Technology improvement and emissions reductions as mutually reinforcing efforts

Observations from the global development of solar and wind energy

Policy brief

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This policy brief, written by Jessika E. Trancik and James McNerney, summarizes a report prepared in advance of COP21. The research was done in consultation with Ye Qi from the Brookings-Tsinghua Center for Public Policy, and Jiaqi Lu, Xiaofan Zhao, Tong Wu from Tsinghua University.

INTRODUCTION

The climate is a shared global resource, and preserving it requires collective action across nations.[1,2] International climate negotiations—including this year's Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change, and international engagement following the conference—present an opportunity to coordinate national and multinational efforts to mitigate climate change.[3,4]

These efforts are unavoidably linked to developing affordable low-carbon energy technologies that can be adopted around the world. Low-carbon energy will necessarily play a major role in achieving the reductions in global greenhouse gas (GHG) emissions that are needed to reach the mitigation goals set by most nations. Other mitigation options include reducing energy demand and GHGs from agriculture, waste and land-use change, but none will be sufficient alone to achieve the low levels of GHG emissions required to limit the global mean temperature increase to 2°C. Even with extreme demand-side efficiency measures, very-low-carbon energy technologies would be required to meet a significant fraction of global demand by 2050—one study finds that 60-80% low-carbon energy is required for the U.S.[5] The cost of low-carbon energy will therefore greatly influence the cost of mitigating climate change.

As negotiations have progressed over the course of meetings on five continents spanning more than two decades, discussions have reflected a growing sophistication about options to enable emissions cuts.[6] However the opportunity to use international climate change negotiations as a platform to collectively support technology innovation has not yet been fully exploited. The potential benefits of doing so are large, and include dramatically reducing climate change mitigation costs and enabling aggressive emissions reductions at a global scale. While the ability to predict technology development over time is inherently limited, growing evidence of fast rates of technological improvement and explanations of the drivers of this improvement provide some insight. Experience that has accumulated in the development of clean energy technologies, and expectations about future improvement potential should begin to more directly inform international climate negotiations.

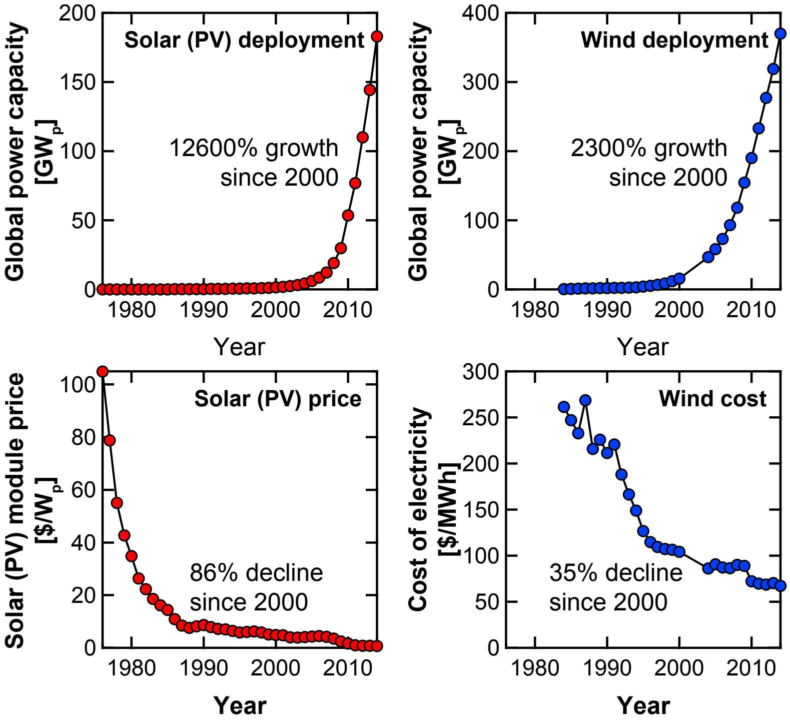
This brief describes the development of solar and wind energy in recent decades, and the potential for future expansion and cost decline under nations' climate change mitigation pledges.[7] A combination of government policies and private sector innovation have resulted in fast rates of solar and wind technology improvement in recent years, and pledges submitted in advance of the 2015 Paris climate negotiations (COP21) could further support this development. Two low-carbon energy sources—solar and wind—are the primary focus of our analysis because of their significant, and possibly exceptional, expansion potential. The insights presented can, however, also inform the evaluation of low-carbon technologies and emissions reduction efforts more broadly.

MUTUAL REINFORCEMENT OF EMISSIONS REDUCTIONS AND TECHNOLOGY IMPROVEMENT

Technologies improve with time and experience. A long-recognized observation known as Wright's Law states that the cost of a technology falls with its level of deployment according to a 'power-law' formula.[8] In intuitive terms, this observation implies that every 1% increase in the deployment of a technology is associated with some fixed percentage decrease in its cost. The percentage decrease is a number that varies across technologies, for example due to differences in technology design characteristics, and is usually measured from historical data. Technologies that are modular and small-scale may improve more quickly, though a wide variety of other factors also affect the rate of cost decline.[8,9] What is most important is that the act of deploying the technology itself is what helps bring down costs.

Any sizable commitment to emissions reduction is likely

FIGURE 1: SOLAR (PV) AND WIND: HISTORICAL GROWTH AND COST REDUCTION



to increase the deployment of low-carbon technologies. When this happens, the costs of these technologies can fall because of several factors. Deploying a technology coincides with and engages a variety of mechanisms, such as economies of scale, research and development (R&D), and learning by firms, which can drive down costs. For technologies that are bought and sold in global markets, such as solar (photovoltaics) modules, improvements accumulate as a result of the cumulative efforts of all nations and firms, and the improved technology benefits all global citizens.

Such cost reductions represent a hidden return to emissions reduction. With lower costs, the amount of low-carbon technology that can be deployed for a fixed expenditure goes up. Lower costs open up new deployment opportunities, creating a positive feedback. The result is a cycle of mutual reinforcement: Decreasing costs enable larger emissions reductions, and larger emissions reductions drive further cuts to cost. The very deployment of low-carbon energy technologies that are necessary to effect emissions cuts helps bring about cost reductions that make further cuts more feasible.

This mutual reinforcement carries significant implications for the strategic collaboration among countries in mitigating climate change. Understanding the positive feedback between technology improvement and emissions reductions may help support collective action on climate change, by lessening concerns about the costs of committing to reducing emissions. The cycle of emissions reductions and technology improvement may allow countries to commit to longer-term emissions cuts, based on plans to phase in low-carbon energy over time at a rate that supports their economic development. By the time the least developed nations are required to cut emissions, technology development through a global collective effort should make doing so a benefit rather than a burden.

(Based on countries' climate policy pledges, for example in China, India, and Costa Rica, some growing economies may already perceive economic opportunity in deploying low-carbon energy.)

In the case of low-carbon energy technologies, the magnitude of this mutual reinforcement can be large. For example, between 2000 and 2014, falling costs of photovoltaics made the cost of avoiding greenhouse gas emissions with this technology fall by 85%. (The abatement cost here is based on a comparison of coal electricity and photovoltaics installed in the U.S.) This drop in cost is significant, as is the observation that the deployment of these technologies was primarily motivated by a collection of climate-change-related government policies.

HISTORICAL PATTERNS OF SOLAR (PV) & WIND DEVELOPMENT

Among low-carbon electricity technologies, solar and wind energy are exemplary of how an expanding, policy-driven market for emissions reductions can be self-reinforcing (Figure 1). Solar and wind energy costs have dropped rapidly over the past few decades, as markets for these technologies have grown at rates far exceeding forecasts. Wind capacity costs fell by 75% over the past three decades. Decreases in the costs of solar have been particularly rapid. For example, since 1976, photovoltaics (PV) module costs have dropped by 99%, meaning that for the same investment, 100 times more solar modules can be produced today. Over the last 15 years, the cost of abating carbon from coal-fired electricity with solar in the U.S. has fallen by a factor of seven. Over the last 40 years, the cost has decreased by at least a factor of 50 (given a flat average coal fleet conversion efficiency in the U.S. during this period).

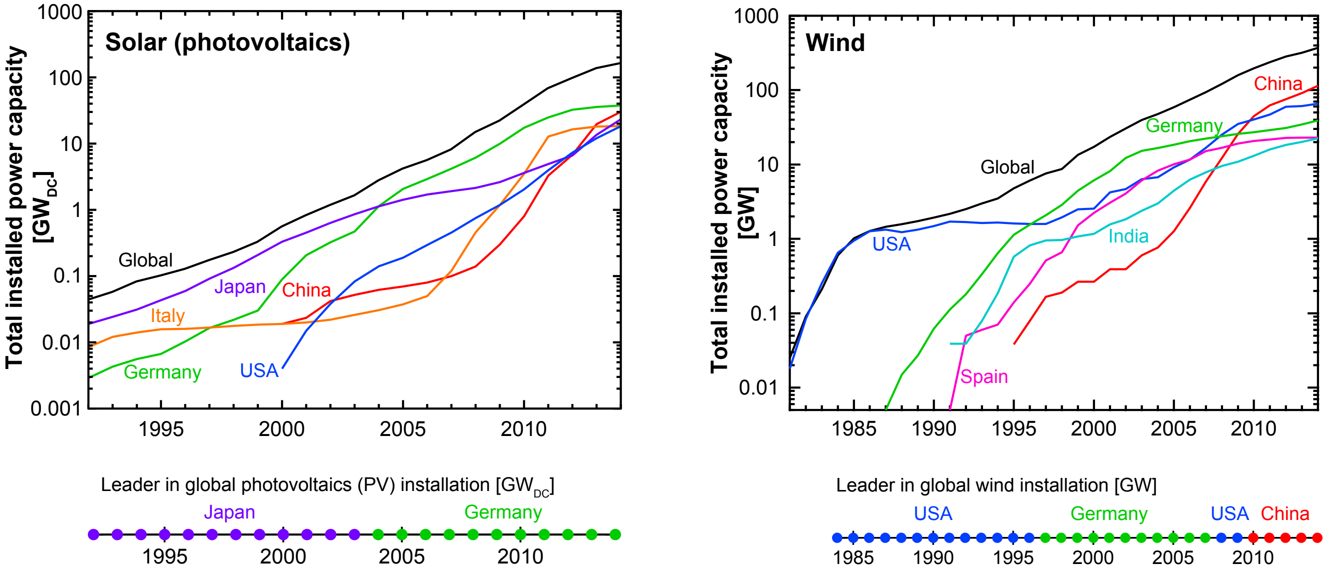
Today, wind energy is cost-competitive, or nearly so, with natural gas- and coal-fired power plants in many regions, as measured by the levelized cost of energy (LCOE). Globally-averaged onshore wind electricity costs are estimated to be lower than central estimates for many other energy sources at the global level. Photovoltaics falls within the range of estimated costs for natural gas and coal electricity at the global level, though it is still significantly above central estimates for the costs of these technologies (Figure 4). However, when the health costs of air pollution are considered, the competitiveness of PV compared to natural gas or coal-fired electricity improves significantly. Furthermore, with a carbon tax of \$100/ton CO_2 (less than the current carbon tax in Sweden[10]), PV is competitive with natural gas or coal fired electricity at the global level.

The installed capacity of wind and solar has doubled roughly every three years, on average, over the past 30 years. These growth rates have exceeded expectations. For example, in its 2006 World Energy Outlook the International Energy Agency projected a cumulative solar (PV) and concentrated solar power (CSP) capacity for 2030 that was surpassed by 2012.[11] The Energy Information Agency 2013 International made a projection for cumulative PV and CSP capacity in 2025 that was similarly surpassed in 2014.[12] While the global expansion in the deployment of wind and especially solar has consistently outstripped projections, fossil generation capacity has largely followed projections, and nuclear generation capacity has significantly undershot projections. IEA projections have been continuously revised upward to capture solar and wind growth.

Getting these technologies to their current state of development was a collective accomplishment across nations, despite minimal coordination. Public policies to stimulate research and market growth in more than nine countries in North America, Europe, and Asia—including the U.S., Japan, Germany, Denmark, and more recently, China—have driven these trends (Figure 2). Firms responded to these incentives by both competing with and learning from one another to bring these low-carbon technologies to a state where they can begin to compete with fossil fuel alternatives. Technology improved as a result of both research and successful private-sector commercialization efforts.

OVER THE LAST 15 YEARS, the cost of avoiding carbon emissions in the U.S. by choosing solar (photovoltaics) over coal-fired electricity has dropped by 85%. Over the last 40 years, the cost has fallen by at least a factor of 50. These cost declines were due to technology improvement, driven by government policies and private sector innovation.

FIGURE 2: COUNTRY LEADERSHIP IN SOLAR (PV) AND WIND



INTENDED NATIONALLY DETERMINED CONTRIBUTIONS

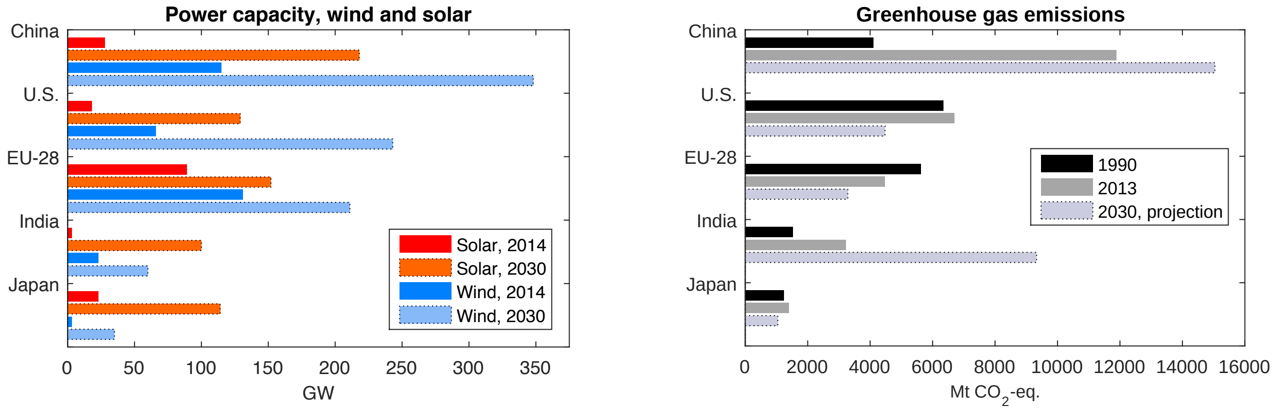
Capacity Growth, Cost Decline

Intended Nationally Determined Contributions, or INDCs, are pledges for emissions reductions by countries. Countries' pledges in advance of COP21 have largely been assessed by their potential to limit global mean surface temperature increase,[13] and have been found to fall short of global climate change mitigation goals. While emissions reduction commitments should be the primary metric by which pledges should be assessed, another important aspect of INDCs is their potential to expand low-carbon energy. The reason that this is important is that technology innovation resulting from expanding renewables markets can reduce the costs of cutting energy sector emissions, and thereby enable more ambitious emissions reduction pledges.

Collectively, current GHG emissions reduction pledges offer an opportunity for substantial clean energy expansion. If the top emitters—China, U.S., EU-28, India, and Japan—achieve a significant share of their proposed cuts by decarbonizing their electricity sectors, the global installed capacity of wind and solar could grow significantly (Figure 3). In a renewables-focused scenario, global installed capacity of solar would grow by a factor of 4.9, and wind by a factor of 2.7. Much of this growth could happen in China, the U.S., India, and the EU. China's wind and photovoltaics capacity could grow by factors of 8 and 3, adding roughly one third of cumulative wind and photovoltaics capacity between 2014 and 2030. At a global scale, it is estimated that wind and solar would provide 8.9% and 3.8% of electricity in 2030 under these

CURRENT CLIMATE CHANGE MITIGATION COMMITMENTS by nations in advance of the 2015 Paris climate negotiations could collectively result in significant further growth in wind and solar installations. If countries and markets emphasize renewables expansion, solar and wind capacity could grow by factors of 4.9 and 2.7 respectively between the present day and 2030.

FIGURE 3: WIND AND SOLAR EXPANSION UNDER INDCs, BY COUNTRY



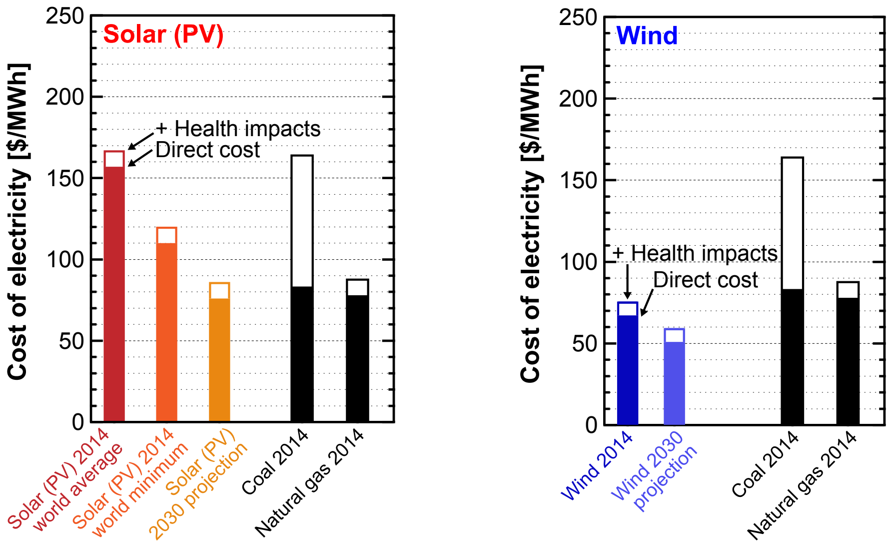
scenarios.

Under these expansion scenarios, the costs of solar and wind energy may decline further. There can be many reasons for the fall in cost. Producers gain experience (‘learning’) as they produce the technology, leading to improved designs and production methods. Scale economies yield cost reductions from increasing the scale of manufacturing, independent of accumulated experience. Improvements are also made through research and development and spillover benefits from borrowing production techniques first developed in other industries. Separating the effects of these mechanisms is often very difficult, but several simple empirical relationships such as Wright’s Law have been shown nonetheless to have some predictive power.[14]

Wright’s Law is the basis for the most widely used approach to forecasting technology costs, and the approach with the best empirical support.[14] This is our primary tool used for projecting the future cost of photovoltaics and wind power under estimated future expansions. Wright’s Law is the observation that, for many technologies, costs fall with the cumulative deployment of the technology according to a formula known as a power-law. For wind and PV hardware costs, the Wright’s Law model has performed relatively well at predicting costs historically. For PV balance-of-system costs, which are dominated by many factors beyond hardware manufacturing—the costs of on-site construction and financing, labor, permitting fees, site inspection and preparation, local taxes—Wright’s Law is not the method of choice. For these costs, expert elicitation provides for better projections.[15]

Based on future technology development scenarios, past trends, and technology cost floors, we estimate that renewables expansion under the current INDC commmitments could achieve a cost reduction of up to 50% for the LCOE of solar (PV) and up to 25% for wind. The projected cost of abating CO_2 emissions from a coal-fired power plant

FIGURE 4: COST COMPETITIVENESS OF SOLAR (PV) AND WIND



with wind is actually negative: $-35\ \$/\mathrm{ton\ CO_2}$. For solar, the projected abatement cost varies from $+15\ \$/\mathrm{ton\ CO_2}$ to $-8\ \$/\mathrm{ton\ CO_2}$. Forecasts are inherently uncertain, but even under more modest cost reduction scenarios, the costs of these technologies decrease over time.

The 2030 LCOE estimates shown provide a basis for assessing the cost-competitiveness of solar (PV) and wind electricity with conventional thermal generation. New solar (PV) generation at the world-average system cost and capacity factor is not economically competitive with average new-build coal and natural gas combined cycle (NGCC) generation today.[1] In most of our 2030 cost reduction scenarios, however, solar reaches costs roughly comparable to coal and NGCC. World-average costs for wind electricity are already competitive with fossil generation today, but further cost declines toward our 2030 projections would make wind power the lowest-cost electricity source in many parts of the world.

The findings above hold for global averages, but not necessarily for individual countries or locations: For example, a country with abundant sunlight may have a much lower LCOE for solar (PV) than the world average; similarly, a country without substantial domestic natural gas reserves may have a significantly higher LCOE for NGCC than the world average. Thus solar may already be cost-competitive with thermal generation in some locations. We emphasize that these conclusions apply to busbar costs only, for utility-scale plants. In locations where policy allows distributed generation to be compensated at retail electricity rates, many solar (PV) and wind generators are already at retail grid parity today.

Projections into the future are inherently uncertain, but conclusions can be drawn that are robust to these uncertainties. Under a wide range of cost evolution scenarios, wind and solar energy are widely cost competitive with other sources by 2030. Even if wind costs remained constant, this technology is already widely competitive. China is an exception: Due to lower coal-fired energy costs in China, solar and wind are both expected to have higher energy costs, even in 2030. However, when the health impacts of coal are monetized and included in electricity cost estimates, solar and wind energy in China are both expected to fall within the cost-competitive range.

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[1] Legacy (fully amortized) plants can achieve much lower levelized operating costs than new generators.

Reinvesting Cost Savings Into Emissions Reduction

The projected decline in the LCOE of PV and wind has important implications for climate change mitigation efforts. Compared to a case in which future cost improvements are not taken into account, this decline enables more ambitious low-carbon energy deployment commitments to be made for the same level of investment. Figure 5 illustrates this effect for PV and wind, with several key assumptions: We assume constant global capacity factors from 2015 to 2030 (17.1% for PV and 35% for wind) and that the levelized cost of electricity for a given project (based on our central cost projections described above) is applicable for the full project lifetime. Project retirements do not affect these results, as typical project lifetimes are longer than the 15-year horizon considered here. We assume that annual deployment (GW/year) evolves with a constant annual percentage change to reach the cumulative target in 2030. While these assumptions simplify the true picture, in which capacity factors and LCOE values vary widely across the globe, this central case reveals general trends that would also apply in a more detailed analysis.

Reaching 858 GW of PV and 1014 GW of wind in 2030 under these conditions would result in the cumulative generation of an additional 8378 TWh of energy from PV and 18,003 TWh from wind over the period from 2015 to 2030, on top of the energy produced by the existing generation fleet in 2014. At today's average costs (157 $/MWh for PV and 67 $/MWh for wind), with no reductions in LCOE, this energy would carry a gross cost (not subtracting the cost of displaced electricity that would otherwise have been generated from other sources) of $1.32 trillion for PV and $1.21 trillion for wind. If projected cost declines are taken into account, however, cumulative deployment levels of 1210 GW PV and 1207 GW wind could be reached by 2030 with the same total capital outlay.

The potential for technology development to amplify emissions reductions is evident in these projections. The more that countries and firms commit to developing renewables, the faster the cost of doing so is expected to fall. This translates to a decrease in the cost of reducing emissions with these technologies over time. At today's cost, reaching a global commitment of installing 1014 GW of wind in 2030 would cost $1.32 trillion. If projected cost declines are taken into account, we estimate the same investment would actually purchase 1207 GW—a 20% increase (Figure 5). Thus projected cost declines would permit a 20% increase to emissions reductions commitments without changing total cost of deployment. Taking into account cost declines for solar, a global commitment of 858 GW could be increased to 1210 GW, yielding a 40% increase to commitments without changing the cost of deployment.

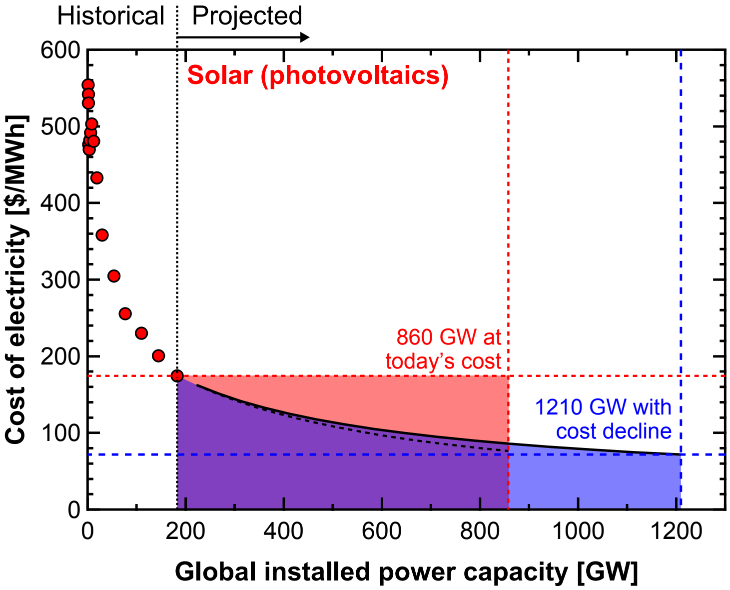
SUSTAINING EMISSIONS REDUCTIONS

Addressing Intermittency

Growth to these levels will require addressing the intermittency of solar and wind as the market share of these technologies grows. Due to the intermittent nature of renewable electricity generation, there is often a temporal or spatial mismatch between electricity generation and electricity demand. Intermittency can compromise the ability of the energy supply to meet demand in a variety of ways. Forecast errors can lead to differences between available power and commitments in the day-ahead market. Uneven resource availability across locations can require costly transmission grid upgrades, and high-frequency fluctuations can require back-up generation. A growing supply of electricity during certain times of the day, as renewable power capacity grows, can also lead to renewable electricity being sold at times of lower-than-average prices. These factors can all lead to declines in the value of renewables as their level of market penetration increases,[16] without additional measures such as energy storage, back-up generation, long-distance transmission, and demand management.

A diverse set of storage technologies in various stages

FIGURE 5: REINVESTING COST SAVINGS INTO EMISSIONS REDUCTION



IF PROJECTED COST DECLINES ARE TAKEN INTO ACCOUNT, the same investment in wind energy would actually purchase 1207 GW—a 20% increase. Thus projected cost declines would permit a 20% increase to emissions reductions commitments, without changing the total cost of deployment. Taking into account cost declines for solar, a global commitment of 858 GW could be increased to 1210 GW, yielding a 40% increase to commitments without changing the cost of deployment.

of development are expected to lower the cost of energy storage significantly. Many of the lowest cost technologies for bulk storage available today, such as pumped hydro storage and compressed air energy storage, tend to be location-constrained. Other storage technologies such as batteries do not have geographic constraints and have shown consistent cost reductions over time.[17] However, a major effort will be required to develop affordable energy storage. Government policies will be required to grow markets for storage technologies and to stimulate innovation.

To mitigate costs due to spatial mismatch, increased investment in transmission infrastructure will allow for improved plant siting—i.e., locating renewables where resource availability is greatest, regardless of the distance from load centers. Additional transmission infrastructure will also provide natural smoothing of the short-term output of renewables.[18] Long-distance transmission can help reduce power fluctuations in wind and solar output as more geographically distant sites will have lower correlations in resource availability.[19]

Finally, demand management technologies and policies work to more closely match electricity demand with electricity generation by catalyzing reductions in demand at times of lower resource availability.[20] Matching demand and generation on both short and long time scales mitigates both the loss in marginal value experienced by renewables at higher penetrations and the grid stability concerns associated with variable generation. Some proposed demand management schemes aggregate household or commercial loads and sell demand reductions to utilities.[21]

Even with investments in bulk energy storage, additional transmission infrastructure, and demand management, lower-carbon, combustion-based technologies such as combined cycle gas turbines (CCGTs) can provide an important bridge toward widespread solar and wind integration. In the event of longer-than-expected disruptions in renewable production or dramatic spikes in demand, CCGTs can quickly spin up to meet demand, a capability that can obviate the need for investment in storage or transmission infrastructure to cover these rare events.[22,23] Targeted investment in natural gas generation capacity will allow for faster widespread deployment of renewable technologies at lower cost and with less risk of supply disruption.

Reducing Soft Costs

Knowledge sharing to bring down the soft costs of low-carbon energy technologies will also be important. Soft costs include payments for labor, permitting and installation, financing, and supply chain margins. Unlike hardware costs, soft costs vary significantly between regions.[24] In low-cost countries such as Germany, soft costs are a slightly more than half these costs in Japan. As figure 4 shows, simply reducing these costs by adopting best practices would significantly improve the competitiveness of solar (PV).

Improvements to modular hardware—which can be manufactured in one location and installed in another—are globally accessible. The case of PV illustrates this point. PV modules and inverters have fallen in cost over the years, and these cost improvements have been accessible to all through the global marketplace for PV modules. Public policy incentives can stimulate the private sector to develop exportable, combined software-and-hardware systems to reduce construction costs around the world.

RECOMMENDATIONS

International climate negotiations offer an opportunity to support a virtuous cycle of emissions reductions and low-carbon technology development. As a path to emissions reductions, solar and wind technologies are already in a cost competitive state in many regions and are still rapidly improving. Further commitments to emissions cuts can accelerate this process. The more that parties to negotiations are aware of the state of these technologies, and the extent to which the positive feedback between emissions reduction policies and technology development can bring on further improvements to these and other low-carbon technologies, the more catalyst there may be for collective action on climate change.

Our major recommendation, therefore, is for parties to international climate negotiations to explicitly consider the technology improvement dynamics that occur in response to emissions reduction efforts. Recent technology improvement arguably shifts the development of low-carbon energy from burden to opportunity for governments and firms. Technology development can be seen as a return to cutting emissions. Recognizing the large size of this return, as has been observed in recent years, can help strengthen emissions reduction commitments.

While climate policies should center on reducing greenhouse gas emissions, and utilizing market forces to select the most cost-effective approach, several strategies to support technology innovation can play a critical role. **These strategies include:**

- making favorable loans widely available globally, to finance low-carbon energy development;
- providing incentives for global knowledge-sharing, and innovation (through competition) by companies, to reduce the ‘soft costs’ of installing low-carbon energy systems in any location;

IMPROVEMENTS TO HARDWARE—which can be manufactured in one location and installed in another—are globally accessible. The case of solar energy (photovoltaics) illustrates this point.

- and adopting government policies to drive innovation in energy storage, demand management, and other means of dealing with renewables' intermittency.

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REFERENCES

[1] E. Ostrom, J. Burger, C. B. Field, R. B. Norgaard, and D. Policansky, “Revisiting the commons: local lessons, global challenges,” *Science*, vol. 284, no. 5412, pp. 278–282, 1999.

[2] T. Dietz, E. Ostrom, and P. C. Stern, “The struggle to govern the commons,” *Science*, vol. 302, no. 5652, pp. 1907–1912, 2003.

[3] J. F. Green, T. Sterner, and G. Wagner, “A balance of bottom-up and top-down in linking climate policies,” *Nature Climate Change*, vol. 4, no. 12, pp. 1064–1067, 2014.

[4] M. Ranson and R. N. Stavins, “Linkage of greenhouse gas emissions trading systems: Learning from experience,” *Climate Policy*, 2015.

[5] J. E. Trancik, M. T. Chang, C. Karapataki, and L. C. Stokes, “Effectiveness of a segmental approach to climate policy,” *Environmental Science & Technology*, vol. 48, no. 1, pp. 27–35, 2013.

[6] J. Gupta, “A history of international climate change policy,” *Wiley Interdisciplinary Reviews: Climate Change*, vol. 1, no. 5, pp. 636–653, 2010.

[7] J. E. Trancik, P. Brown, J. Jean, G. Kavlak, M. Klemun, M. Edwards, J. McNerney, M. Miotti, J. Mueller, and Z. Needell, “Technology improvement and emissions reductions as mutually reinforcing efforts: Observations from the global dvelopment of solar and wind energy,” tech. rep., Institute for Data, Systems, and Society, MIT, 2015.

[8] J. D. Farmer and J. E. Trancik, “Dynamics of technological development in the energy sector,” in *London Accord Final Publication* (J. P. Onstwedder and M. Mainelli, eds.), 2007.

[9] J. McNerney, J. D. Farmer, S. Redner, and J. E. Trancik, “Role of design complexity in technology improvement,” *Procceedings of the National Academy of Sciences*, vol. 108, no. 22, pp. 9008–9013, 2011.

[10] International Energy Agency, “Energy policies of IEA countries Sweden 2013,” tech. rep., 2013.

[11] International Energy Agency, “World Energy Outlook 2006-2014,” tech. rep., 2006.

[12] U.S. Energy Information Administration, “International Energy Outlook 2013,” tech. rep., U.S. Energy Information Administration, 2013.

[13] G. P. Peters, R. M. Andrew, S. Solomon, and P. Friedlingstein, “Measuring a fair and ambitious climate agreement using cumulative emissions,” *Environmental Research Letters*, vol. 10, no. 10, p. 105004, 2015.

[14] B. Nagy, J. D. Farmer, Q. M. Bui, and J. E. Trancik, “Statistical basis for predicting technological progress,” *PLoS ONE*, vol. 8, p. e52669, 2013.

[15] Fraunhofer Institute, “Current and future cost of photovoltaics,” tech. rep., 2015.

[16] L. Hirth, “The market value of variable renewables, The effect of solar wind power variability on their relative price,” *Energy Economics*, vol. 38, pp. 218–236, 2013.

[17] B. Nykvist and M. Nilsson, “Rapidly falling costs of battery packs for electric vehicles,” *Nature Climate Change*, 2015.

[18] T. Brown, "Transmission network loading in Europe with high shares of renewables," *IET Renewable Power Generation*, vol. 9, no. October 2014, pp. 57–65, 2015.

[19] E. Fertig, J. Apt, P. Jaramillo, and W. Katzenstein, "The effect of long-distance interconnection on wind power variability," *Environmental Research Letters*, vol. 7, no. 3, p. 034017, 2012.

[20] B. Dupont, C. De Jonghe, L. Olmos, and R. Belmans, "Demand response with locational dynamic pricing to support the integration of renewables," *Energy Policy*, vol. 67, pp. 344–354, 2014.

[21] B. Biegel, L. H. Hansen, J. Stoustrup, P. Andersen, and S. Harbo, "Value of flexible consumption in the electricity markets," *Energy*, vol. 66, pp. 354–362, 2014.

[22] C. Carraro, M. Tavoni, T. Longden, and G. Marangoni, "The optimal energy mix in power generation and the contribution from natural gas in reducing carbon emissions to 2030 and beyond," 2013.

[23] A. Lee, O. Zinaman, and J. Logan, "Opportunities for synergy between natural gas and renewable energy in the electric power and transportation sectors," tech. rep., National Renewable Energy Laboratory, 2012.

[24] K. Ardani, D. Seif, R. Margolis, J. Morris, C. Davidson, S. Truitt, and R. Torbert, "Non-hardware ("soft") cost-reduction roadmap for residential and small commercial solar photovoltaics, 2013-2020," Tech. Rep. NREL/TP-7A40-59155, National Renewable Energy Laboratory, 2013.