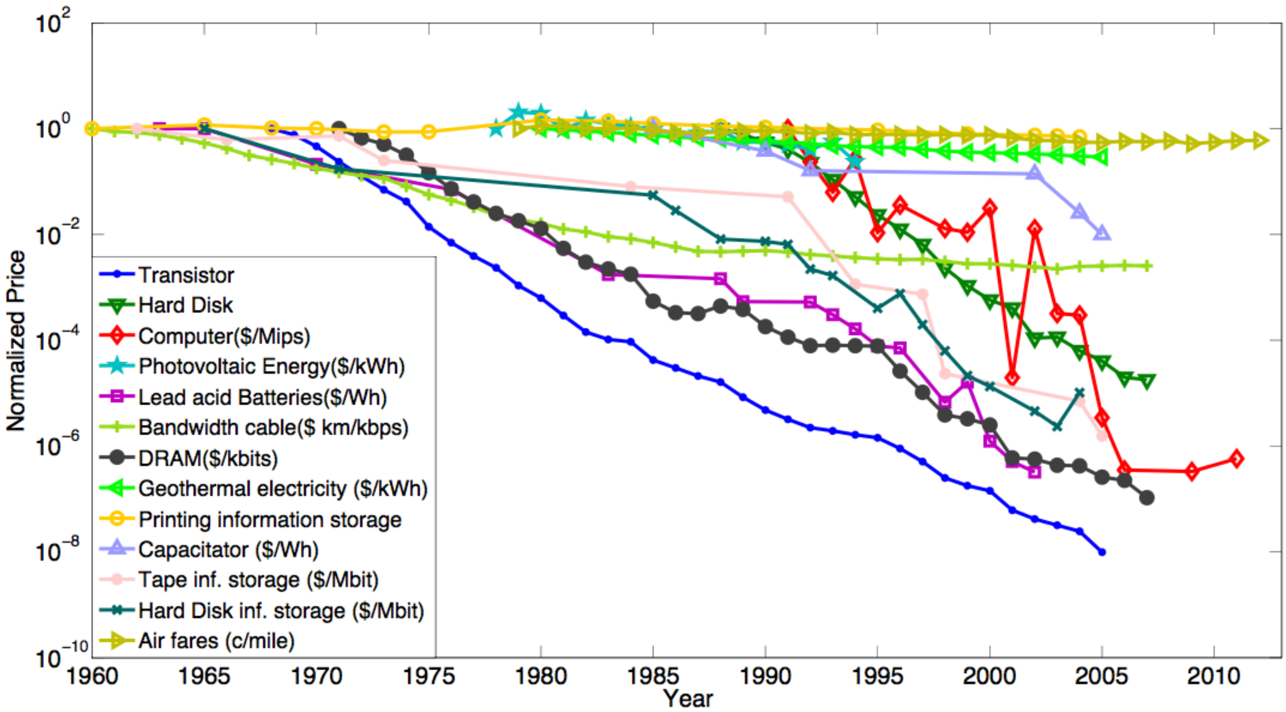
Source: Chart from J. Doyne Farmer, data from the Santa Fe Institute Performance Curve Database.

Figure 3. No long-term trend in U.S. coal costs



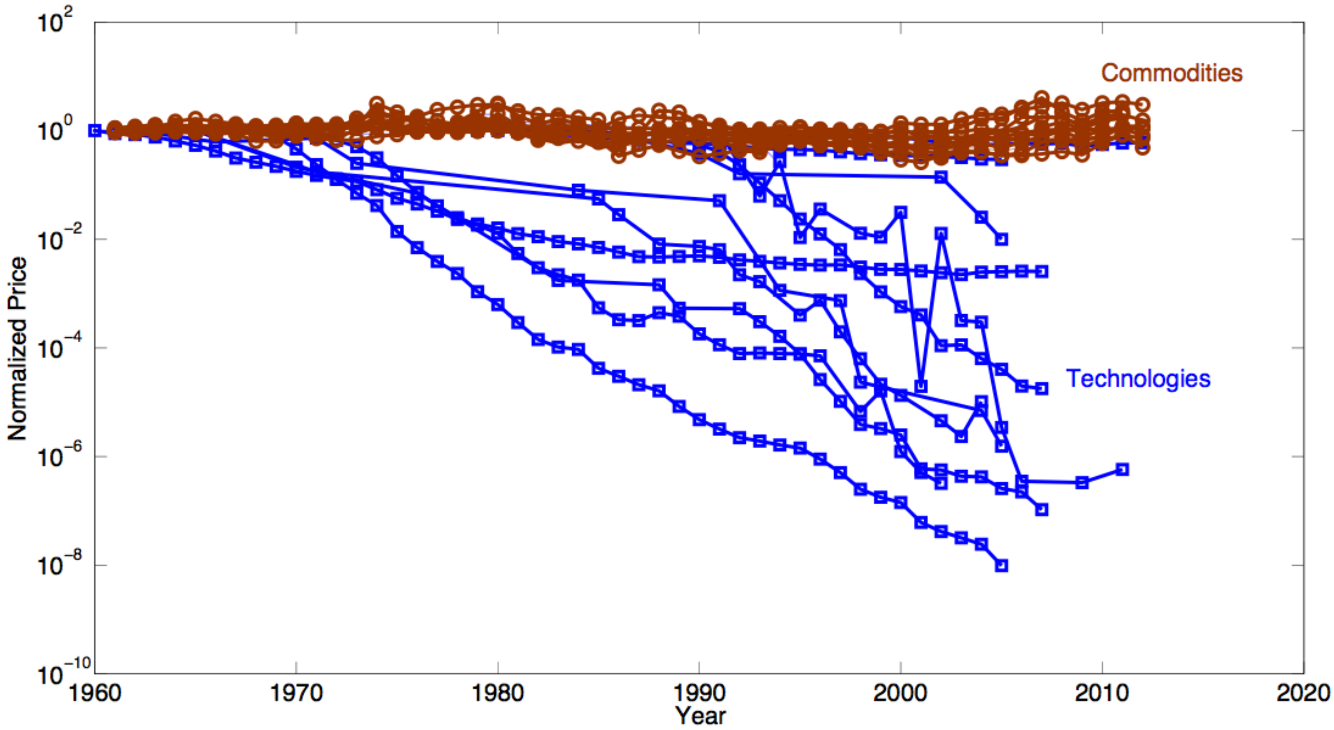
Source: McNerney, Farmer and Trancik (2011).

Figure 4. Technology prices decline



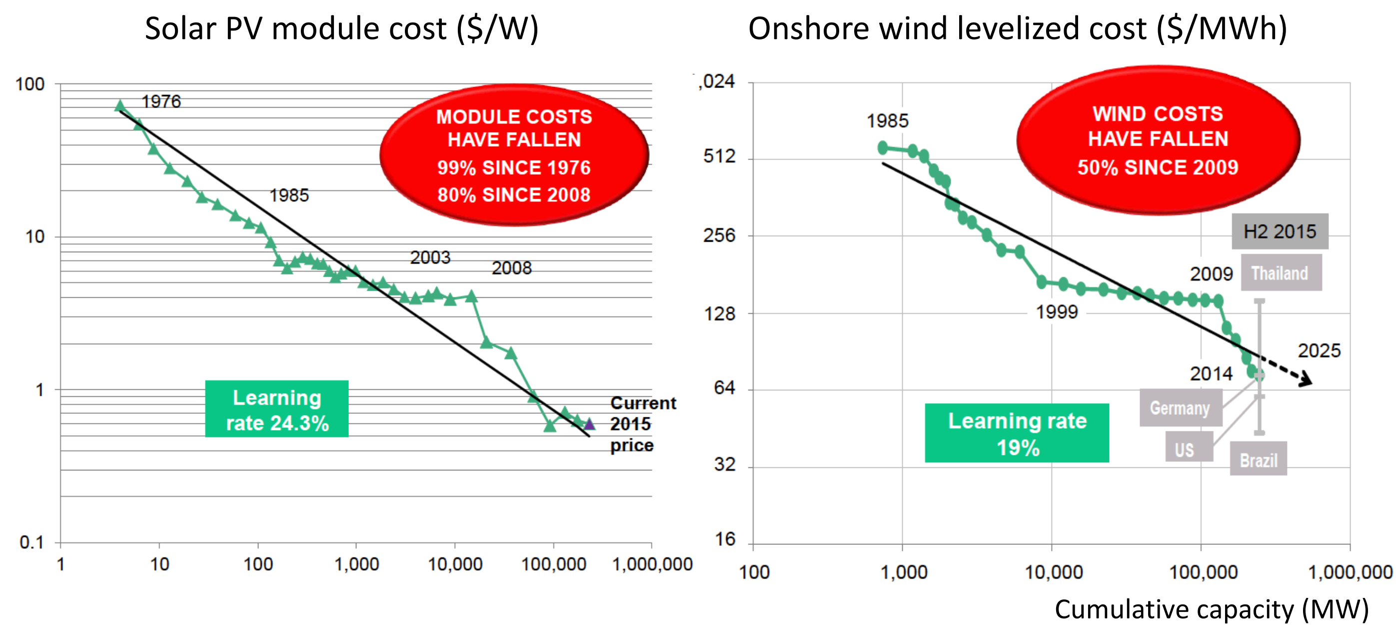
Source: Chart from J. Doyne Farmer, data from Santa Fe Institute Performance Curve Database.

Figure 5. Technologies vs. commodities price changes



Source: Chart from J. Doyne Farmer, data from Santa Fe Institute Performance Curve Database.

Figure 6. Wright's Law experience curves for solar and wind



Source: Michael Liebreich, Bloomberg New Energy Finance Summit, 5 April 2016.
Note: Solar prices in 2015 USD, wind prices in 2014 USD.