U.S. DEPARTMENT OF ENERGY

Revolution…Now

The Future Arrives for Five Clean Energy Technologies – 2015 Update

November 2015

U.S. DEPARTMENT OF ENERGY

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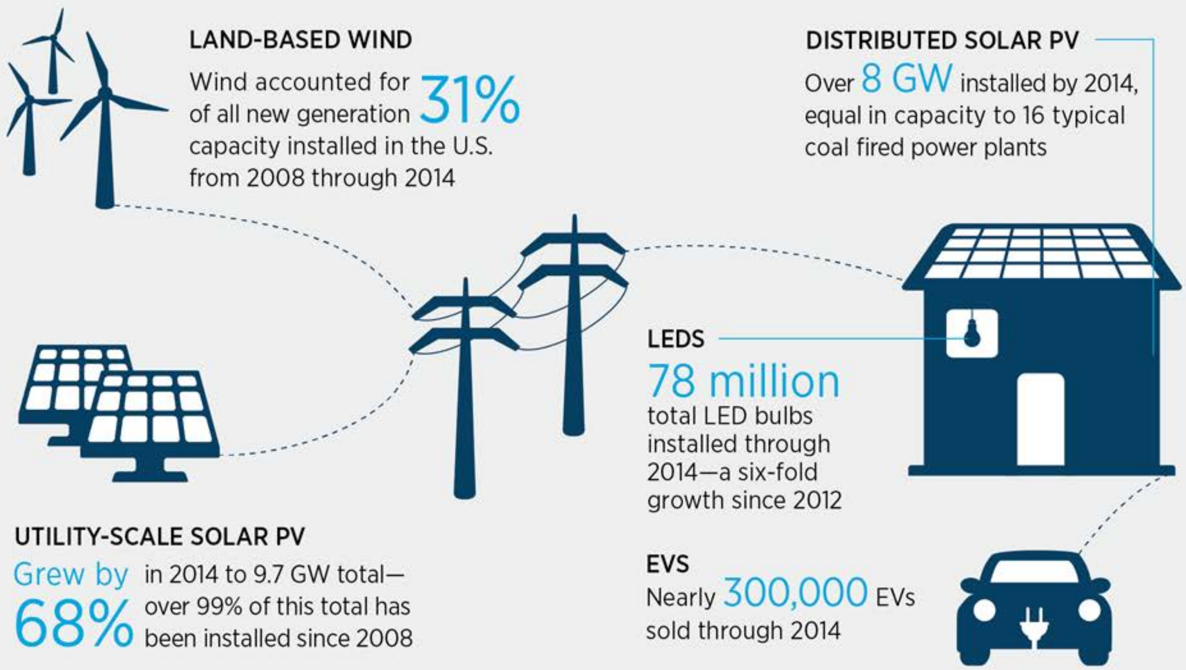
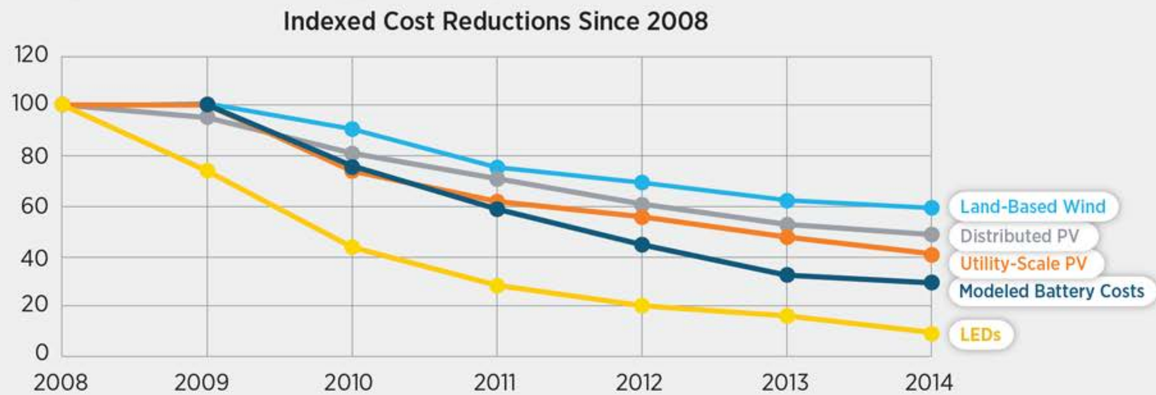
Accelerating Clean Energy Deployment



Falling Costs for Clean Energy Technologies



Deployment Sources:
Land-Based Wind: Wiser, R; Bolinger, M. 2014 *Wind Technologies Market Report*. LBNL. August 2015. http://go.usa.gov/3SRFQ
Utility & Distributed PV: GTM & SEIA, *U.S. Solar Market Insight: 2014 Year-in-Review*. March 2015. Assuming one coal plant is typically 0.5 GW.
LEDs: U.S. Department of Energy. Solid-State Lighting Program. *Adoption of Light Emitting Diodes in Common Lighting Applications*. Prepared by Navigant Consulting, July 2015. http://go.usa.gov/3SRzJ
EVs: Argonne National Laboratory. *2014 Vehicle Technologies Market Report*. March 2015. http://go.usa.gov/3S735.

Cost Sources:
Land-Based Wind: Wiser, R; Bolinger, M. 2014 *Wind Technologies Market Report*. LBNL. August 2015. http://go.usa.gov/3SRFQ. Bolinger, M.; Wiser, R., *MEMORANDUM - Documentation of a Historical LCOE Curve for Wind in Good to Excellent Wind Resource Sites*, LBNL, June 11, 2012. Updated Feb. 10, 2014.; and Moné, C.; Lantz, E. *Fiscal Year 2015 WWPTO LCOE Reporting Memorandum*. NREL September 2015.
Utility-Scale PV: Bolinger, M.; Seel, J. *Utility-Scale Solar 2014: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States*. LBNL, 2015. http://go.usa.gov/3SReG.
Distributed PV: Barbose, G.; Darghouth, N. *Tracking the Sun VIII: The Installed Price of Residential and Non-Residential Photovoltaic Systems in the United States*. LBNL, 2015. http://go.usa.gov/3SRz3.
LEDs: U.S. Department of Energy, SSL Program, *LED Lamp & Luminaire Product Tracker – A19 Lamps*. Q2 2015.
Modeled Batteries: Costs are modeled costs for high-volume battery systems, derived from DOE/UIS Advanced Battery Consortium PHEV Battery development projects.

Expanding Scope

For decades, America has anticipated the transformational impact of clean energy technologies. As the federal government and industry made long-term investments to support those technologies, some critics became impatient, claiming a clean energy future would "always be five years away." Today, the clean energy future has arrived.

In 2013, the U.S. Department of Energy (DOE) released the *Revolution Now* report, highlighting four transformational technologies: land-based wind power, silicon photovoltaic (PV) solar modules, light-emitting diodes (LEDs), and electric vehicles (EVs). That study and its 2014 update showed how dramatic reductions in cost are driving a surge in consumer, industrial, and commercial adoption for these clean energy technologies—as well as yearly progress.

In addition to presenting the continued progress made over the last year in these areas, this year's update goes further. Two separate sections now cover large, central, utility-scale PV plants and smaller, rooftop, distributed PV systems to highlight how both have achieved significant deployment nationwide, and have done so through different innovations, such as easier access to capital for utility-scale PV and reductions of non-hardware costs and third-party ownership for distributed PV.

Along with these core technologies, this update briefly introduces three additional technologies on the cusp of wider deployment and cost reduction in the coming years: smart building systems, fuel-efficient freight trucks, and vehicle lightweighting.

Today, clean energy technologies are providing real-world solutions—not only do they reduce the carbon pollution that causes climate change, but they also drive a domestic energy economy with technologies that are increasingly cost-competitive with existing conventional technologies, even without accounting for the climate benefits. Clean energy manufacturing and installations have also become major opportunities for American workers in the 21st century.

Even though we are seeing the results of the enormous progress these technologies have achieved, there is still more that can be accomplished. DOE's recent *Quadrennial Technology Review* identified hundreds of clean energy research and innovation opportunities in our homes, businesses, cars and trucks, and in the power sector, that with sustained investment will provide real-world solutions to our energy challenges.[1]

With the continued progress of the core technologies in this report, and more innovations on the horizon, the clean energy revolution is clearly transforming the way we produce and use energy.

[1] Found at http://energy.gov/qtr.

Land-Based Wind Power

Notes: 1 gigawatt (GW) = 1,000 megawatts (MW). All costs shown are inflation adjusted to dollar year 2014 and exclude the production tax credit (PTC). Wind capacity as reported by market reports.[2] "Wind Cost" represents estimated levelized cost of energy from a representative wind site, and "Lowest Wind Cost" represents costs derived from power purchase agreements from good to excellent wind resource sites in the interior of the country.[3]

Big Fans of Wind Power

Wind power is firmly entrenched as a mainstream power source: between 2008 and 2014, wind power accounted for 31% of all new generation capacity added in the United States.[4] As of 2014, there were more than 65,000 megawatts (MW) of utility-scale wind power deployed across 39 states[5]—enough to generate electricity for more than 16 million households[6]—with another 13,600 MW under construction as of the first quarter of 2015.[7] Wind now provides 4.4% of total U.S. electricity generation, 23 states have at least 500 MW of wind installed, and in nine states, wind exceeds 10% of total in-state electricity generation.[8,9] This ramp up in generation has yielded enormous benefits: wind power in the United States in 2013 reduced annual carbon dioxide emissions by more than 115 million metric tons and reduced water consumption by more

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[2] Wiser, R; Bolinger, M. *2014 Wind Technologies Market Report*. LBNL. August 2015. http://go.usa.gov/3SRFQ.
[3] Ibid; Bolinger, M.; Wiser, R., *MEMORANDUM - Documentation of a Historical LCOE Curve for Wind in Good to Excellent Wind Resource Sites*, LBNL, June 11, 2012. Updated Feb. 10, 2014.; and Moné, C.; Lantz, E. *Fiscal Year 2015 WWPTO LCOE Reporting Memorandum*. NREL September 2015.
[4] Wiser, R; Bolinger, M. *2014 Wind Technologies Market Report*. LBNL. August 2015. http://go.usa.gov/3SRFQ. Note that this report has an error and incorrectly states this number as 33%.
[5] Ibid.
[6] Wind generated 181,791 GWh in 2014 (Energy Information Administration, *Electric Power Monthly*, "Table 1.1.A. Net Generation from Renewable Sources: Total (All Sectors)." October 2015. http://go.usa.gov/cYAZm). The average American household consumed 10,932 kWh in 2014 (Energy Information Administration. *How much electricity does an American home use?* October 2015. http://go.usa.gov/cYAKh).
[7] American Wind Energy Association. *AWEA U.S. Wind Industry First Quarter 2015 Market Report*. April 2015.
[8] Energy Information Administration. *Electric Power Monthly – Detailed State Data*. http://www.eia.gov/electricity/data/state/. Accessed October 2015.
[9] Wiser, R; Bolinger, M. *2014 Wind Technologies Market Report*. LBNL, August 2015. http://go.usa.gov/3SRFQ.

than 36 billion gallons, all while supporting more than 50,000 U.S. manufacturing, construction, and wind operations jobs.[10]

Wind in the Sales

This success has been enabled in part due to recent reductions in the cost of wind power as U.S. wind power prices have reached an all-time low. Power purchase agreements for wind have fallen from rates up to 7 cents/kilowatt-hour (kWh) in 2009 to an average of 2.4 cents/kWh in 2014.[11] This low-cost wind power arises from projects installed in excellent resource locations in the central part of the country and is reflective in part of the federal production tax credit (PTC).

This significant reduction in cost in only five years is a result of multiple factors. First, DOE's sustained investment in improving wind technology, with $2.4 billion dollars invested in wind research and development between 1976 and 2014, has honed the technology and enabled many key improvements such as the taller turbines and longer blades highlighted below.[12]

Additionally, new transmission projects, such as those in the recently completed Texas Competitive Renewable Energy Zone transmission build-out, have enabled wind development in more areas of the country. Recent expanded coordination among grid operators has increased the ability of the grid to accept higher levels of wind generation while reducing curtailment.[13] State renewable portfolio standards and federal PTC policies have assisted deployment of continued investment in U.S. wind manufacturing.

Together, these investments, infrastructure projects, and policies have made wind a low-cost, zero-carbon alternative that contributes to the transformation of the U.S. electricity generation portfolio.

Growing Up

Continued innovation in next generation wind technologies could soon enable cost-competitive wind potential nationwide. One of the biggest changes in recent years is that wind turbines themselves are getting bigger: a wind turbine installed today on average has 108% longer blades and is 48% taller than one installed in 1999.[14] Taller turbines and longer blades allow access to the stronger and more consistent wind speeds that occur at higher altitudes, produce more electricity per tower thus minimizing the land area needed, and enable more cost-effective wind power. DOE estimates that the continued development of taller wind towers coupled with larger rotors and advanced turbine designs would grow wind's potential electrical output by 67% above

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[10] U.S. Department of Energy. "Chapter 2 – Wind Power in the United States." *Wind Vision*. March 2015. http://go.usa.gov/crxhR.
[11] Wiser, R; Bolinger, M. *2014 Wind Technologies Market Report*. LBNL. August 2015. http://go.usa.gov/3SRFQ. Note that these prices include the effect of the federal PTC and as such are lower than what is displayed in the chart above.
[12] Inflation adjusted to 2014 dollars using U.S. Bureau of Economic Analysis GDP budget deflator. 1978-2008: Pelsoci, T.; *Retrospective Benefit-Cost Evaluation of U.S. DOE Wind Energy R&D Program*. June 2010. http://go.usa.gov/3SRFY. 2009-2014: DOE Office of Energy Efficiency and Renewable Energy budget justification documents at http://go.usa.gov/3SRMx.
[13] Wiser, R; Bolinger, M. *2014 Wind Technologies Market Report*. LBNL. August 2015. http://go.usa.gov/3SRFQ.
[14] Ibid.

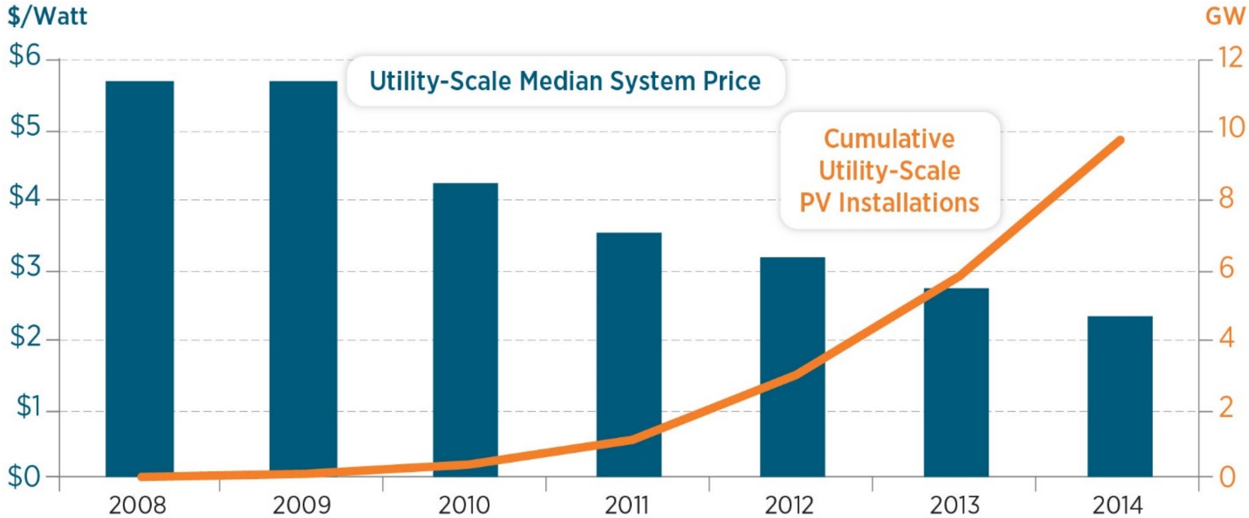
the wind technologies currently deployed, opening up an additional 700,000 square miles—or about one-fifth of the United States—for wind development.[15] This expansion of potential wind generation also occurs in much of the Southeastern portion of the country, an area that has historically not seen significant wind development.

In addition to these technological innovations, investments in supercomputing power are further optimizing whole wind plants and unlocking future cost reductions and efficiency improvements. Advanced computational modeling of the complex wind interactions across turbines coupled with improved sensing, advanced controls, and wind forecasting will increase efficiency and reliability to create the next generation of wind power technologies.

In many parts of the country, wind power is already becoming a cost-effective low carbon solution that supports U.S. jobs in manufacturing and construction—but wind still has large additional untapped potential, as shown in a recent DOE report which outlined how wind could generate 20% of the nation's electricity by 2030.[16] With ongoing technological innovation, transmission expansion, and continued federal and state support, wind can continue to grow and unlock its wide array of benefits in all 50 states.

[15] U.S. Department of Energy. *Enabling Wind Power Nationwide*. May 2015. http://go.usa.gov/3SRMj.
[16] U.S. Department of Energy. *Wind Vision*. March 2015. http://energy.gov/eere/wind/wind-vision.

Solar PV: Utility-Scale



Notes: All prices are in $/$W_{DC}$ and inflation adjusted to dollar year 2014. 1 gigawatt (GW) = 1,000 megawatts (MW). Prices as reported in market report.[17] "Utility-scale" cumulative installations as reported in source in GW_{DC}.[18]

Stepping Out of the Shade

Although the energy potential of the sun is limitless for practical purposes, the cost of converting that energy into usable electricity has long kept solar PV out of reach for all but a few niche applications. However, over the last several years, thanks to cost declines and technological advances, solar PV went from a novelty to a large-scale generation source purchased by electric utilities to meet demand.

Utility-scale PV has rapidly emerged as a mainstream technology over the last few years. By 2014, the total capacity of large utility-scale solar PV reached 9.7 GW with over 99% of these installations occurring after 2008.[19] This trend has continued with 15% of all electric generating capacity brought online from January to September 2015 arising from utility-scale PV.[20]

59% Cheaper

This large deployment is a result of the dramatic decline in the price of PV systems. Between 2008 and 2014, the cost for a PV module declined from $3.57/watt (W) to about $0.71/W.[21] Total cost declines mirrored this hardware cost reduction due to improvements in installation and business practices: the total cost of utility-scale PV systems fell from $5.70/W in 2008 to

[17] Bolinger, M.; Seel, J. *Utility-Scale Solar 2014: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States*. LBNL, September 2015. http://go.usa.gov/cYAp4.
[18] GTM & SEIA, *U.S. Solar Market Insight: 2014 Year-in-Review*. March 2015.
[19] Ibid.
[20] Federal Energy Regulatory Commission, Office of Energy Projects, *Energy Infrastructure Update for September 2015*. October 2015. http://go.usa.gov/craZB.
[21] Mints, P., *Photovoltaic Manufacturer Shipments: Capacity, Price & Revenues 2014/2015*. SPV Market Research. April 2015.

$2.34/W in 2014—a decrease of 59%.[22] This means solar is increasingly reaching cost parity with traditional electrical generation from natural gas and coal in parts of the United States.

A combination of DOE, federal, state, and industry actions helped achieve this drastic cost reduction in a short period of time. DOE's $4.1 billion investment in PV technology research and development (R&D) from 1975 through 2008 accelerated the cost reduction progress by an estimated 12 years, while providing a net economic benefit of $16.5 billion.[23] The federal Investment Tax Credit (ITC) along with state renewable portfolio standards and other state and local incentives for PV in the United States—as well as the European Union members, Japan, China, and other countries—have also effected solar deployment, further reducing manufacturing costs.

How Low Can You Go?

In 2014 and 2015, several PV system installers won power purchase contracts over traditional sources of generation and signed power purchase agreements with utilities to provide electricity at a cost between 4 to 5 cents/kWh. These are not just simple one-off projects with unusually good economics; utilities have on multiple occasions received proposed projects in this price range with aggregate capacity of more than 10 times the capacity requested.[24] Even though those prices are enabled by the federal tax credit, they represent a price offering that would have seemed shockingly low just a few years ago.

The utility-scale PV industry was, in part, kick-started by DOE's Loan Programs Office (LPO). Through funding provided by the Recovery and Reinvestment Act of 2009, the LPO financed the first five utility-scale solar PV projects over 100 MW in the United States with more than 1,500 MW of total capacity. Today, utility-scale solar is being financed by the private sector at increasing scale. As of summer 2015, there were 21 privately financed utility-scale solar PV projects over 100 MW either built or under construction.[25,26]

These low prices are also a result of new types of financial instruments specifically for clean energy projects like utility-scale solar PV, which provide a low cost source of capital. For example, as of mid-2015, six specially structured publicly traded companies had financed approximately 4,500 MW of solar, offering dividend yields between 3% and 7%.[27] As a testament to solar's technological progress, enormous potential, and overall maturity of the industry, large financial institutions now view utility-scale solar PV as an attractive investment.

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[22] Bolinger, M.; Seel, J. *Utility-Scale Solar 2014: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States*. LBNL, September 2015. http://go.usa.gov/cYAp4.

[23] "Retrospective Benefit-Cost Evaluation of DOE Investment in Photovoltaic Energy Systems." DOE, August 2010. http://go.usa.gov/3SRMh. Inflation adjusted to 2014 dollars using U.S. Bureau of Economic Analysis GDP budget deflator.

[24] Bolinger, M.; Seel, J. *Utility-Scale Solar 2014: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States*. LBNL, September 2015. http://go.usa.gov/cYAp4.

[25] U.S. Department of Energy, Loan Programs Office. *Powering New Markets: Utility-Scale Photovoltaic Solar*. February 2015. http://go.usa.gov/3SRez.

[26] SEIA. "Major Solar Projects in the United States: Operating, Under Construction, or Under Development." Updated Aug. 20, 2015.

[27] Based on internal NREL analysis of the market and yieldco investor presentations from the first half of 2015.

A Solar Flare of Activity

As of mid-2015, there were more than 27,000 MW of utility-scale solar projects under development, with 3,600 MW already under construction.[28] Even if only a portion of these projects are built, it will easily double existing capacity over the next few years. This large pipeline of planned projects is partially due to the pending expiration of the ITC at the end of 2016, which has allowed the industry to flourish by providing clear, long-term policy certainty.[29] So, as with wind, sustained federal and state support can help continue this rapid pace of utility-scale solar deployment beyond the next few years.

In the longer term, the potential for solar to eventually provide a much larger share of our electricity portfolio is dramatic: enough solar resource and land area is available for utility-scale PV to generate over 69 times the electricity needs of the nation.[30] With the help of additional investments and innovations in inverters, electricity storage, advanced materials, and new electricity market structures, more of this potential of clean energy could be unlocked.[31] The recent burst of activity in this sector has exceeded expectations, but for the future of utility-scale PV the sky really is the limit.

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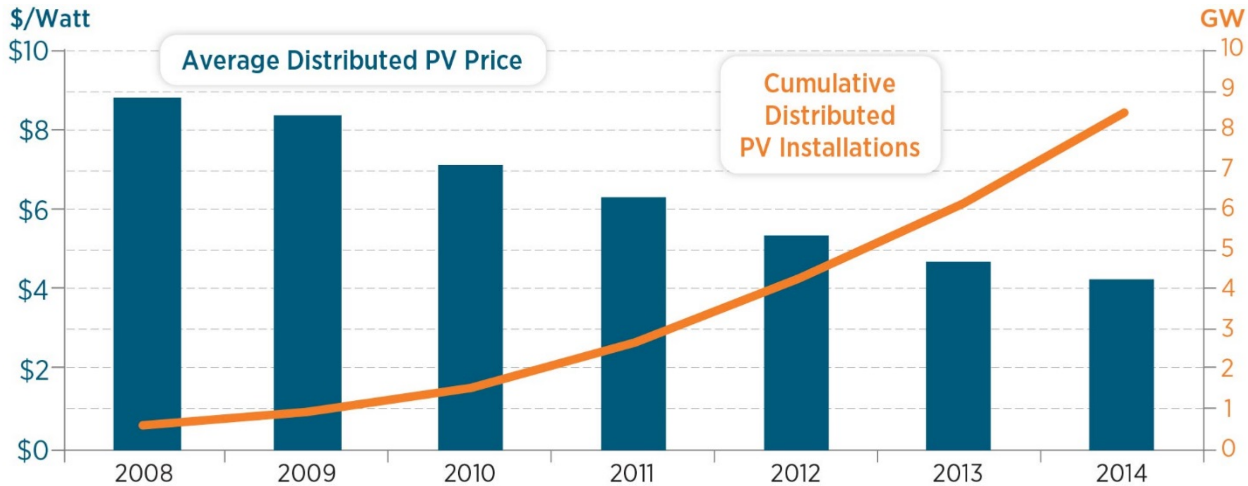
[28] SEIA. *Major Solar Projects in the United States: Operating, Under Construction, or Under Development*. Updated Aug. 20, 2015.

[29] Deutsche Bank Group, *Paying for Renewable Energy: TLC at the Right Price*. DB Climate Change Advisors. December 2009.

[30] Utility PV technical potential 282,800 TWh (Lopez, A; Roberts, B.; Heimiller, D.; Blair, N.; and Porro, G; *U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis*. NREL. July 2012. http://go.usa.gov/3SRtC). Total 2014 U.S. electricity generation 4,093 TWh (Energy Information Administration, *Electric Power Monthly*, "Table 1.1. Net Generation by Energy Source: Total (All Sectors)," October 2015. http://go.usa.gov/cYF5P).

[31] U.S. Department of Energy. *Quadrennial Technology Review*. Chapter 4, "Advancing Clean Electric Power Technologies," September 2015. http://energy.gov/qtr.

Solar PV: Distributed Generation



Notes: All prices are in $\$/W_{DC}$ and inflation adjusted to dollar year 2014. 1 gigawatt (GW) = 1,000 megawatts (MW). Capacity weighted average as reported by market report for residential systems only.[32] Non-residential systems are typically larger and have lower reported prices. Capacity is cumulative distributed residential and non-residential capacity, in GW_{DC}.[33]

Raise the Roof(top)

Distributed PV systems use the same basic PV technology as larger utility-scale projects, but they differ in one key aspect: they are located where the electricity is used. These systems are often on individual consumers' rooftops and are frequently not owned by a power company. This is unlike the vast majority of electricity generation facilities, where a power company generates electricity at a central plant and then sends it to consumers via the electric grid.

Although distributed PV technology has been available for years, falling prices over the last decade have unlocked its potential not only for the average homeowner but also for larger consumers like businesses and schools. Many installations are small enough to fit on a roof, but there is nothing tiny about distributed PV's growth. As of the summer of 2015, there have been nearly 800,000 cumulative distributed PV installations. This represents almost 10,000 MW in capacity, which is nearly equal to the capacity of utility-scale installations.[34]

Soft Costs

The cost of solar energy system hardware (i.e., panels, inverters, etc.) has dropped significantly, but the non-hardware "soft" costs of solar—such as permitting, installation, interconnection, and maintenance fees—remain a major barrier to greater deployment nationwide and can account for up to 68% of total system costs.[35] To address this problem, DOE launched the Rooftop Solar Challenge in 2011 to slash red tape and make installing rooftop solar PV easier, faster, and more affordable, and the on going Race to 7-Day Solar prize competition continues to drive innovation

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[32] Barbose, G.; Darghouth, N. *Tracking the Sun VIII: The Installed Price of Residential and Non-Residential Photovoltaic Systems in the United States*. LBNL, 2015. http://go.usa.gov/3SRz3.
[33] GTM & SEIA, *U.S. Solar Market Insight: 2014 Year-in-Review*. March 2015.
[34] GTM & SEIA. *U.S. Solar Market Insight Report: Q2 2015*. September 2015.
[35] GTM & SEIA. *U.S. Solar Market Insight Report: Q3 2014*. November 2014.

in this area. Efforts such as these appear to be turning the tide; even though module costs have been relatively constant since 2012, distributed PV prices have continued to drop, indicating that soft costs have been the major source of price reductions for the last two years.[36]

Although these recent declines in soft costs have been impressive, this area continues to hold the greatest potential for future cost reductions. For example, specific cities with the most favorable PV permitting processes were found to have prices up to 12% lower than the median state-wide price.[37] Similarly in 2014, despite comparable hardware costs, residential system pricing in Germany was reported to be $2.13/W compared to $4.17/W in the United States.[38] These examples indicate the huge potential to make further soft cost reductions.

A Capital Idea

Years ago, consumers had only one option if they wanted to install PV on their homes: pay for the whole system upfront and wait for savings to accrue over time. This created a major barrier, as most consumers could not afford the upfront costs, even if they would actually end up saving money over the life of the system. However, consumers today have many new options available to them. Third-party-ownership of PV systems has revolutionized the distributed PV market. Similar to leasing a car, third-party ownership allows consumers to benefit from lower electricity payments without purchasing the whole PV system directly. The success of this model has been clear—third-party financing accounted for more than 72% of U.S. residential PV systems installed in 2014.[39]

In addition, other business and financing innovations such as zero-down solar loans, shared community solar, and property assessed clean energy financing (also called PACE) are making it much easier and more affordable for consumers to install rooftop PV.

Forecast: Sunny

The cost reduction and deployment growth of distributed PV is expected to continue, as experts project the installed prices of residential PV systems to fall an additional 16-33% by 2020.[40] An August 2015 DOE LPO announcement provided guidance on how distributed energy projects may be eligible for DOE loan guarantees; those loan guarantees, along with other policy support, could enable innovative technology solutions to overcome remaining market barriers and deliver clean, cost-competitive distributed solar energy right to consumers' doorsteps in virtually every state in the nation.[41]

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[36] Barbose, G.; Darghouth, N. *Tracking the Sun VIII: The Installed Price of Residential and Non-Residential Photovoltaic Systems in the United States*. LBNL, 2015. http://go.usa.gov/3SRz3.

[37] Wiser, R.; Dong, C. *The Impact of City-level Permitting Processes on Residential Photovoltaic Installation Prices and Development Times.* LBNL, 2013. http://go.usa.gov/3SRtF.

[38] Barbose, G.; Darghouth, N. *Tracking the Sun VIII: The Installed Price of Residential and Non-Residential Photovoltaic Systems in the United States*. LBNL, 2015. http://go.usa.gov/3SRz3.

[39] GTM Research (2015). *U.S. Residential Solar Financing 2015-2020.*

[40] Feldman, et. al. *Photovoltaic System Pricing Trends: Historical, Recent, and Near-Term Projections - 2015 Edition*. LBNL and NREL. August 2015. http://go.usa.gov/3SRMH.

[41] U.S. Department of Energy, Loan Programs Office. *Distributed Energy Projects*. Accessed September 2015. http://go.usa.gov/3SRz9.

LED Lighting

Notes: Kilolumen is a measure of visible light output by a source. Price data is in nominal dollars as reported in internal tracking report.[42] Cumulative LED A-type bulb installations as reported in market report.[43]

Turning Up the Lights

Stand underneath a traditional incandescent bulb and a LED bulb[44] and you will soon feel the difference between the two— heat. While both produce the same amount of light, the incandescent bulb is too hot to touch, a clear sign that much of the energy it uses is being wasted. LED technologies have cut this wasted energy out of lighting: the best performing 60 W equivalent LED bulbs available now consume 85% less energy than incandescent bulbs.[45] LEDs are spurring a dramatic change in lighting due to their vast energy savings potential, lower costs, improved performance, and added benefits like long lifetime and maintenance savings.

These benefits are moving LEDs into the mainstream. From 2012 to 2014, total installations of common home LED bulbs increased six-fold from 13 million to 78 million—particularly rapid growth considering there were fewer than 400,000 installations as recently as 2009. LED bulbs now account for 2.4% of all currently installed lighting of this type – growth enabled by the nearly 90% reduction in cost since 2008.[46]

This success is a direct result of government-industry R&D investments to bring down costs, improve efficiency and performance, and foster domestic manufacturing of LED lighting

[42] U.S. Department of Energy, SSL Program, *LED Lamp & Luminaire Product Tracker – A19 Lamps.* Q2 2015.
[43] U.S. Department of Energy. Solid-State Lighting Program. *Adoption of Light Emitting Diodes in Common Lighting Applications.* Prepared by Navigant Consulting, July 2015. http://go.usa.gov/3SRzJ.
[44] In this report, "LED bulbs" refers to A-Type bulbs that are common in household applications.
[45] Calculated from U.S. Department of Energy. *LED Lighting Facts – CALiPER Snapshot "Light Bulbs"*, October 2013. http://go.usa.gov/3SRzA. See page 3, note 6. The best performing LED bulb approaches 90 lumens/W efficacy. To produce 800 lumens this LED draws 8.89 W of power, a 85% reduction compared to the 60 W of power drawn by the equivalent incandescent bulb.
[46] U.S. Department of Energy. Solid-State Lighting Program. *Adoption of Light Emitting Diodes in Common Lighting Applications.* Prepared by Navigant Consulting, July 2015. http://go.usa.gov/3SRzJ.

components and products. In the past decade, modest yet highly strategic investments by DOE have helped to make the United States the hub of LED lighting innovation. Today, America is beginning to reap the rewards of these years of investment. Looking at the bigger picture across all LED product types, LED installations prevented 7.1 million metric tons of CO_2 emissions and saved $1.4 billion in energy costs in 2014 alone.[47]

Beyond the Bulb

DOE and many in the lighting industry are looking toward the potential energy savings in the commercial and industrial sectors offered by replacing fluorescent overhead lighting common in most offices and manufacturing facilities. Energy impacts in these applications are disproportionally high relative to market share because of the large number of installations and extended operating hours. In contrast to lighting in homes, which average less than two hours of operation per day, commercial and industrial lighting fixtures average about 12 hours of operation per day.

Achieving the greatest possible market adoption and energy savings from LED products will require ongoing technology R&D improvements. Unlike conventional lighting sources, LED technology has significant headroom for additional technology advancements and DOE is working with industry to continue to reduce costs through improved materials and optics, optimized product design and assembly, boosting lumen outputs, and integrating LEDs with lighting control systems, which will enable even greater energy savings. DOE analysis has shown that with aggressive research and development, LED product efficiency can still be almost doubled, from the current 125-135 lumens per watt to 230 lumens per watt.[48]

A Bright Future

Fully capitalizing on the promise of LED technology will catapult our nation forward in creating a clean energy future. Energy-efficient technologies like LED lighting not only reduce the consumption of fossil fuels, they go hand-in-hand with making renewable energy more competitive. For example, further cost reductions in LED lighting will make it far more affordable and practical to construct zero-energy buildings—buildings so energy efficient that renewable energy systems can offset all or most of their annual energy consumption. Likewise, the conversion to LED street lighting will enable cities and towns across the country to dramatically reduce their energy and maintenance costs.

LEDs are projected to reach over 80% of all lighting sales by 2030 driven by performance increases and cost savings relative to conventional lighting.[49] This would save Americans $26

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[47] U.S. Department of Energy. Solid-State Lighting Program. *Adoption of Light Emitting Diodes in Common Lighting Applications.* Prepared by Navigant Consulting, July 2015. http://go.usa.gov/3SRzJ. Emission savings calculated by converting the reported 143 trillion BTU of source energy savings to site energy using a 3.05 site-to-source ratio, converting to electricity savings using 3412 BTU/kWh, and multiplying by the national CO_2 emission intensity of 1,136 lbs CO_2/MWh as reported by eGRID 2012 (http://go.usa.gov/crX6e).

[48] Efficiency (luminaire efficacy) is projected to reach 196 lumens/W in 2020. U.S. Department of Energy. Solid-State Lighting Program. *Solid State Lighting R&D Plan.* May 2015. http://go.usa.gov/cr4Sh.

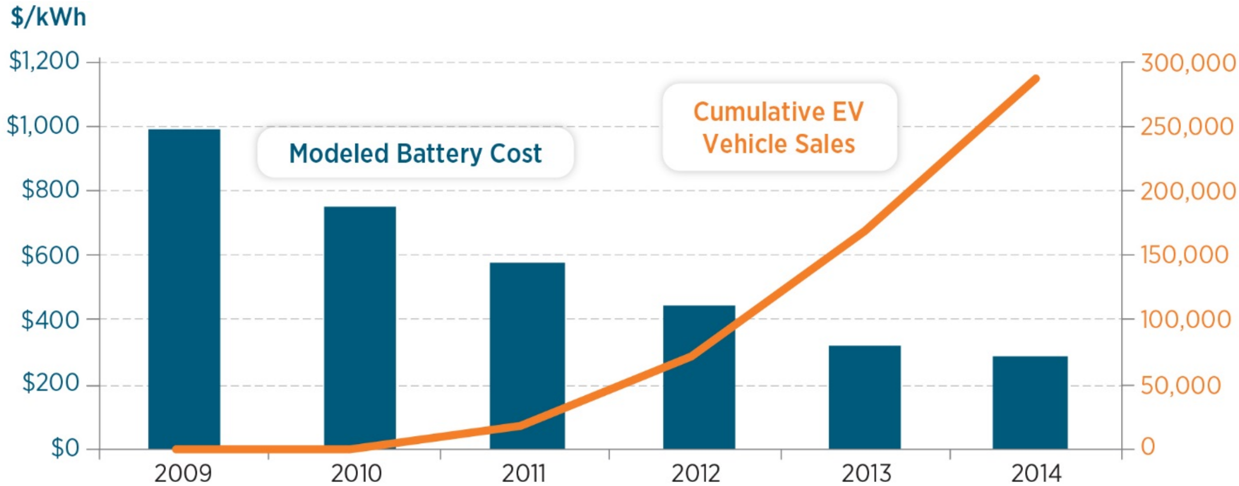
[49] U.S. Department of Energy. Solid State Lighting Program. *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications.* Prepared by Navigant Consulting, August 2014. http://go.usa.gov/3SRuB.

billion per year in electricity costs,[50] while cutting America's lighting electricity use by nearly half.[51] Developing this technology domestically also allows American manufacturing to benefit from exporting LEDs to rapidly electrifying developing nations while enabling those countries to save money and cut emissions by leapfrogging over less efficient lighting technologies.

[50] Calculated from: 261 TWh projected electricity savings from LEDs in 2030 (Ibid). Average retail electricity price for 2014 of 10.1 cents/kWh for residential, commercial, and industrial sectors (U.S. Department of Energy, Energy Information Administration. *Electric Power Monthly*. "Table 5.3. Average Price of Electricity to Ultimate Customers" Accessed October 2015. http://go.usa.gov/cYMpk).

[51] U.S. Department of Energy. Solid State Lighting Program. *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications.* Prepared by Navigant Consulting, August 2014. http://go.usa.gov/3SRuB.

Electric Vehicles



Notes: Costs are modeled costs for high-volume battery systems, derived from DOE/UIS Advanced Battery Consortium PHEV Battery development projects and are representative of nominal dollars. Sales as reported by market tracker, here "EVs" include all plug-in hybrid and battery plug-in vehicles.[52]

Putting it into High Gear

Americans bought nearly 120,000 electric vehicles (EVs) in 2014, more than double the number purchased in 2012. This brings the total number of EVs on U.S. roads to nearly 300,000 by the end of 2014.[53] Today, EVs are supporting America's energy and climate goals and helping domestic manufacturing remain globally competitive in the 21st century.

This is good news for our climate, our health, and our economy. With zero tailpipe emissions, EVs reduce local air pollution and help us breathe a little easier. They also enhance our energy security by reducing our oil use, while substantially cutting carbon emissions. For example a representative EV reduces greenhouse gas emissions by 48%, compared to a gasoline fueled car.[54] EVs also will become cleaner over time as the nation's electricity supply continues to move to lower-emitting energy sources.

This continued growth is the direct result of combined federal, state, and industry efforts to bring down the cost of EVs through research and development of better batteries, promoting consumer adoption through tax and other incentives, and supporting public and private investments in domestic EV manufacturing capacity. DOE's utility partnership agreement with Edison Electric Institute is intended to pick up this pace by collaborating with 70 utilities to accelerate EV and charging infrastructure deployment. Continued collaboration and investment in public education and outreach initiatives along with industry, state and federal support build on these successes to ensure the continued increase in EV adoption.

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[52] Argonne National Laboratory. *2014 Vehicle Technologies Market Report*. March 2015. http://go.usa.gov/3S735.
[53] Ibid.
[54] EV emissions are highly sensitive to geographic location; this number is based on the national electricity generation fuel mix: U.S. Department of Energy, Alternative Fuels Data Center. *Emissions from Hybrid and Plug-In Electric Vehicles.* Accessed October 2015. http://go.usa.gov/3Snq9.

Charging Ahead with Batteries

The increase in EV sales in recent years has been enabled by the development of lower-cost lithium-ion batteries supported by DOE research, which will continue to be a critical area going forward. DOE models for EV battery fabrication costs have indicated that the expected cost of EV batteries at high-volume has fallen by an astounding 70% since 2008.[55]

The cost and performance of batteries are a key factor in continuing to lower the costs of EV ownership. In addition to universities and industry, DOE has been a leader in battery R&D investment: between 1992 and 2012, DOE invested $1 billion dollars in battery R&D, which advanced the state-of-the-art by six years and created $3.5 billion worth of economic value.[56] This investment continues to pay off as rapidly falling costs mean that near-future battery costs may be as low as $200/kWh by 2020.[57] Looking ahead, DOE is working with industry, academia, and its national laboratories toward achieving an even more aggressive goal of $125/kWh modeled production costs by 2022.[58]

We can now see firsthand the results of advanced research in EV batteries making their way into the market. For example, the energy storage capacity of the second-generation Chevrolet Volt battery increased by 15% compared to the previous generation. [59] In general, optimization of cell chemistry, design, and performance decrease the mass of battery packs, allowing EVs to travel farther with full performance.

Road to the Future

Automakers are taking advantage of these innovations to design lower-priced EVs that are poised to be strong competitors. For example, multiple automakers plan on delivering 200-mile-range EVs for less than $40,000 around 2017.[60] As EVs accounted for 1.6% of all passenger cars sold in 2014,[61] the potential for the next generation of EVs to impact transportation is large.

Improved charging infrastructure will also maintain momentum for EVs. There are now more than 30,000 public and private EV charging outlets in the United States,[62] and as of August 2015,

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[55] Modeled costs are validated through applied research, and represent calculated high-volume commercial production costs, rather than market price.

[56] Inflation adjusted to 2014 dollars using U.S. Bureau of Economic Analysis GDP budget deflator. U.S. Department of Energy. *Benefit-Cost Evaluation of U.S. DOE Investment in Energy Storage Technologies for Hybrid and Electric Cars and Trucks*. Prepared by STI International. December 2013. http://go.usa.gov/3SnqJ.

[57] Nilson, M.; Nykvist, B.; *Rapidly Falling Costs of Battery Packs for Electric Vehicles*. Nature Climate Change, April 2015. http://dx.doi.org/10.1038/nclimate2564.

[58] U.S. Department of Energy. *EV Everywhere Grand Challenge*. January 2014. http://go.usa.gov/3Sn3B.

[59] "Chevrolet Introduces All-New 2016 Volt," *General Motors*, January 12, 2015. Accessed Aug. 25, 2015: http://media.gm.com/media/us/en/gm/news.detail.html/content/Pages/news/us/en/2015/Jan/naias/chevrolet/volt/0112-volt-2016-intro.html.

[60] Davies, A. "Chevy Could Beat Tesla to Building the First Mainstream Electric Car," *Wired*. Accessed Aug. 21, 2015: http://www.wired.com/2015/01/chevrolet-bolt-ev.

[61] 118,882 EVs sold in 2014 (Argonne National Laboratory. *2014 Vehicle Technologies Market Report*. March 2015. http://go.usa.gov/3S735) compared to 7,687,619 total passenger cars sold in 2014 (Ward's Auto U.S. Car and Truck Sales, 1931-2014. January 2015. http://wardsauto.com/keydata/historical/UsaSa01summary).

[62] U.S. Department of Energy, *Alternative Fuels Data Center*. "Alternative Fueling Station Counts by State," Accessed October 2015. http://go.usa.gov/3S7rh. Residential EVSE locations or "wall outlets" are not included.

the DOE Workplace Charging Challenge had partnered with more than 230 organizations that have committed to providing EV charging for employees, increasing range confidence for potential EV owners.[63] This expanded charging network, along with EV-supportive municipal codes for public and private parking facilities and workplace charging, is helping to drive continued success. In addition, Tesla Motors has developed coast-to-coast fast charging for their customers in the United States comprised of about 500 stations and nearly 3,000 chargers across America and several in Canada, allowing cars to charge in minutes instead of hours.[64] The future of EV charging research and development now lies in wireless power transfer—charging a car without a power cord—which could open even more doors for future EVs in America.

As EVs have become mainstream, automakers are competing aggressively to design and deploy the electric car of the future. With over 360,000 EVs deployed as of September 2015,[65] America has one of the largest EV markets in the world and more and more Americans are abandoning the gas pump and powering their cars with affordable, clean, and secure American energy.

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[63] Workplace Charging Challenge Newsletter: July 2015.
[64] "Tesla Supercharger." Accessed Aug. 21, 2015: http://www.teslamotors.com/supercharger.
[65] Argonne National Laboratory, *Light Duty Electric Drive Vehicles Monthly Sales Update*, Accessed October 2015. http://go.usa.gov/c3PeV.

Revolution… Next

Our mission is innovation that continues to reduce the costs of a low carbon future from the near term to the end of the century. The technologies highlighted in this report are already making a big impact and are easily visible: wind towers dot the landscape, solar panels sprout on rooftops, LEDs are on every hardware shelf, and the latest EV models can be seen on many neighborhood streets.

Other emerging technologies that are not quite as visible will lead the next phase of the clean energy revolution. In each case, deployment has begun to accelerate, costs have started falling, and large-scale deployment could transform portions of the energy sector. The technologies discussed here are among those to keep an eye on over the next five to 10 years.

Sweet Suite of Smart Building Technologies

A suite of new technologies will transform the way buildings use energy and interact with human occupants. These "smart building" technologies may be easy to overlook, because they are housed in familiar heating, ventilation, and air conditioning (HVAC) units and smart electricity meters. However, their potential to increase the comfort of building occupants while saving energy is immense. These devices can self-configure; communicate and self-diagnose maintenance issues; learn building functions, floor plans, and layouts; and track occupancy information to avoid complicated, expensive installation and maintenance scenarios and improve user comfort. This feedback automates energy efficiency improvements and will help avoid the need to crack a window when the office becomes too hot in the winter or bundle up when the air conditioning is blasting in the summer.

Companies with large commercial facilities are starting to recognize the benefits of these technologies and are working to retrofit existing heating and cooling units. These controls make smart business sense with an average energy savings of 55% per unit, resulting in a one- to three-year return on investment.[66] The potential for wider energy savings is also huge. Commercial HVAC represents 250 billion kilowatt-hours of electricity use[67] and the addition of smart controls to a subset of very large HVAC units less than 10 years old could lead to a savings of 37 billion kWh/year—more than the total amount of electricity generated in Nevada.[68]

Smart meters on homes and businesses can enable energy savings and increase the flexibility of the electricity grid. Advanced metering devices enable two-way communication between the meter and the electricity provider and interface with smart thermostats and appliances (including those large connected building HVAC units). Both allow utilities to better manage peak power demand and assist the consumer in managing their own building energy use.[69] With 51.9 million smart meters installed as of 2013, households and businesses are starting to take advantage of this infrastructure and savings opportunities.[70]

Key challenges to wider adoption of these technologies include the ability to install the product directly out of the box, more easily install upgrades and perform maintenance, and enhancing security. Smarter buildings will mean smarter energy use, which will lead to greenhouse gas reductions, energy bill savings, and more comfortable homes and offices. It doesn't take years of schooling to see the time has come for this smart idea.

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[66] Wang, W.; et. al. *Advanced Rooftop Control (ARC) Retrofit: Field-Test Results*. Pacific Northwest National Laboratory (PNNL), July 2013. http://go.usa.gov/3Sn3w.

[67] 60% of cooling and ventilation load from: U.S Department of Energy, *Buildings Energy Data Book*, Table 3.1.4. Accessed October 2015. http://buildingsdatabook.eren.doe.gov/.

[68] Internal U.S. Department of Energy Building Technologies Office calculations and http://www.eia.gov/electricity/state/nevada/.

[69] Pratt, R.G., et. al. *The Smart Grid: An Estimation of the Energy and CO2 Benefits*. PNNL. January 2010. http://go.usa.gov/3Snc5.

[70] U.S. Department of Energy, Energy Information Administration. *Electric Power Annual 2013*. "Table 10.10. Advanced Metering County by Technology Type." Accessed October 2015. http://go.usa.gov/3Snx4.

Freight Trucks That Can Keep on Trucking

Tractor trailers, big rigs, semi-trucks, 18-wheelers—whatever you call them, these heavy trucks are critical to economic activity, serving as the backbone of our domestic freight transport, hauling nearly 73% of freight tonnage. Although freight trucks comprise only 4% of on-road vehicles, they are responsible for almost 26% of U.S. on-road fuel consumption, representing a huge potential for reducing the U.S. transportation sector's energy and climate change impacts.[71]

DOE's Vehicle Technologies Office initiated the SuperTruck program in 2010 with the goal of increasing the freight efficiency of long-haul trucks by 50% in 2015 compared to 2009. Four teams were competitively selected for this five-year effort, and were led by Cummins/Peterbilt, Daimler Trucks North America (DTNA), Navistar, and Volvo Trucks North America. These manufacturers represent more than 90% of the U.S. market share for trucks. This program has been a success with the top performing truck so far greatly exceeding the original goal, achieving a 115% improvement in freight efficiency.[72]

The technologies that enable these significant fuel efficiency improvements are actually a suite of innovations that, in aggregate, result in big impacts. Modifications to the trailer that improve aerodynamics and low rolling resistant tires can be easily paired with existing trucks to achieve up to 27% fuel savings. One incredibly simple but effective example is the "skirts" that are now often observed below the side and between the wheels of the trailer to reduce drag. Soon to be released engines are expected to be at least 15% more efficient and will include advanced powertrain electronics that will deliver gains in fuel economy through optimization and precise control of combustion, fuel injection, air handling, and reductions in friction and other energy losses.

With a combined DOE and industry investment of $270 million in developing SuperTruck innovations, the technologies are already seeing commercial deployment or will be commercially available in the near future. Overcoming the challenges that still remain in bringing some of the more advanced solutions to market is a core goal of the Department's follow on SuperTruck II effort. Taken as a whole, SuperTruck technologies could achieve significant market penetration in the near term and could result in a cumulative savings of nearly 290 million barrels of oil by 2020.[73]

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[71] Federal Highway Administration, *Highway Statistics 2013*. "Table VM-1: Annual Vehicle Distance Traveled in Miles and Related Data." Accessed October 2015. http://go.usa.gov/3SnxP.

[72] U.S. Department of Energy, Vehicle Technologies Office. *SuperTruck Team Achieves 115% Freight Efficiency Improvement in Class 8 Long-Haul Truck.* April 2015. http://go.usa.gov/3SnxG.

[73] U.S. Department of Energy. *DOE SuperTruck Program Benefits Analysis*. Prepared by TA Engineering. December 2012. http://go.usa.gov/3SnC3.

Vehicle Lightweighting: Lighten the Load and Hit the Road

Vehicle lightweighting is a key tool in developing the next generation of cars that achieve significantly greater fuel economy and reductions in greenhouse gas emissions. This is an effective method of saving both energy and fuel because a lighter vehicle requires less power to accelerate. This allows the engine—a large source of mass in the car—to be downsized while maintaining vehicle performance. For example, a 10% weight reduction can increase vehicle fuel economy by 6% to 8% and for EVs lightweighting can increase how far the vehicle can travel on battery power.[74]

Lightweighting requires new materials to be developed to replace the conventional steel and other heavy car components without compromising strength, performance, or safety. Some of these new materials, such as high-strength steel and aluminum, are already in use, and advanced material innovations such as composites made from polymer matrices, carbon fiber, and glass fiber are working their way to market. New manufacturing processes have also been developed to process these materials at scale. Many of these materials and manufacturing innovations were proven through a recent lightweighting project supported by DOE, which culminated with the demonstration of a 23.5% lighter 2013 Ford Fusion.[75] This demonstration used today's materials with unique manufacturing processes that previously had not been implemented at high volumes. As a result, these innovations are ready for market entry.

Investment in this area is also growing: Ford announced that its 2016 line of F-150 trucks will include aluminum parts that shed nearly 700 pounds compared to previous models. In addition, vehicle components manufacturer Magna, as a result of a DOE-funded program, has built two plants in the United States to produce special types of lightweight aluminum parts that are otherwise impossible to manufacture domestically. Earlier this year DOE's LPO announced a conditional commitment for a $259 million loan to Alcoa, Inc. to support the expansion of an existing manufacturing facility to produce advanced high-strength aluminum for automakers such as Ford.[76] Other innovations like carbon fiber wheels, fiberglass coil springs, and lightweight body panels are just beginning to be introduced into the luxury car segment. For example BMW's I3 EV has carbon fiber body and other manufacturers like Tesla, Mercedes Benz, and Land Rover have aluminum body vehicles currently available in the market.

With industry, academia, and national labs, DOE continues to invest in reducing technical gaps in lightweight structural materials (aluminum, magnesium, future generations of advanced high-strength steel, and carbon fiber composites) and processes to accelerate their use to improve efficiency in high volume vehicles. Continued investment will enable a huge potential savings in this area. Projected innovations in lightweighting and advanced high efficiency engines deployed in one quarter of the U.S. fleet could result in a savings of five billion gallons per year by 2030.[77]

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[74] U.S. Department of Energy, *Quadrennial Technology Review.* 2011. p.39. http://go.usa.gov/3SnC9.
[75] U.S. Department of Energy. *Road to Fuel Savings: Ford, Magna Partnership Help Vehicles Shed the Pounds*. August 2014. http://go.usa.gov/3SnCA.
[76] U.S Department of Energy. *Energy Department Offers Conditional Commitment to Alcoa to Support Manufacturing of Aluminum for Automotive Sector*. March 2015. http://go.usa.gov/3SnCJ.
[77] U.S. Department of Energy, Vehicle Technologies Office. *Lightweight Materials for Cars and Trucks*. Accessed October 2015. http://go.usa.gov/3SnrB.

Conclusion

The clean energy technologies highlighted here are transforming how our nation produces and uses energy. While challenges and uncertainty exist for these technologies, it is clear that they are not some far away opportunity, but are now a significant part of the energy landscape. We can and should plan on using them to clean our air, reduce our reliance on unstable oil markets, and help build an economy that is more competitive and more efficient, while reducing carbon pollution.

There are even more technologies that are just on the horizon. These will increase the efficiency of the vehicles we depend on for travel and move goods, and the systems we use to manufacture new products and control our buildings. Although not as visible to the public eye, these technologies are every bit as important to the future clean energy economy, holding the potential for significant energy savings.

DOE will continue to encourage these innovations by providing support for R&D, consumer education, and industry and stakeholder engagement. With continued progress in critical renewable and energy-efficient technologies like these, we can look forward to a future of clean, American-made energy.