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ISSUE BRIEF

BY ROBERT A. MANNING

Renewable Energy's Coming of Age: A Disruptive Technology?

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In an era of emerging transformational technologies that promise to have disruptive economic and strategic impacts—from 3D printing and robotics to biotech—renewable energy is rarely at the top of futurists' lists.[1] But maybe it should be. Continuing long-term trends point to a steady decline in prices and parallel increases in efficiency by 2035. Solar and wind energy in particular will, at a minimum, provide a substantially larger portion of electricity in the United States, Europe, and elsewhere than they do now. Currently, more than 31 billion tons of CO_2 are released worldwide annually from electricity use and transportation; heightened concerns about climate change have been a key driver of the surge in the investment and deployment of renewable energy, and will likely continue to drive innovation in and the adoption of sustainable clean-energy sources into the future.

Gradually but inexorably, the world is transforming how it creates and uses energy. The European Union (EU), for example, seeks to get 20 percent of its energy from renewable sources by 2020, with an additional legally binding target of 27 percent by 2030, as outlined in its 20-20-20 energy/climate plan.[2] Similarly, US President Barack Obama aims to get 20 percent of US electricity from renewables by 2020.[3] These goals are all in the realm of the feasible. One unusually optimistic study by the US Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) projects that in the best-case scenario, assuming major investments are made in the US energy system, renewables could provide 80 percent of the country's electricity by 2050.[4] The Organization for Economic Cooperation and Development (OECD) nations, for their part, will obtain over 54 percent of their power capacity from renewables by 2040, up from one-third in 2014, according to a recent Bloomberg energy

1 McKinsey Global Institute's study, "Disruptive Technologies: Advances That Will Transform Life, Business and the Global Economy," May 2013, includes renewable energy as a potentially disruptive technology, but forecasts that it will provide only 16 percent of world energy by 2025. See http://www.mckinsey.com/insights/business_technology/disruptive_technologies.

2 The EU's plan is to obtain 20 percent of its electricity from renewables and to achieve a 20 percent reduction in energy use and a 20 percent reduction in greenhouse gas emissions by 2030.

3 The White House, Office of the Press Secretary, "Fact Sheet: President Obama Announces New Actions to Bring Renewable Energy and Energy Efficiency to Households across the Country," August 24, 2015, https://www.whitehouse.gov/the-press-office/2015/08/24/fact-sheet-president-obama-announces-new-actions-bring-renewable-energy.

4 National Renewable Energy Laboratory (NREL), "Renewable Electricity Futures Study," 2012, http://www.nrel.gov/analysis/re_futures/.

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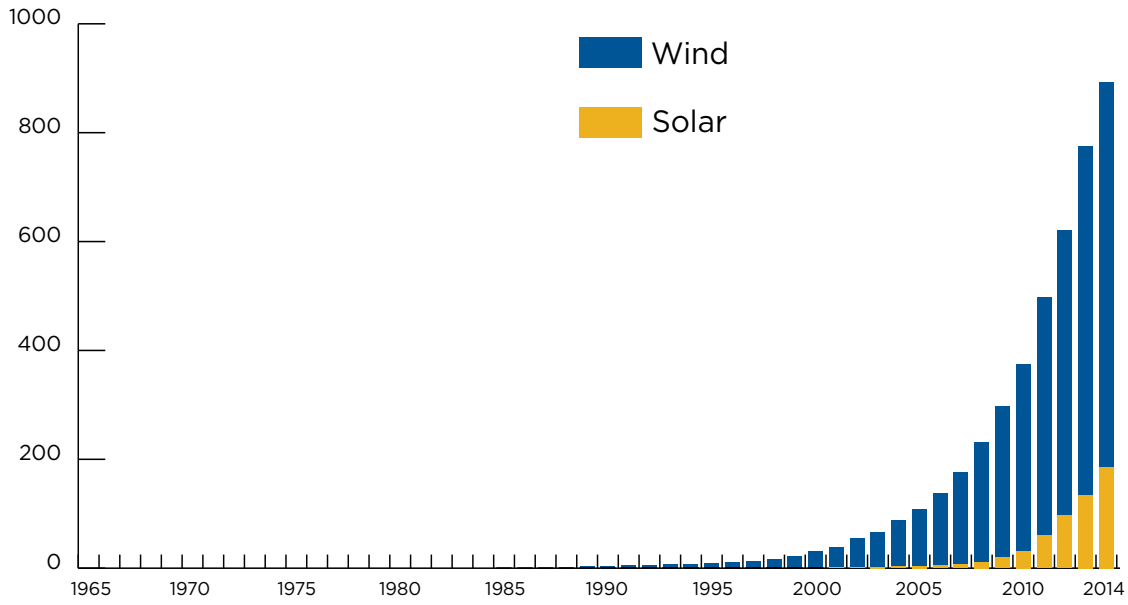
Graph 1. World Total Consumption of Solar and Wind Energy (Terawatt-hours)



Source: *BP Statistical Review of World Energy*, 2015.

outlook report.[5] When Saudi Arabia, the world's largest oil exporter, seeks to become a global solar power, the energy paradigm is clearly starting to shift.[6]

In the best-case scenario, the intersection of solar and wind with other key transformational technologies—such as energy storage, big data, and advanced materials—could approach an inflection point by 2035-40. These technologies could displace fossil fuels' leading role in the energy mix so that a transition to a post-petroleum world can begin.

Historically, however, energy transitions have tended to occur slowly over several decades. For example, the global transition from wood to coal began in 1840, when coal accounted for 5 percent of energy use; coal did not reach 50 percent of worldwide energy use until 1900.[7] The massive scale of required investment and infrastructure, in addition to the slow maturation process of cost-competitive new technologies, helps explain the lengthy timetable required to transform energy systems.

This report explores several key questions regarding the potential rise in wind and solar energy use:

- What are the prospects for more than incremental increases in solar and wind energy to 2035?
- What are the economic, political, and technological impediments to breakthroughs in renewables that would impede the transformation of the energy markets?
- What would be the economic and geopolitical consequences of a major shift from relying on natural gas and coal as sources of electricity to solar and wind?
- Who would be the winners and losers of such a shift?

Why Solar and Wind?

Renewable resources—those that are naturally replenished on a human timescale—include hydropower, biomass (wood), biofuels, geothermal, and ocean tides.[8] Renewables currently comprise 14 percent of total electricity use in the United States.[9] Solar and wind make up 6 percent of that figure, while hydropower, wood, and biofuels account for the rest.

This piece focuses on solar and wind energy for three reasons: they are the fastest growing sources of renewable energy by an order of magnitude; they are converging with other rising and complementary

5 Bloomberg New Energy Finance, "New Energy Outlook 2015: Long-Term Projections of the Global Energy Sector," 2015, http://about.bnef.com/content/uploads/sites/4/2015/06/BNEF-NEO2015_Executive-summary.pdf.

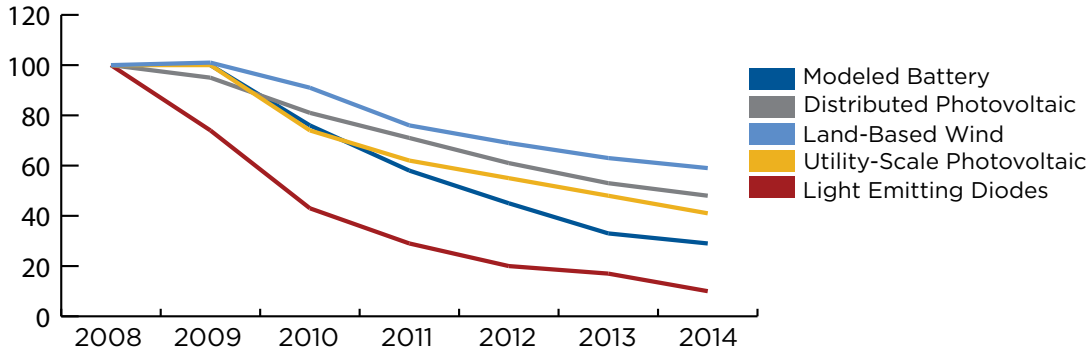
6 See, for example, Jeffrey Ball, "Why the Saudis are Going Solar," *Atlantic*, July/August 2015, http://www.theatlantic.com/magazine/archive/2015/07/saudis-solar-energy/395315/.

7 Daniel Yergin, "The Power Revolutions," *Wall Street Journal*, August 21, 2015, http://www.wsj.com/articles/the-power-revolutions-1440172598.

8 While nuclear power is also technically a source of clean energy in that it does not produce greenhouse gas emissions (GHGs), it is not in the same sense renewable and produces radioactive waste so it is not counted in this category.

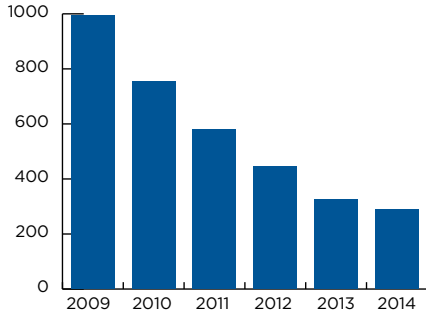
9 US Energy Information Administration (EIA), "Annual Energy Outlook 2015," April 14, 2015, http://www.eia.gov/forecasts/aeo/section_elecgeneration.cfm.

Graph 2. Index Cost Reductions Since 2008



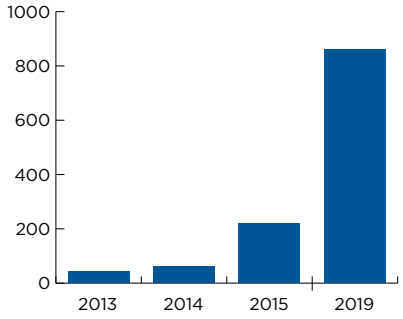
Source: Revolution. . . Now (Washington, DC: US Department of Energy, 2015).

Graph 3. Modeled Battery Cost (dollar per kWh)



Source: Revolution. . . Now (Washington, DC: US Department of Energy, 2015).

Graph 4. Expected Growth of the US Energy Storage Market (in gigawatts)



Source: GTM Research and Energy Storage Association.

technologies such as battery storage, big data, and smart grids; and they have the most disruptive potential. From 2010 to 2014, wind energy accounted for 28 percent of new US-installed electricity capacity; it has accounted for 33 percent of all new electricity capacity since 2007. Since 2008, $125 billion has been invested in wind.[10] Solar energy in the United States grew an astounding 418 percent from 2010 to 2014, accounting for 38 percent of new installed electricity capacity.[11]

While costs of wind and solar energy have steadily declined since the 1980s, they have plummeted dramatically over the past decade, and their respective capacity has expanded at a phenomenal rate. Global wind power expanded from 48 gigawatts (GW) in 2004 to 318 GW by the end of 2013; photovoltaic solar capacity grew from 2.6 GW to 139 GW over the same period.[12] In some areas, wind and solar are now cost-competitive with coal and natural gas much of the time. Another element of the incentive structure for wind and solar is the fact that twenty-nine US states have renewable energy mandates with renewable targets.

Despite these impressive jumps, growth in solar and wind energy has been impeded by their intermittent nature (their performance is limited to when the sun is shining and the wind is blowing), but improved energy storage and smart grids have the potential to overcome this problem and transform current energy systems. As for alternative sources of renewable energy, hydropower is expected to grow modestly, and technology breakthroughs in nonfood-based biofuels are possible, though after more than two decades of research, they have yet to become commercially scalable. Hydrogen (H_2) also holds promise to become a major renewable power source for both electricity and transport. For the foreseeable future, however, it remains a wildcard,

10 American Wind Energy Association (AWEA), "Get the Facts," http://www.awea.org/Resources/Content.aspx?Item Number=5059; US Department of Energy (DOE), "Enabling Wind Power Nationwide," May 2015, p. 5, http://energy.gov/sites/prod/files/2015/05/f22/Enabling-Wind-Power-Nationwide_18MAY2015_FINAL.pdf.

11 Solar Energy Industries Association, "Solar Industry Data," http://www.seia.org/research-resources/solar-industry-data.

12 Camila Stark, Jacquelyn Pless, Jeffrey Logan, Ella Zhou, and Douglas J. Arent, "Renewable Electricity: Insights for the Coming Decade," Joint Institute for Strategic Energy Analysis, NREL, February 2015, http://www.nrel.gov/docs/fy15osti/63604.pdf.

pending breakthroughs in the clean separation of H_2 and scalability, as well as questions about who will pay for the cost of a supporting infrastructure.[13]

Though renewable energy currently constitutes only a modest portion of energy use in the United States, it has become more prominent in parts of Europe. In the United States, about 14 percent of electricity is generated by renewables.[14] In the EU, the use of renewables varies among the twenty-eight countries, but overall, renewables supply roughly 25 percent of EU electrical power, much of which has been heavily subsidized.[14] Nevertheless, the vast majority of the world's energy (particularly for transportation) still comes from fossil fuels; this trend is projected to continue to 2035 and beyond.[15]

Evolution of Solar Power

There are two types of deployed solar energy: photovoltaic (PV)—which constitutes the vast majority of deployed solar power—and concentrated (or thermal) solar power (CSP). Roughly 90 percent of commercial, utility, and residential PV solar modules are composed of crystalline silicon-based wafers, which are typically covered with glass. The remainder is composed of thin-film cells of semiconducting material, layered with insulating glass or plastic. The overwhelming majority of PV modules are silicon based because this variety is cheaper, nontoxic, and very reliable. CSP converts sun to heat, using mirrors and then electricity. While CSP may have potential for wider use, it has been mainly deployed for commercial use on a small scale, and investment has diminished as the price of PV solar cells has plummeted.[16]

PV modules typically convert about 16-17 percent of the sun's light into energy, though a recent breakthrough by the Elon Musk-founded energy provider SolarCity promises a 22 percent conversion rate for rooftop PV.[17]

Some have slightly higher conversion rates, and varied emerging solar technologies have converted sunlight at rates of 35 percent or higher at the laboratory/research level. However, there is little indication that they can be scaled up to be cost-competitive in the near future (see below). Projections for the expanded use of solar energy are based on roughly current conversion rates. The prospect of major increases in renewable energy is based on the emerging technology of enhanced energy storage and smart grids able to digitize electricity use.

THE PROSPECT OF MAJOR INCREASES IN RENEWABLE ENERGY IS BASED ON THE EMERGING TECHNOLOGY OF ENHANCED ENERGY STORAGE AND SMART GRIDS ABLE TO DIGITIZE ELECTRICITY USE.

Nonetheless, more advanced solar technologies are in the research stage. An NREL primer says "second-generation solar cells are called thin-film solar cells because they are made from amorphous silicon or nonsilicon materials such as cadmium telluride. Thin-film solar cells use layers of semiconductor materials only a few micrometers thick. Because of their flexibility, thin-film solar cells can double as rooftop shingles and tiles, building facades, or the glazing for skylights."[18]

Third-generation solar cells are also in the development stage; many of these are engineered using new nanomanufactured materials. These new solar technologies include solar inks, which use conventional printing press technologies; solar-absorbing quantum dots; and luminescent solar concentrators. According to Los Alamos National Laboratory researcher Victor Klimov, "In these devices, a fraction of light transmitted through the window is absorbed by nanosized particles (semiconductor quantum dots) dispersed in a glass window, re-emitted at [an] infrared wavelength invisible to the human eye, and wave-guided to a solar cell at the edge of the window."[19]

13 For an upbeat assessment of hydrogen power's potential, see Joan Ogden, Christopher Yang, Michael Nicholas, and Lew Fulton, "The Hydrogen Transition," UC Davis Institute of Transportation Studies, July 29, 2014, http://steps.ucdavis.edu/files/08-13-2014-08-13-2014-NextSTEPS-White-Paper-Hydrogen-Transition-7.29.2014.pdf.

14 Eurostat, "Energy from Renewable Sources," http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_from_renewable_sources#Renewable_energy_available_for_final_consumption.

15 Institute for Energy Research, "BP Energy Outlook to 2035," February 26, 2015, http://instituteforenergyresearch.org/analysis/bp-energy-outlook-to-2035/.

16 For a comprehensive assessment of the prospects and challenges for the future of solar energy, see Massachusetts Institute of Technology "The Future of Solar Energy," May 2015, https://mitei.mit.edu/system/files/MIT%20Future%20of%20Solar%20Energy%20Study_compressed.pdf.

17 Eric Wesoff, "Is SolarCity's New PV Module the 'World's Most Efficient Rooftop Solar Panel'?", *Greentech Media*, October 2, 2015, http://www.greentechmedia.com/articles/read/Is-SolarCitys-New-PV-Module-the-Worlds-Most-Efficient-Rooftop-Solar-Pane.

18 NREL, "Solar Photovoltaic Technology Basics," http://www.nrel.gov/learning/re_photovoltaics.html.

19 Dexter Johnson, "A Clearer Outlook for Quantum Dot-Enabled Solar Windows," IEEE Spectrum, August 27, 2015, http://spectrum.ieee.org/nanoclast/semiconductors/materials/a-clearer-outlook-for-quantum-dot-enabled-solar-windows; http://spectrum.ieee.org/nanoclast/green-tech/solar/quantum-dot-solar-cells-break-conversion-efficiency-record.

In the Yale University blog *environment360*, Cheryl Katz writes: "Among the most promising technologies are multi-junction cells with layers of light-harvesters that each gather energy from a separate slice of the solar spectrum, super-efficient semiconductor materials like perovskite and gallium-arsenide, and cells made with tiny but powerful solar-absorbing 'quantum dots.' Technical hurdles, such as making new materials able to withstand the elements, remain. Nonetheless, researchers say, efforts now underway could begin to dramatically increase solar power generation within a decade or two."[20] Perovskite may lower costs further and increase efficiency.[21] These are a few examples of research and development (R&D) projects that could by 2030-35 substantially lower costs and increase the efficiency of solar energy.

What has spurred the explosion of solar energy is, to a large extent, the spectacular drop in the Levelized Cost of Energy (LCOE). This is the industry metric for assessing and comparing the total cost of different energy-producing sources. LCOE measures all costs—installation, financing, operation, maintenance, incentives, salvage value, and revenue requirements—over the lifecycle of the energy technology, divided by the amount of energy per kilowatt hour (kWh) it produces.

The LCOE for solar PV dropped by 50 percent between 2010 and 2014 alone, and by 80 percent since 2000.[22] Massive Chinese overproduction, increased overall global production, subsidies, and government mandates have driven down costs and are likely to continue doing so over the next two years[24] Since 2009, solar photovoltaic has grown tenfold and now accounts for about 1 percent of global electricity production. In some areas where solar is concentrated in the United States (e.g., California and the sunny Southwest), it is at times cost-competitive with coal and gas. In the United States, roughly 50 percent of solar energy is utility scale and about 50 percent is residential, though through 2016, installed utility-scale solar is projected to increase more than residential by a substantial margin.

A study by the investment banking firm Lazard found that, since 2010, in some scenarios "wind [and] solar PV have become increasingly cost-competitive with conventional generation technologies, on an unsubsidized basis, in light of material declines in the pricing of system components (e.g., panels, inverters, racking, turbines, etc.), and dramatic improvements in efficiency, among other factors."[23] In the United States, residential solar has also taken off due to creative financing schemes that reduce front-end costs and accelerate the repayment schedule by selling electricity to the grid. Residential solar also benefits from "net metering": selling power to utilities at peak demand periods of the day when solar is producing.

Evolution of Wind Power

As mentioned above, the rise of wind power has a similar narrative to that of solar. One major difference, however, is that wind produces an amount of electricity that is an order of magnitude greater than solar. In the United States, wind capacity grew from 6 GW in 1996 to 66 GW in 2015.[24] An additional 13 GW are in the construction phase and are expected to go online by the end of 2016.[25] Another major difference is that wind is largely a utility-scale technology. Wind also features declining costs, improved performance, tax credit subsidies, and production mandates in twenty-nine US states (thirty-nine US states have utility-scale wind capacity); it now generates about 5 percent of US electricity. Like solar, wind is location-specific; it is most prominent in the windy Midwest plains states.

The United States has more than forty-eight thousand utility-operated wind turbines, and more than eighteen million American homes are powered every year by the country's installed wind capacity.[26] However, the perils of being an intermittent energy source are underscored by the reality that, despite a 9 percent increase in wind capacity in 2015, US wind production is down by 6 percent as a result of unusually soft wind patterns.[27]

In parts of Europe, wind rivals gas and coal as a major source of electricity; for example, wind already provides 39 percent of Denmark's electricity.[28] Wind energy use is only projected to grow. According to the European

20 Cheryl Katz, "Will New Technologies Give Critical Boost to Solar Power?", environment360, Yale University, December 11, 2014, http://e360.yale.edu/feature/will_new_technologies_give_critical_boost_to_solar_power/2832/.

21 Dario Borghino, "Study Claims Perovskite Solar Cells Can Recoup Their Energy Cost Within Three Months," *Gizmag*, August 4, 2015, http://www.gizmag.com/perovskite-solar-cells-energy-payback-time/38550/.

22 Stark et al., "Renewable Electricity: Insights for the Coming Decade," http://www.nrel.gov/docs/fy15osti/63604.pdf.

23 Lazard, "Lazard's Levelized Cost of Energy Analysis—Version 8.0," September 2014, https://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf.

24 AWEA, "Get the Facts," http://www.awea.org/Resources/Content.aspx?ItemNumber=5059.

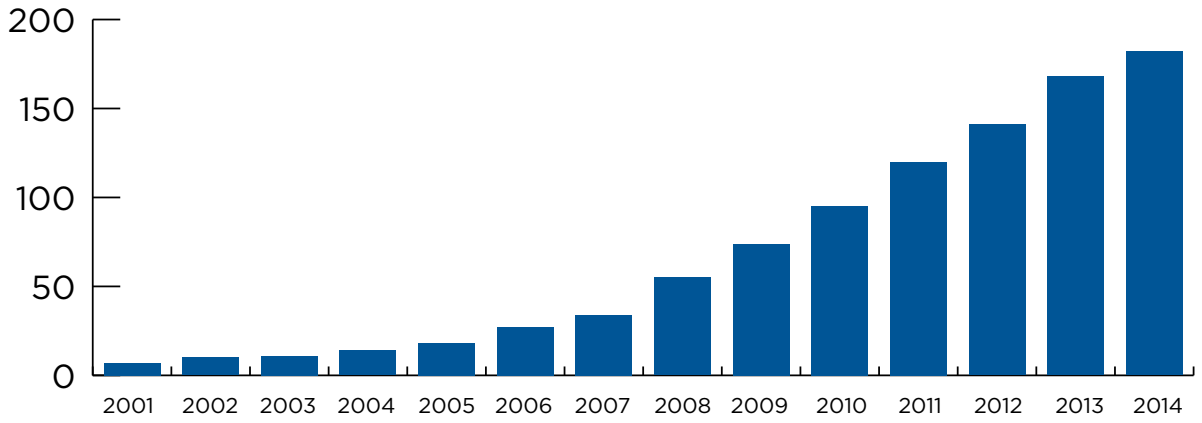
25 Chris Mooney, "The U.S. Wind Energy Boom Couldn't Be Coming at a Better Time," *Washington Post*, August 10, 2015, http://www.washingtonpost.com/news/energy-environment/wp/2015/08/10/the-boom-in-wind-energy-couldnt-be-coming-at-a-better-time/.

26 Gaurav Agnihotri, "Germany Now Faced With Thousands of Aging Wind Farms," *Oilprice.com*, September 28, 2015, http://oilprice.com/Alternative-Energy/Wind-Power/Germany-Now-Faced-With-Thousands-Of-Aging-Wind-Farms.html.

27 Gregory Meyer, "US Clean Energy Suffers From Lack of Wind," *Financial Times*, September 1, 2015, http://www.ft.com/intl/cms/s/0/b967b6d4-5058-11e5-8642-453585f2cfcd.html#axzz3rnEi1Lpm.

28 Tierney Smith, "5 Countries Leading the Way Toward 100% Renewable Energy," *EcoWatch*, January 9, 2015, http://ecowatch.com/2015/01/09/countries-leading-way-renewable-energy/.

Graph 5. Wind Power's Growth in the United States since 2001 (GWh)



Source: US Energy Information Administration, 2015.

Wind Energy Association (EWEA), "there is now 128.8 GW of installed wind energy capacity in the EU—approximately 120.6 GW onshore and just over 8 GW offshore." EWEA estimates that wind energy capacity will more than double by 2030 and has come up with low-, middle-, and high-end projections. In the low-end scenario, installed capacity would grow by 251 GW. In the middle-range scenario, 320 GW would be added, enabling wind to meet 24 percent of EU electricity demand by 2030.[29]

There are looming questions both in the United States and the EU about continued political support for large subsidies, the tradeoff of climate benefits for high consumer electricity rates, and in some cases (e.g., Germany), the costs of decommissioning aging wind turbines and replacing them with updated technology.[30] One significant difference between the United States and the EU is that offshore wind, though still comprising less than 20 percent of the EU's wind capacity, has attained a higher degree of public acceptability there than it has in the United States, where it still generates much controversy. To date, there are fourteen offshore wind projects in the United States, which, if realized, could add 4.9 GW in capacity. These projects are in various stages of approval and development, with two under construction and some facing significant political opposition.[31]

The DOE projects that wind could provide 20 percent of US electricity by 2030.[32] While ambitious, such a target is not inconceivable. Reaching it would require continued improvements in wind technology, some level of subsidy, and investments in the US energy system to integrate wind output into the US grid. Though wind is a relatively mature technology, expected significant if incremental improvements in its components—turbines, towers, blades, and materials—and reduced construction and maintenance costs to 2030 are likely to enhance wind's cost-competitiveness.

Advances in wind technology have led to greatly improved productivity and increased geographic possibilities, allowing energy production where less windy conditions might have prevented wind investment in the past. A combination of increased rotor diameter, high heights for the hub (the level of the turbine's central rotor hub above the ground), and larger and improved blade design continue to increase efficiency.[33] Wind growth estimates are also based upon ongoing improvements in new materials, such as ceramics, carbon fiber, and graphene; on engineering design, which allows for longer and more durable blades able to produce in less windy conditions; and on reduced development costs that would result from larger-scale wind farms.[34] The increased use of sensors to assess

29 European Wind Energy Association, "Wind in Power: 2014 European Statistics," http://www.ewea.org/statistics/european/.

30 Agnihotri, *Oilprice.com*, http://oilprice.com/Alternative-Energy/Wind-Power/Germany-Now-Faced-With-Thousands-Of-Aging-Wind-Farms.html.

31 Wendy Koch, "U.S. Offshore Wind Power Nears Takeoff with 14 Projects," *USA Today*, September 8, 2014, http://www.usatoday.com/story/money/business/2014/09/06/us-gearing-up-offshore-wind-power/15087263/.

32 DOE, "20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply," July 2008, http://www.nrel.gov/docs/fy08osti/41869.pdf.

33 DOE, "Enabling Wind Power Nationwide," May 2015, pp. 10-12, http://www.energy.gov/sites/prod/files/2015/05/f22/Enabling-Wind-Power-Nationwide_18MAY2015_FINAL.pdf.

34 James Manyika, Michael Chui, Jacques Bughin, Richard Dobbs, Peter Bisson, and Alex Marrs, "Disruptive Technologies: Advances That Will Transform Life, Business, and the Global Economy," McKinsey Global Institute, McKinsey & Company, May 2013, http://www.mckinsey.com/insights/business_technology/disruptive_technologies.

wind resources is another expected technological enhancement.[35]

There have been several improvements made to wind tower design in recent years. For example, hub heights have increased substantially, enabling towers to capture more wind in the typically windier higher elevations. In 2013, typical hub heights for wind towers were eighty meters, a 45 percent increase in height since 1998. Similarly, the average rotor diameter in the United States increased from about fifty meters in 2000 to around one hundred meters or more for 80 percent of turbines in 2014. In Germany, turbine heights average 116 meters, and some exceed 140 meters. The DOE estimates that continued innovations in hub heights, rotors, and larger turbines could expand wind production from a net capacity factor of 30 percent to 67 percent, increasing wind capacity to areas such as the Northeast, West, and mid-Atlantic states, where it previously was not economically feasible.[36] The current net capacity factor for onshore wind turbines in high wind areas is typically about 35 percent—up from around 22 percent in the late 1990s. Siemens is planning to build a factory in Germany to produce next-generation offshore turbines that may supply 10 megawatts (MW) or more of wind energy. The German firm is one of numerous private sector actors partnering with the DOE on next-generation wind technologies.[37]

Such innovation and cost reductions in the installation and maintenance of offshore wind facilities could also reduce costs and further expand wind capacity. Of the lower forty-eight states, twenty-eight have a coastal boundary and use 78 percent of US electricity.

The Enablers: Smart Grid and Energy Storage

Many factors will impact the pace and scope of the expansion of solar and wind energy use. These include federal and state tax credits, feed-in tariffs (in the EU), growing pressures of climate change, and a projected low-price environment for natural gas. But looking over the coming two decades to 2035, the key obstacle and/or enabler will be the degree to which the grid system is modernized and digitized into a smart grid (a process already underway); in the longer term, advancement will hinge on breakthroughs in cost-competitive energy storage. To effectively integrate burgeoning intermittent energy sources like solar and wind into the grid, smart grids are key; and over time, the limits of such integration will likely be determined by cost-competitive energy storage.

INNOVATION AND COST REDUCTIONS IN THE INSTALLATION AND MAINTENANCE OF OFFSHORE WIND FACILITIES COULD ALSO REDUCE COSTS AND FURTHER EXPAND WIND CAPACITY. OF THE LOWER FORTY-EIGHT STATES, TWENTY-EIGHT HAVE A COASTAL BOUNDARY AND USE 78 PERCENT OF US ELECTRICITY.

Smart Grid

A "smart grid" is a digitized infrastructure of the electricity system, transforming electricity systems much the same way that the smartphone transformed telecommunications from the use of landlines. It uses computer technology to create two-way communication between all nodes of the electricity network—supply, transmission, distribution, and consumption—creating a more efficient, reliable, and resilient system. Automated technology relays information from sensors and smart meters employed at homes and offices, allowing the utility to adjust and control power flows in real time in each individual device, or in millions of devices, from a central location.

This automated system allows utilities to gauge shifts in demand in real time; more-rapidly respond to power outages; and integrate intermittent sources of electricity like solar, wind, and eventually electric vehicles into the grid. Thus, spikes in demand for electricity—such as in the summer, when air conditioners are running full bore—could be more easily met by surging solar energy during peak day demand. Utilities can also offer discounts to consumers who reduce energy use at peak

35 Stark et al., "Renewable Electricity: Insights for the Coming Decade," http://www.nrel.gov/docs/fy15osti/63604.pdf.

36 The net capacity factor is the ratio of actual energy output to potential energy output; DOE, "Enabling Wind Power Nationwide," http://www.energy.gov/sites/prod/files/2015/05/f22/Enabling-Wind-Power-Nationwide_18MAY2015_FINAL.pdf.

37 William Steel, "Siemens Looks Toward Next-Generation 10-20 MW Wind Turbines," *Clean Technica*, September 15, 2015, http://cleantechnica.com/2015/09/15/siemens-looks-toward-next-generation-10-20-mw-wind-turbines/; US Office of Energy Efficiency and Renewable Energy, "Next-Generation Wind Technology," http://energy.gov/eere/next-generation-wind-technology.

periods. If privacy concerns can be met, accumulated big data could also lead to a range of applications beyond optimizing grid operations and ultimately to a new business model.

Today, the US electric grid serves 144 million consumers via 5,800 power plants, 3,200 utilities, 2.7 million power lines, 6,000 substations, and 600,000 distribution circuits. Nine hundred generators feed into a high-voltage transmission network that transports electricity through a number of transformers so that the voltage appropriate for household or business consumption is distributed through regulated utilities.[38] Until recently, the adoption of smart grid technologies has been gradual, and the grid has changed little over the past century.

SMART GRIDS AND THE GROWING ROLE OF RENEWABLES IN THE GRID SYSTEM ARE A MIXED BLESSING FOR UTILITIES. WHILE THEY OFFER NEW OPPORTUNITIES, MORE RELIABILITY, AND GREATER EFFICIENCY, THEY ALSO INCREASINGLY CHALLENGE UTILITIES TO FIND A NEW BUSINESS MODEL.

Estimates of the costs and benefits of a smart grid vary. One widely cited estimate by the Electric Power and Research Institute gauges the net costs to be in the $380-$476 billion range and the net benefits to be $130-$200 trillion.[39] EU Climate Action and Energy Commissioner Miguel Arias Cañete said in a March 2015 speech that the EU needed to invest $400 billion euros by 2020 in order to modernize its transmission and distribution grids.[40] In the United States, investment has been lagging. According to the DOE, more than $9 billion has been collectively invested from the public and private sectors. Much of this investment was stimulated by the 2009 American Recovery and Reinvestment Act. In addition to investment, new standards must be developed to more fully integrate renewable sources into the grid and establish smart grids.

In both the United States and the EU, smart grids are being built piecemeal, smart meter by smart meter, utility by utility. Some fifty million smart meters have been installed in the United States, covering about 43 percent of electricity customers, though many are not fully integrated into a smart grid. Cañete argues that if EU member states follow through on commitments, 75 percent of European households will have smart meters by 2020.

But smart grids and the growing role of renewables in the grid system are a mixed blessing for utilities. While they offer new opportunities, more reliability, and greater efficiency, they also increasingly challenge utilities to find a new business model. Utilities do not pay for the operation and maintenance of distributed energy, such as rooftop solar, on the grid. However, under net metering, utilities in both the United States and the EU must pay for the excess electricity fed into the grid by rooftop solar residences at peak rates. In areas where there are large concentrations of rooftop solar (e.g., Hawaii and some parts of California), this is raising costs, lowering profits, and in some cases, reducing customers. Thus, utilities are campaigning against it.

In a prescient 2013 report "Disruptive Challenges," the Edison Electric Institute warned that:

> "…A variety of disruptive technologies are emerging that may compete with utility-provided services. Such technologies include PV solar, battery storage…wind, micro turbines, and electric vehicle enhanced storage. As the cost curve[s] for these technologies improve, they could directly threaten the centralized utilities model."[41]

While this reflects a long-term trend, in some areas renewables are already beginning to impact utilities. The issue is a bit different in Europe, where the transmission and distribution elements of power provision have been unbundled and are separately managed and operated. But looking out to 2035, the need for new,

38 Council on Foreign Relations, "CFR Backgrounders," http://www.cfr.org/united-states/modernizing-us-energy-grid/p36858; See Christopher Guo, Craig Bond, and Anu Narayanan, "The Adoption of New Smart-Grid Technologies: Incentives, Outcomes, and Opportunities," RAND Corporation, 2015, for detailed assessments of the current grid situation and the costs and benefits of installing a smart grid, http://www.rand.org/pubs/research_reports/RR717.html.

39 Electric Power Research Institute, "Estimating the Costs and Benefits of the Smart Grid," 2011, https://www.smartgrid.gov/files/Estimating_Costs_Benefits_Smart_Grid_Preliminary_Estimate_In_201103.pdf.

40 Miguel Arias Cañete, "Smart Grids for a Smart Energy Union," speech delivered at the European Commission, March 31, 2015, http://europa.eu/rapid/press-release_SPEECH-15-4734_en.htm.

41 Peter Kind, "Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electric Business," Energy Infrastructure Advocates for Edison Electric Institute, January 2013, http://www.eei.org/ourissues/finance/documents/disruptivechallenges.pdf.

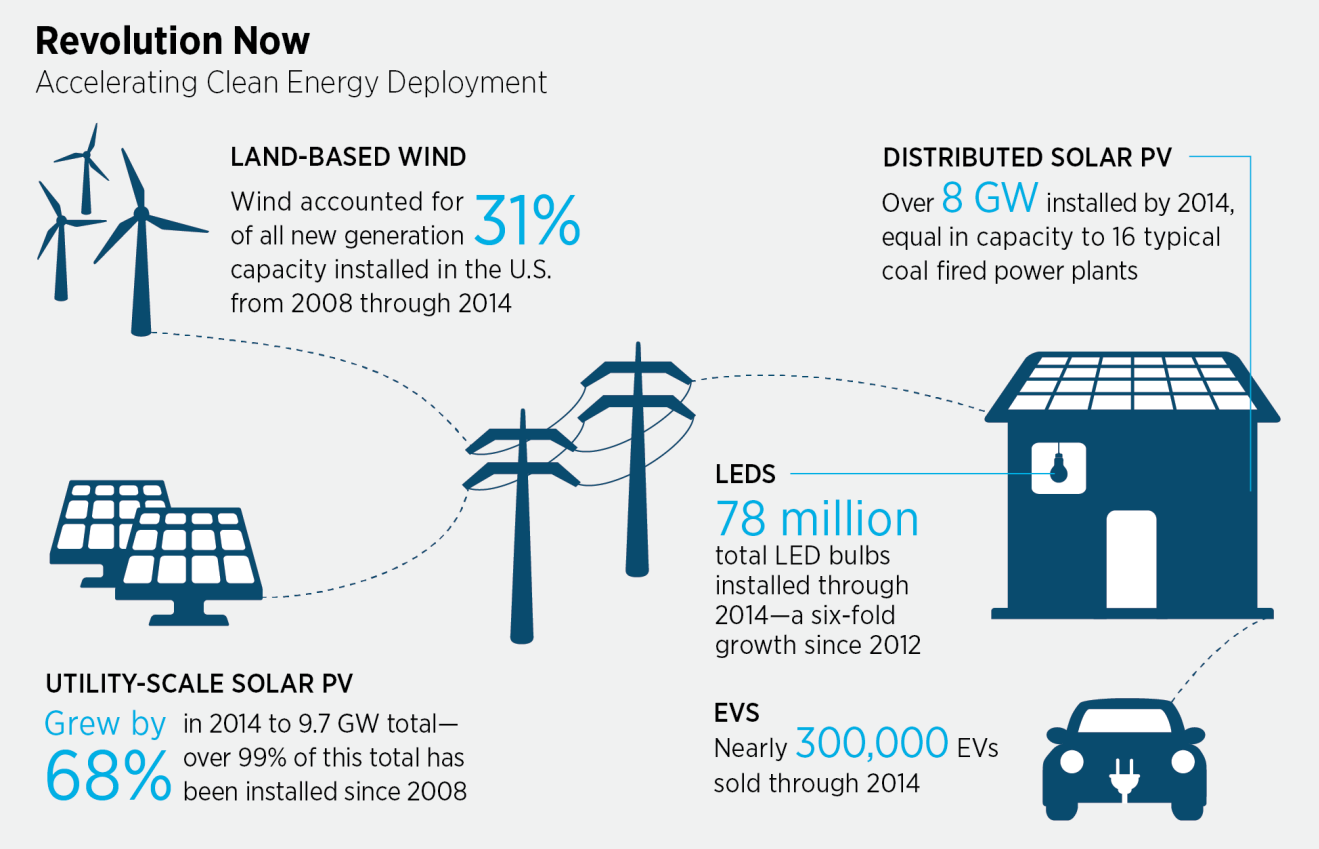


Photo credit: Revolution. . . Now (Washington, DC: US Department of Energy, 2015).

more decentralized business models reflecting the rise of renewables, smart grid technology, and growing energy storage capabilities will acquire more urgency. For example, if solar and wind costs continue falling and energy storage becomes economic, distributed energy for residential and/or commercial buildings or factory complexes may enable them to produce their own energy independent of the grid or become net electricity producers feeding the grid. While this may allow utilities to delay making investments to expand capabilities, it will also result in diminished markets.

Energy Storage

Perhaps the "X factor" determining the degree to which renewable energy accelerates and becomes disruptive is the development of more efficient and cost-competitive energy storage. Energy storage systems change electricity into a form that can be stored and turned back into electrical energy when needed. Currently, utilities store less than 4 percent of electricity, principally using an old method of pumped hydro-electric storage (PHES). PHES essentially pumps water uphill when demand is low and releases it downhill to power turbines when demand is high. But substantial investment—over $5 billion since 2000—and steady, incremental progress over the past quarter century in R&D are lowering energy storage costs, increasing the capacity of lithium ion (Li-ion) batteries (energy storage devices), and raising the prospect that more economically competitive and effective grid-level energy storage may accelerate.

Two events since 2013 show how battery storage may be approaching a tipping point. First, in 2014, Tesla electric car CEO Elon Musk announced the creation of a $5 billion "Gigafactory" in Nevada, which will produce batteries that can hold fifty gigawatt-hours (GWh) of electricity by 2020 (more than the total amount produced globally in 2013). Second, California's recent adoption of a grid energy storage mandate in 2015 requires the state's three large utilities to install 1.3 GW of energy storage capacity by 2020. It is not a coincidence that those developments were accompanied by a third in May 2015: Musk unveiled two versions of a new, rechargeable battery—the 100 kWh Powerpack and the 10 kWh Powerwall—aimed at residences with solar power.

Tesla is not pioneering any new technology. Rather, its batteries are using existing Panasonic Li-ion technology that is otherwise used to power cellphones and other consumer devices. Tesla's business model assumes that the scale of production will lower costs. Battery researchers often cite $100 per kWh as the point at which batteries (currently, one-third the cost of e-vehicles)

Solar testing facility in Aurora, Colorado. *Photo credit:* Energy.gov/Flickr.

become competitive with conventional power sources. Tesla has lowered costs to about $250 per kWh. While its Powerpack has sold well, mostly to businesses as a backup power source, its Powerwall at a $7,000 installation price is not cost-competitive and will not threaten utilities by turning rooftop solar residences into autonomous energy sources, at least in the near term.[42]

But energy storage technologies are not static; rather, they are in ferment. In the United States, energy storage is popular with venture capital firms, and the DOE's Advanced Research Project Agency-Energy (ARPA-E) is funding twenty-one grid-scale battery technologies in a race to a renewable future.

So far, Li-ion batteries, whose costs have come down by about 90 percent since 1995, are at the center of R&D efforts. In terms of weight, energy density, and output, they have proven to be more practical than other energy storage technologies. Yet, the task of moving lithium ions through electrolytes, cathodes, and anodes to release energy effectively and safely has proven to be enormously complex. Researchers working at the molecular level have made small improvements, experimenting with different materials, but the difficult physics and electro-chemistry have made progress slow and incremental over more than two decades.[43] In order to obtain a 300-mile range for e-vehicles on a single charge, Li-ion batteries need to almost double their energy density.

There are other types of energy storage in various stages of development. These range from flow batteries to salt water batteries to ultracapacitators using new energy-conducting materials such as graphene. The larger point of this technical discussion is that an enormous competitive effort is underway in the United States, the EU, China, and Japan to develop game-changing energy storage. Looking out to 2030-35, while the timeframe and scope of improved technology is unknowable, the possibility of developing the $100 per kWh battery over the coming two decades and exponentially increasing the deployment of energy storage, both for residences and businesses as well as e-vehicles, is not far-fetched. Growing efforts to develop commercial technology for grid scale batteries are showing signs of lab-scale/proof-of-concept capabilities.[44] The International Renewable Energy Agency projects annual battery storage capacity will grow from 360 MW to 14 GW between 2014 and

42 Jonathan Fahey, "Is Tesla's Powerwall Home Battery Worth the Price?" *San Jose Mercury News*, May 22, 2015, http://www.mercurynews.com/business/ci_28164614/is-teslas-powerwall-home-battery-worth-price.

43 See Steve LeVine, *The Powerhouse: Inside the Invention of a Battery to Save the World*, (New York: Viking, 2015), for an excellent depiction of the R&D efforts and why the process is so difficult.

44 DOE, "Energy Storage: A Key Enabler of the Smart Grid," September 2009, http://www.netl.doe.gov/File%20Library/research/energy%20efficiency/smart%20grid/whitepapers/Energy-Storage_2009_10_02.pdf.

2023.[45] Game-changing commercial breakthroughs do not appear imminent, but in a 2025-35 timeframe, transformational breakthroughs in energy storage would not be surprising.

Conclusion: Winners and Losers in Alternative Futures Scenarios

As the transformation of global energy systems unfolds, what are the likely environmental, economic, and geopolitical consequences? Who will be the winners and losers of such a transformation? While the pace and degree of gains and losses is impossible to predict, exploring the drivers and impediments of alternative futures offers a useful way to consider likely potential outcomes:

1. Incremental Change

In this scenario, only small, marginal technological advances in solar, wind, and energy storage occur. The period is marked by an interval of low global economic growth (in the 3-3.5 percent range into the 2020s), as China falls into the middle income trap and struggles to implement market reforms, which curbs the growth of energy demand. Other emerging economies lack the dynamism they displayed at the beginning of the century. As a result, the relative increase in global energy demand is around 1-2 percent.

The slow-growth global economy features declining OECD demand. As the knowledge economy and services expand, the link between economic growth and energy consumption is severed. Increased oil and gas supplies from Iranian, African, Eastern Mediterranean, and US exports result in oil prices in the $40-$60 per barrel range, as global demand approaches its peak. Budget pressure leads to the expiration of the US investment tax credit for solar energy, and the EU phases out feed-in tariffs in the early 2020s. Low natural gas prices further slow the pace of investment in solar and wind renewables, in grid modernization, and in e-vehicles. However, a 20 percent decline in the solar LCOE helps spur the continued growth of solar and wind. This, in addition to gas displacing much of coal use, results in a decline in world CO_2 emissions growth to less than 2 percent in OECD countries and to 3.5 percent in developing economies.

The fossil fuel industry, particularly coal and, post-2030, natural gas, will likely see a significant drop in demand, though in the United States, gas will continue to replace coal as an electricity source. The difficulty for e-vehicles to become cost-competitive with internal combustion vehicles, combined with the cost of creating a new infrastructure of charging stations, suggests that the electrification of transport will advance incrementally and only partially in the 2030-35 timeframe.

Obviously, the world's petro-states—Russia, Iran, Saudi Arabia, the other Gulf Cooperation Council (GCC) states, Venezuela, and other Latin American producers—will face growing challenges to diversify their economies. Those with large gas reserves—Russia, Iran, newly developed East African states, and Eastern Mediterranean gas producers—will have more time to transition to renewable-centric energy. Natural gas will be a transition technology whose use may begin to decline in 2030-35, but will likely be sustained at its current scale up to mid-century. The EU's continued growth in renewables, combined with increasing US exports and the addition of Eastern Mediterranean gas, spurs a growing global liquefied natural gas market. This allows the EU to decrease its dependency on Russian gas, which drops from one-third of EU imports now to under 15 percent by 2025.

2. A Tipping Point

In the second scenario, technological breakthroughs and the increased scale of use drop the LCOE of solar by more than 50 percent by 2035. Renewables and their infrastructure achieve the roughly $12 trillion in needed investment, two-thirds of which is in Asia. Cheaper new materials and larger, more efficient turbines trim onshore wind costs by 30 percent; offshore wind accelerates as construction costs diminish.[46] Improvements in grid-scale battery storage lower costs to below $150 per kWh.[47] In the 2020-25 timeframe, more extreme weather and other increasing climate change effects prompt the United States and the EU to increase subsidies for renewables and accelerate investment in smart grids and R&D for energy storage.

The United States, the EU, and China all meet Kyoto Protocol GHG emissions targets. By 2025, China implements market reforms and creates a new consumer-led service and knowledge economy, reducing coal use by 50 percent and rapidly deploying solar and wind energy sources as it sustains its leading role in the production of both technologies. Renewables are increasingly price-competitive with coal and gas for

45 International Renewable Energy Agency, "Battery Storage for Renewables: Market Status and Technology Outlook," January 2015, http://www.irena.org/DocumentDownloads/Publications/IRENA_Battery_Storage_report_2015.pdf.

46 The projections for this scenario are based on the following sources: Bloomberg, "New Energy Outlook 2015," http://about.bnef.com/content/uploads/sites/4/2015/06/BNEF-NEO2015_Executive-summary.pdf and McKinsey Global Institute's modeling in James Manyika et al., "Disruptive Technologies," May 2013, chapter 12, on renewable energy, http://www.mckinsey.com/insights/business_technology/disruptive_technologies.

47 Battery storage efforts, not only for Li-ion, but also for liquid metal and other types, are already close to being commercialized. See Richard Martin, "Race for a New Grid Battery Hits a Speed Bump," MIT Technology Review, September 30, 2015, http://www.technologyreview.com/news/541851/race-for-a-new-grid-battery-hits-a-speed-bump/.

electricity in many areas. The EU reduces its dependence on Russian gas to below 10 percent as wind, solar, and hydro renewable energy deployment increases EU electricity use from clean energy to over 60 percent. EU nations, like Sweden and Denmark, heavily invest in nonfossil fuels and join Iceland in achieving 100 percent clean electricity by 2030. Fifty percent deployment of electric and/or hydrogen powered vehicles reduces oil demand dramatically. In the United States, California and Hawaii attain 70 percent of their electricity from renewables.[48]

MODERNIZING THE UNITED STATES' ENERGY INFRASTRUCTURE AND BUILDING A SMART GRID ARE KEY TO BETTER INTEGRATING SOLAR AND WIND ENERGY INTO THE ELECTRICITY SYSTEM AND FOR MORE EFFICIENT USE AND PRICING OF ELECTRICITY.

Developing countries are the winners. In Africa and South Asia, many of the 1.3 billion who now lack modern energy services will leapfrog large grid investments and use breakthroughs in solar, wind, and energy storage to achieve decentralized, distributed energy systems.[49] The majority of newly deployed solar will be off-grid rooftop solar, benefiting from cheaper PV cells and energy storage breakthroughs.

For Russia, these developments, combined with its demographic problems, reduce its role both in its "near abroad" (former Soviet Republics) and beyond. Post-Putin leadership in the 2025-30 timeframe moves to modernize Russia's economy and reaches a new accommodation, with the EU and NATO facilitating EU investment. The Middle East, with its petro-states hit by low oil and gas prices and declining global demand squandering the potential advantage of its demographic bulge, remains mired in sectarian conflict and is on a trajectory of strategic marginalization.

48 Sweden already has an ambitious plan to phase out fossil fuels. See Lorraine Chow, "Sweden to Become One of World's First Fossil Fuel-Free Nations," *EcoWatch*, September 25, 2015, http://ecowatch.com/2015/09/25/%E2%80%8Bsweden-fossil-fuel-free/.

49 International Energy Agency, "Topic: Energy Poverty," http://www.iea.org/topics/energypoverty/.

3. *Green Nirvana*

In this scenario, the technology trends outlined in the second scenario occur sooner—in the early 2020s. The breakthroughs spur investments worldwide in excess of $12 trillion, as green energy becomes a driver of economic growth. The technologies are diffused globally by 2035. Solar and wind have become fully cost-competitive with coal and natural gas without subsidies. The United States achieves 80 percent of its electricity from renewables and nuclear energy; the EU achieves 90 percent. Advances in energy storage accelerate the electrification of transportation, with 75 percent electric- and hydrogen-powered autos, which are mostly self-driving. The business model of auto ownership is replaced by an autonomously-driven, on-demand model.

GHG emissions are stabilized at just below four hundred parts per million (ppm), below the level feared to accelerate climate change. Concentrated efforts to eliminate methane slow climate change effects. The world is on a trajectory to zero net GHG emissions by 2040-45.

In this scenario, the impact on petro-states is similar to that in the second scenario, but more severe. Saudi Arabia and GCC states invest petrodollars into solar, wind, and nuclear and mitigate the political impact of declining oil demand. Russia is the biggest loser, struggling to modernize its economy and accept its diminished regional and global role.

Probability: Of the three scenarios, the likeliest, with roughly 50 percent probability, is a scenario that would see more incremental change in both wind and solar technology and energy storage than in the first scenario, but less progress than in the second. Renewable subsidies continue. The costs and efficiencies of solar, wind, and energy storage and the investment in smart grids increase more than in scenario one, but less than in scenario two and not enough to take advantage of enhanced energy storage technology. Technological improvements in wind, solar, and battery storage occur incrementally, but more than envisioned in scenario one.

RECOMMENDATIONS

1. Modernizing the United States' energy infrastructure and building a smart grid are key to better integrating solar and wind energy into the electricity system and for more efficient use and pricing of electricity. To date, these improvements have been occurring on the local and state level. *Construction of a smart grid should be a national priority for the United States. It should be pursued in partnership with state and local governments as well as with utilities. The EU should also make investing in a smart grid a priority for its integrated EU energy policy*.

2. Government-funded research has been—and continues to be—an important catalyst for accelerating the development and deployment of new energy technologies. *The US Department of Energy's ARPA-E should continue its work and expand support for innovative pre-competitive R&D in energy storage.*

3. The adoption of offshore wind energy in the United States faces a public acceptance deficit and is lagging behind that of the EU. Improving wind energy technology addresses much of the concern about harm to birds, and the benefits that come from increasing the electricity supply and combatting climate change far outweigh popular concerns. *The administration should work with state and local governments to lead a national conversation and public education campaign on why offshore wind power is an important component of a clean energy strategy.*

4. The accelerating deployment of renewable energy over the period to 2030 will displace substantial dependence on natural gas and coal. This will almost certainly impact the geopolitics of energy, both in regard to GCC states and countries of concern such as Russia, Iran, Venezuela, and their allies whose dependence on Russia and Organization of Petroleum Exporting Country (OPEC) states will be substantially reduced. The White House should request a National Intelligence Estimate on the strategic impact of a substantial increase in renewables on US geopolitical interests out to 2030.

5. One major impediment to the widespread adoption of electric vehicles (and hydrogen vehicles, should the technology ever prove commercially viable) is the lack of convenient recharging stations. This contributes to "range anxiety" for drivers going long distances and even among urban drivers; the lack of access to convenient recharging stations is a factor inhibiting the expansion of electric vehicles. *The United States should conduct a feasibility study on the adoption of user fees for recharging stations as a means of financing a rapid expansion of charging stations to accelerate the use of electric vehicles.*

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