U.S. DEPARTMENT OF ENERGY

The Future Arrives for Five Clean Energy Technologies – 2016 Update

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Acknowledgments

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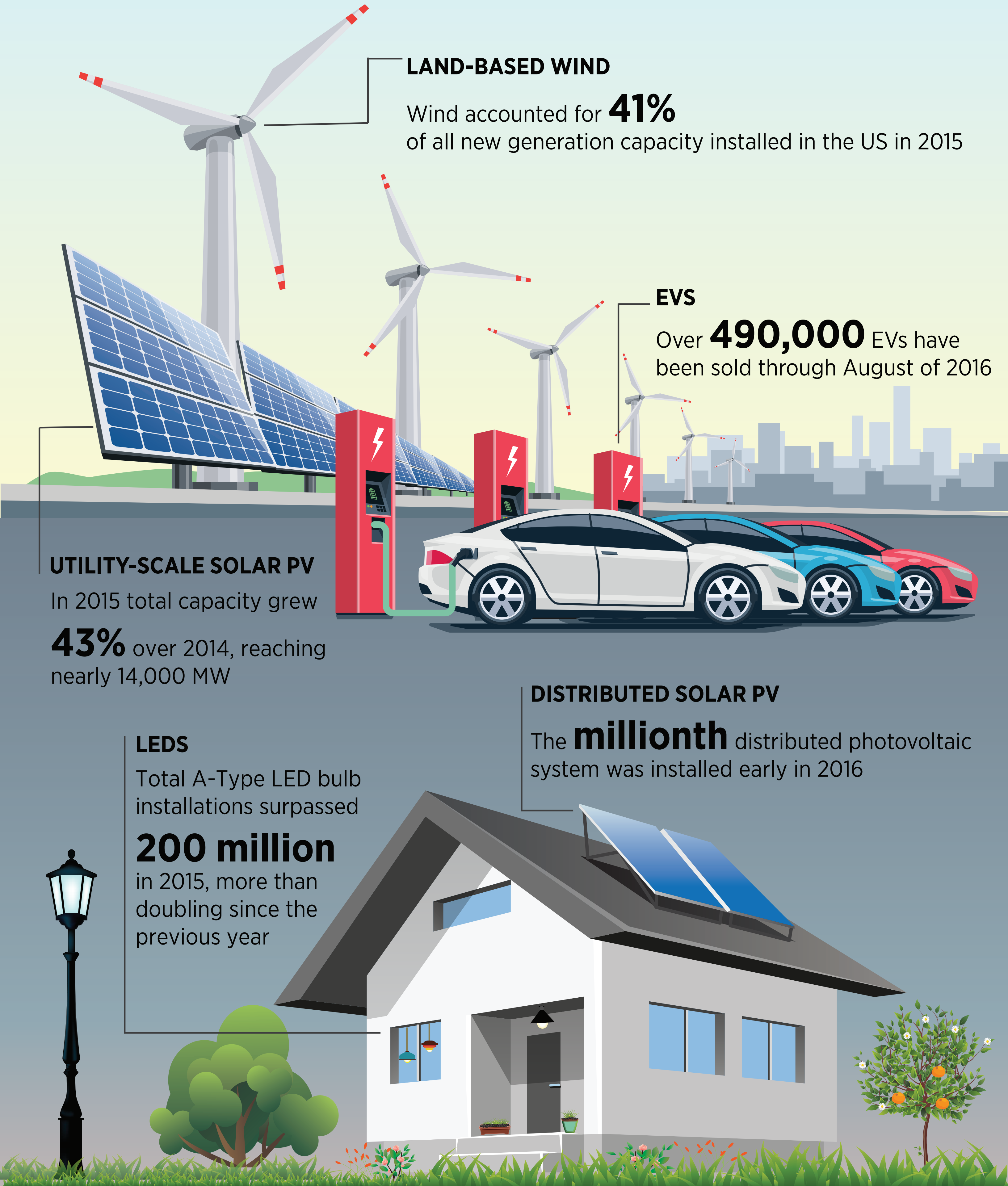
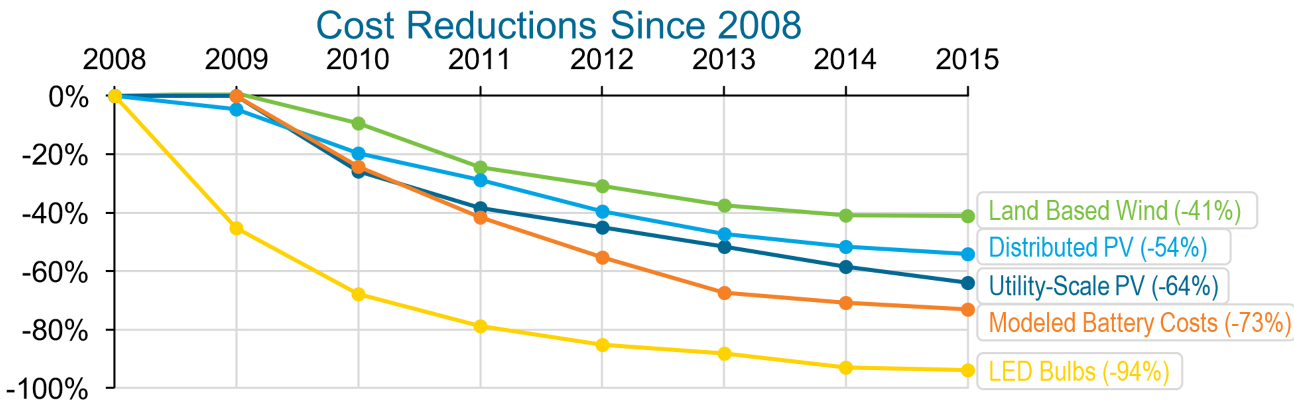




Notes: Land based wind costs derived from levelized cost of energy from representative wind sites from references [1] and [2]. Distributed PV is average residential installed cost from reference [3]. Utility-Scale PV is median installed cost for utility-scale PV systems from reference [4]. Modeled battery costs are at high-volume production of battery systems, derived from DOE/UIS Advanced Battery Consortium PHEV Battery development projects. LED bulbs are for A-type bulbs from reference [5].

Accelerating Progress

Decades of investments by the federal government and industry in five key clean energy technologies are making an impact today. The cost of land-based wind power, utility and distributed photovoltaic (PV) solar power, light emitting diodes (LEDs), and electric vehicles (EVs) has fallen by 41% to as high as 94% since 2008. These cost reductions have enabled widespread adoption of these technologies with deployment increasing across the board.

Combined, wind, utility-scale and distributed PV accounted for over 66% of all new capacity installed in the nation in 2015. [6] Total installations of LED bulbs have more than doubled from last year, [5] and cumulative EV sales are about to pass the half-million mark. [7]

These technologies are now readily available and our country has already begun to reap the benefits through their increased adoption. As these clean technologies are broadly deployed there is a reduction in the emissions that contribute to climate change, the air we breathe is better quality because of a decline in air pollutants, and we are expanding economic opportunities for American workers and manufacturers. In 2014 the manufacturing sectors for wind turbines, photovoltaic panels, lithium ion batteries, and LEDs have added $3.8 billion dollars in value to the U.S. economy. [8]

As we continue to advance international action on climate change under the Paris Agreement – which established a long-term worldwide framework to reduce global greenhouse gas emissions – these five technologies have and will play a critical role in providing opportunities to reach global climate goals.

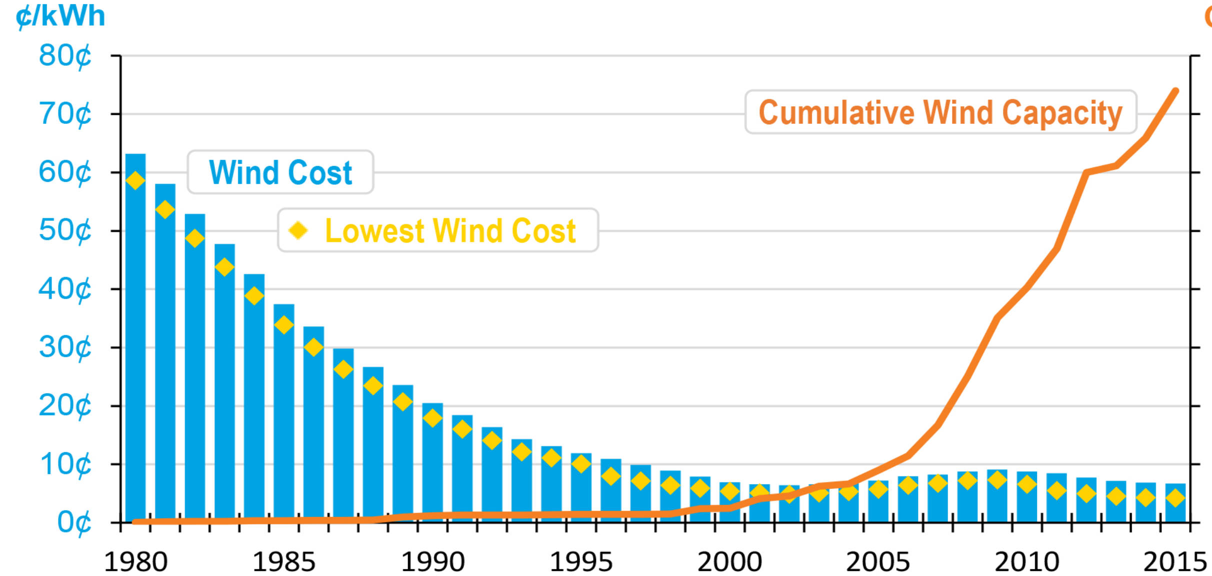
The technologies highlighted in this report exemplify how the clean energy revolution is already underway, is already providing real-world benefits, and continues to promise new solutions on the horizon to address our most pressing energy challenges.

Through the Mission Innovation initiative announced in 2015, 20 countries and the European Union have committed to double their respective clean energy research and development investment over five years. This surge will surely lead to breakthroughs in other clean energy technologies that today still seem futuristic, just as many of the technologies in this report seemed just a few years ago.

We have seen incredible achievements from these technologies, but we must continue to strive to innovate and develop the technologies that remain to be unlocked.

In addition to the emerging technologies highlighted in last year's report — super efficient trucks, smart buildings, and light weighting materials — this report will highlight four additional technologies — hydrogen fuel cells, smart energy management, grid connected batteries, and big area additive manufacturing — which are on the cusp of future widespread deployment.

Wind



Cost data from references are inflation adjusted to dollar year 2015, and exclude the production tax credit. "Wind Cost" data estimates the levelized cost of energy from a representative wind site from references [1] and [2] and "Lowest Wind Cost" represents costs derived from power purchase agreements from good to excellent wind resource sites in the interior of the country as reported in reference [9]. [1] Deployment data also from reference [9]. 1 gigawatt (GW) = 1,000 megawatts (MW).

Blowing Down Barriers

Wind power surged in 2015 with capacity growing by 12% since 2014, representing 41% of all new capacity installed in the U.S. last year. [9] As of 2015, there were nearly 74,000 megawatts (MW) of utility-scale wind power deployed across 41 states and territories [9]—enough to generate electricity for more than 17 million households.[2]

Overall, wind capacity has nearly tripled since 2008. Wind provided nearly 5% of total U.S. electricity generation in 2015. In 23 states more than 500 MW of wind have been installed, and twelve states have seen their wind generation exceed 10% of total in-state electricity generation. [9] This intense ramp up in installed generation has yielded enormous benefits. In 2015, wind power in the U.S. reduced annual carbon dioxide emissions by more than 132 million metric tons and decreased water consumption by more than 73 billion gallons.

These environmental benefits are in addition to the nearly 90,000 U.S. manufacturing, construction, and wind operations jobs contributing to a stronger U.S. economy. [10] In whole, the domestic manufacturing of wind turbine components was able to add approximately $2 billion to the U.S. economy in 2014 alone. [8]

Wind in the Sales

This success of wind deployment has been enabled, in part, by recent cost reductions of wind power as U.S. wind prices have reached all-time lows. Power purchase agreements for wind have fallen from rates of up to 7 cents/kilowatt-hour (kWh) in 2009 to an average of 2 cents/kWh today in certain regions of the country.[3]

This significant reduction in cost and massive increase in deployment in a few years is a result of multiple factors, including government investments, infrastructure development, and federal and state incentives. First, DOE invested $2.4 billion dollars in wind research and development between 1976 and 2014.[4] These continued investments in key technology improvements such as the taller turbines and longer blades highlighted below have helped drive down cost and improve performance.

1 One large capacity project was excluded from reference [9] based on unusual circumstances identified in the citation.
2 Wind generated 190,927 GWh in 2015. [18] The average American household consumed 10,932 kWh in 2014. [96]
3 Note that these prices come from reference [9] and include the effect of the federal PTC and as such are lower than what is displayed in the chart above.
4 Inflation adjusted to 2015 dollars using U.S. Bureau of Economic Analysis GDP budget deflator. Investment data and impacts for 1978-2008 from reference [97], data for 2009-2014 investments from reference [98].

Additionally new transmission expansion projects, such as the recently completed Texas Competitive Renewable Energy Zone transmission build-out, have enabled wind development in more areas of the country — such as the central part of the country that already has optimal wind resource locations. Expanded coordination among grid operators has also increased the ability of the grid to accept higher levels of wind generation. [9]

Finally, policy has played a vital role in driving continued deployment of wind at both the state and national level. State renewable portfolio standards have created mandates to build renewable energy in more than half the states in the country. At the federal level, the production tax credit (PTC) has provided a financial incentive to wind projects, increasing their value relative to other generation technologies.

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.

New Windows of Opportunity

Continued innovation in next generation wind technologies could soon enable cost-competitive wind in new areas and new markets.

Beyond lowering costs in existing markets around the country, taller towers and longer blades could allow for development of more wind projects in areas like the Southeastern U.S. that historically have not seen significant wind development. For example, a wind turbine installed today on average has 108% longer blades and is 48% taller than one installed in 1999. [9] The longer blades allow each turbine to capture more energy, and taller towers allow access to the stronger and more consistent wind speeds that occur at higher altitudes in many parts of the country. Combined, these innovations allow each turbine to produce more electricity, reducing both the number of turbines needed to produce a given amount of electricity and the land area needed for their installation.

These innovations enable a new generation of more cost-effective wind power. DOE estimates that the continued development of taller wind towers coupled with larger rotors and advanced turbine designs would allow wind to be cost-effectively deployed across the country. [11]

In addition, the development of wind energy in the waters off our nation's coasts holds enormous potential. The technical potential of offshore wind resources is enough to generate more electricity than twice what the U.S. generated from all sources of electricity in 2015. [12]

The nation will have begun to take advantage of this offshore wind potential later this year as the 30 MW Block Island project, located off the shore of Rhode Island, should be fully operational by the end of 2016. This will be the first commercial offshore wind power plant to operate in the U.S. By the end of 2015, the Department of the Interior had awarded 11 commercial leases totaling 14,600 MW of capacity. [12] While the domestic offshore wind industry still faces challenges, the potential of this technology to capture high wind resources close to coastal load centers makes it a key future source of clean electricity for the nation.

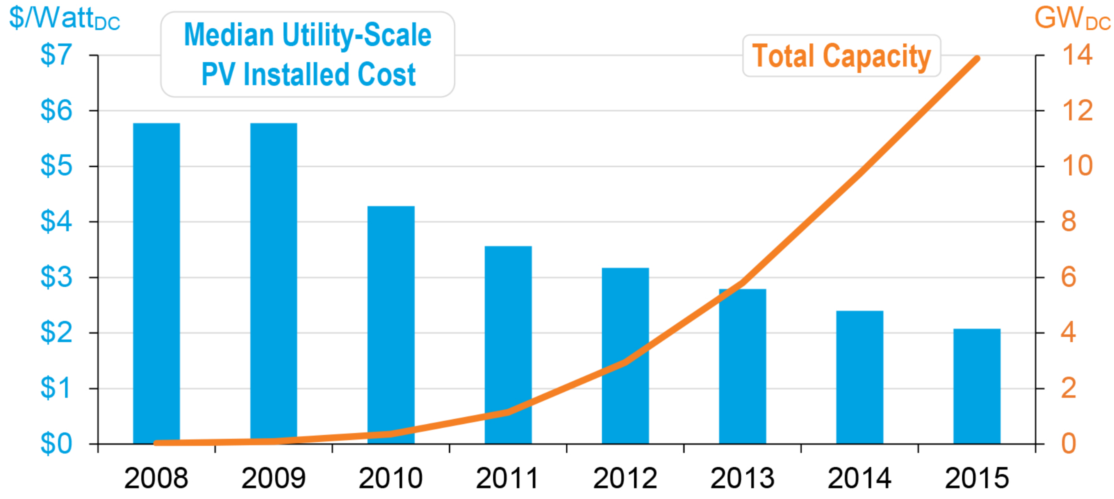
Wind is also being purchased by new types of customers beyond traditional utilities. In 2015 nearly 2,000 MW of wind power was contracted by corporations, representing companies across the retail, financial, technology, and manufacturing sectors — rapid growth considering only about 100 MW of wind power was contracted by corporations in 2011. [13] This investment has been driven by a combination of competitive prices, environmental responsibility, and the desire to invest in local economies.

Whirlwind of Activity

At the end of 2015, more than 110,000 MW of wind power was being considered by utilities and transmission system operators for installation across the country representing nearly a third of all new proposed electricity generation capacity. [9] Wind has massive untapped potential, as shown in a recent DOE report, *Wind Vision*, which outlined how wind could generate 20% of the nation's electricity by 2030 and 35% by 2050. [14] Technological advancements are expected to continue to drive down costs in the future — a recent elicitation of wind experts indicated wind energy costs could fall another 35% by 2050. [15]

With continuous 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.

Solar PV: Utility-Scale



Costs from reference [4]; Deployment from reference [16]. Costs shown are the median costs and exclude the effect of the Investment Tax Credit. 1 gigawatt (GW) = 1,000 megawatts (MW). Costs and capacity are reported as DC power.

Shedding Light on Expanded Solar Deployment

Annually, enough solar energy and land area is available in this country for utility-scale solar PV to generate ten times the energy needed to power the entire nation.[5] The challenge really lies in cost-effectively capturing and converting this sunlight into useful forms of energy. However, significant cost reductions in recent years has led to expanded deployment of utility-scale PV, and nationally we are poised to take advantage of this nearly limitless source of energy.

Utilities and the power sector are installing more utility-scale PV, as the installation cost of utility-scale PV has steadily declined year after year, falling over 64% since 2008. This drop in cost has enabled explosive growth with total capacity reaching more than 13,900 Megawatts (MW)[6] in 2015, a growth of 43% over 2014. [16] The amount of capacity installed in 2015 represented 15% of all utility-scale domestic electric generation capacity installed that year. [6] This deployment trend continues to accelerate. In 2015, utility-scale PV generated 23 billion kWh, [17] enough electricity to power over 2.1 million American homes.[7] In the first half of 2016, utility-scale PV generated 15 billion kWh – a 34% increase over the same time period as last year. [18]

The Dawn of New Markets

Since 2008, installation of utility-scale PV costs have fallen 64%, to a new low of $2.08/Watt. [4] These installed costs have translated into record-low prices for electricity from solar power. Only five years ago, contracts for utility-scale PV power were commonly at ¢10/kWh. As of 2015 average prices are well below ¢5/kWh, with a number of future projects already planned to deliver electricity below ¢3.5/kWh. It's important to note that these low costs are reflective in part of the location of projects in excellent solar resource locations and of the federal investment tax credit (ITC).

Falling prices aren't limited to the sunniest parts of the country either. While the majority of projects still arise from the sunny Southwestern markets, 42% of new utility-scale PV power contracts signed since 2013 are east of the Rocky Mountains, including Texas along with Southeastern and Midwestern parts of the country. [4]

5 97.528 Quads of energy was consumed in the U.S. in 2015, [99] and the annual technical potential of utility-scale PV in the U.S. is estimated to be 282,800 TWh (equal to 965 Quads). [100]

6 Utility-scale PV capacity and cost figures are provided in terms of DC power unless otherwise indicated.

7 The average home consumed 10,932 kWh in 2014. [96]

In addition to expanding to new areas of the country, utility-scale PV is also being purchased by non-utility consumers. Corporations are increasingly realizing the benefits of directly procuring solar power from developers. In 2015 more than 1,000 MW of solar PV capacity was contracted by corporations representing the retail, finance, technology, and manufacturing industries, and this amount has quadrupled over the amount contracted in 2014. [13] In 2016 it is predicted that over 1,000 MW of utility-scale PV will be contracted with non-utility customers, [16] and it highlights how going solar increasingly makes business sense for many of these interested corporations.

Similarly, with support from the DOE's Federal Energy Management Program, the Federal government is increasingly directly contracting utility-scale PV. For example in 2015 the Department of the Navy procured 210 MW of a utility-scale PV project to support fourteen Navy installations in California. [19] Taken together, these trends indicate how rapidly solar power is expanding: analysts expect that, for the first time, over half of all installations in 2016 will occur due to factors outside of Renewable Portfolio Standard obligations. [16]

Powerful Benefits

Utility-scale PV deployment to date have resulted in substantial environmental and human health benefits. A recent DOE study found that, in 2014, solar power saved 17 million metric tons of CO_2, worth approximately $700 million in benefits. In addition, there were another $890 million worth of benefits from improved air quality due to the reduction of air pollution thanks to the deployment of solar.

The study also found that water consumption was reduced by 7.6 billion gallons, equal to 0.5% of the total water consumption from the power sector, with the majority occurring in drought stricken areas like California. When looking at all of the benefits together, they are worth over $1.5 billion dollars. [20]

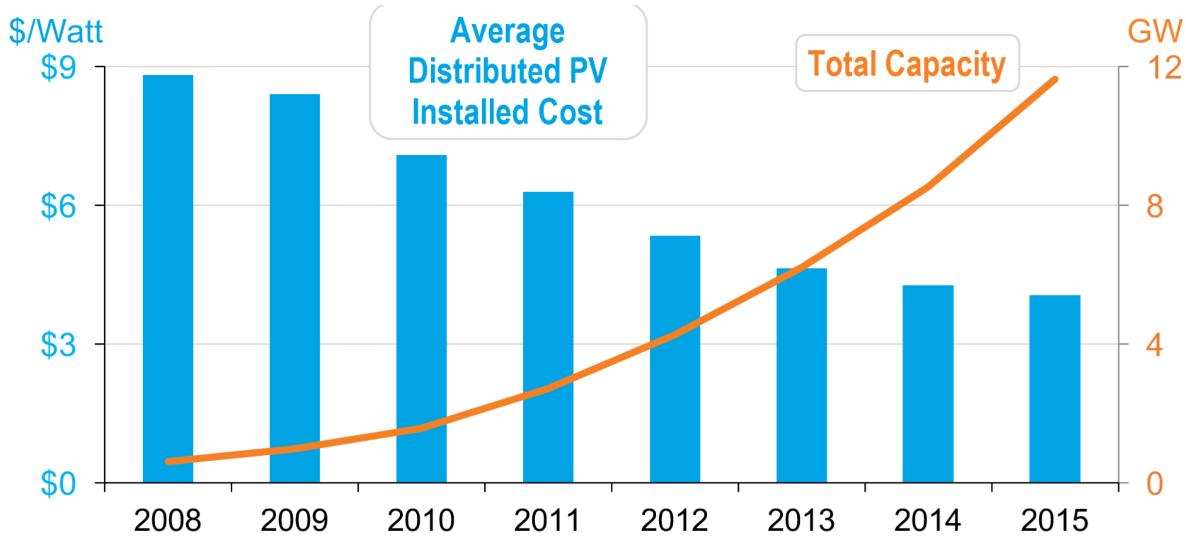
In addition, the entire solar sector, inclusive of distributed and utility-scale PV, has provided immense economic opportunities and has supported an estimated 220,000 domestic jobs at the end of 2015. [21] Similarly, the manufacturing of solar photovoltaic modules and their components has added $1 billion in overall value to the United States economy in just 2014. [8]

These benefits continue to add up as deployment expands. For example, should the SunShot Vision scenario of solar power providing 27% of all domestic generation by 2050 come to fruition, there would be an estimated $167 billion worth of savings through reduced health and environmental impacts. This includes preventing 25,000 to 59,000 premature deaths through 8-11% reduction in air pollution from power plants. [20] It could also bring economic benefits with total solar employment up to 335,000 jobs. [21]

A Bright Future

The amount of utility-scale solar projects in the pipeline is truly staggering. It took decades to achieve a cumulative installation of 10,000 MW of PV, but it looks possible that 10,000 MW of utility scale solar will be installed this year alone due to the previously anticipated expiration date of the investment tax credit. As of mid-2016, there were more than 21,000 MW of utility-scale solar projects under development, with 8,400 MW of that total already under construction. [22] With continued cost reductions and technology improvements, the future of this clean energy technology is bright.

Solar PV: Distributed



Cost data from reference [3], deployment data from reference [16]. Costs are average installation costs for residential sector PV and exclude the effect of the Investment Tax Credit. 1 GW = 1,000 MW.

Shining On

Sunlight is available nearly everywhere and that means that unlike traditional power generating sources, solar power can potentially be available anywhere there is sunshine. Distributed PV systems use the same basic PV technology as larger utility-scale projects, but they can be small enough to fit on a consumer's rooftop. A robust assessment of the available roof space in the US indicated that the total potential of electricity generation from distributed rooftop PV is equal to 38.6% of the nation's total electricity consumption. [24]

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 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. Over 3,110 MW[8] of distributed systems were installed in 2015, a 34% increase over 2014. [16] This past spring, the millionth distributed PV system was installed, an indication of how widespread this technology has become. [25] Through the end of 2015 a cumulative 11,638 MW had been installed in the United States, [18] generating an estimated 12 billion kWh in 2015, and providing enough electricity to power over 1.1 million American homes.[9]

Appraising Sunshine

The rise in installations of distributed solar has been enabled in part by a 54% reduction in installed cost since 2008. This reduction means the average installation was approximately $4.05/Watts in 2015 for residential systems. [3] In addition it's also important to note that this deployment trend is reflective in part of the federal investment tax credit (ITC) and supporting state policies such as net energy metering.

The cost reductions and supporting federal and state policies mean that more and more consumers are recognizing the value of solar power. The value in terms of cost savings are well known: in 20 states and in 42 of America's 50 largest cities, financing a residential solar energy system currently costs less than purchasing electricity from a

8 Distributed PV capacity and cost figures are provided in terms of DC power unless otherwise indicated. In general distributed PV refers to capacity that is installed behind-the-meter and is less than 5 MWAC in capacity, although individual references vary in their definitions.

9 The average home consumed 10,932 kWh in 2014. [95]

customer's local utility – commonly termed "grid parity". [26, 27] However, the value of solar power is also being recognized in new ways. Specifically, research of real estate markets revealed that home buyers were willing to pay $15,000 more for a home with an average-size solar photovoltaic system, equivalent to four additional dollars per watt of solar power installed. [28, 29] The DOE's Solar Training and Education for Professionals (STEP) program is helping to ensure solar continues to be valued in the real estate market by educating agents and appraisers about solar energy. [30] DOE has also funded tools to help the real estate professionals properly evaluate new and existing distributed PV systems. [31]

Distributing Benefits

A number of actions have recently been undertaken to ensure that as the distributed solar market grows, all consumers have access to clean energy opportunities. A recently announced Clean Energy Savings for All Initiative aims to deploy 1,000 MW of solar to low- and moderate-income families by 2020. [32] In addition, almost 50% of homes and businesses are not able to host their own solar system because they may be renters, might live in a multi-family building with shared roof space, or simply don't have an appropriate roof to host a PV system. [33] For these consumers, community solar, also known as shared solar, allows groups of consumers to collectively own shares of a single solar system located nearby. This enables them to share the benefits of solar power. An analysis shows that community solar could represent nearly half of the distributed solar market by 2020. [33] The recently launched National Community Solar Partnership is working to bring together federal agencies, non-profits, and private partners to unlock community solar's potential in the nation. [34]

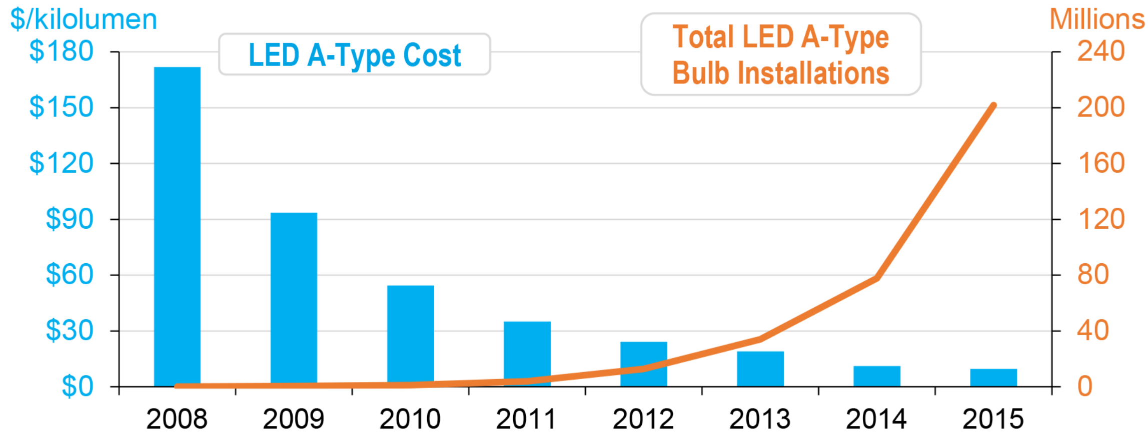
A Capital Idea

Another key factor in distributed PV comes not from technical innovations, but from advances in how consumers can pay for solar power. Third-party-ownership of PV systems – where consumers lease a PV system instead of purchasing it outright – has revolutionized the distributed PV market. This 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 between 45%-90% of domestic residential PV systems installed in leading state markets in 2015. [16] Continued development of new financing options such as solar loans could lower the cost of energy from distributed PV an additional 10%-20% over historical methods. [35] For example, Property Assessed Clean Energy (PACE) programs allow homeowners to finance solar PV through no upfront cost and pay back the loan through their property tax bills. Recent actions that provide guidelines for developing PACE programs, clarify how Federal Housing Administration mortgage insurance and Veteran's home loan guarantees apply to homes with PACE assessments, and provide technical assistance to states and local communities will help further expand these opportunities to make financing solar easier for all Americans. [32]

Sunny Days Ahead

The 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. [36] Combined with innovative new financing and other solutions aimed at making distributed PV accessible to a wider array of consumers, this means more Americans will have the opportunity to realize the wealth of benefits provided by solar power.

LEDs



Cost and deployment data from source [5]. "LED Bulb" refers to A-type bulbs. Kilolumen is a measure of visible light output by a source. Price data is inflation adjusted to 2015 dollar-years.

Turning Up the Lights

Stand underneath a traditional incandescent bulb and a LED bulb[10] and you will soon feel the difference between the two — heat. While both produce the same amount of light, the incandescent bulb is hot to the 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.[11] 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 and drastically increasing their deployment. In one year, total installations of common home LED bulbs more than doubled from 77 million to 202 million—a particularly rapid growth considering there used to be fewer than 400,000 installations as recently as 2009. LED bulbs now account for 6.0% of all currently installed A-type bulbs – growth enabled by an enormous 94% reduction in cost since 2008. [5] Looking at the bigger picture across all LED product types, LED installations prevented 13.8 million metric tons of CO_2 emissions and saved $2.8 billion in energy costs in 2015 alone.[12]

This success is a direct result of research and development (R&D) investments made by both government and industry that have brought down costs, improved efficiency and performance, and fostered domestic manufacturing of LED lighting components and products. Thanks in large part to these investments, the U.S. today is the hub of LED lighting innovation. Today, America is beginning to reap the rewards of those years of investment.

Beyond the Bulb

While common A-type LED bulbs represent the largest number of LED installations, other lighting applications have seen higher LED market penetration. For example, directional bulbs and large area outdoor lighting fixtures have LEDs penetrating 11% and 21% of installations respectively. However, a large number of installations does

10 In this report, "LED bulbs" refers to A-Type bulbs that are common in household applications.

11 Calculated from reference [101] 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, an 85% reduction compared to the 60 W of power drawn by the equivalent incandescent bulb.

12 Emission savings calculated by converting the reported 278 trillion BTU of source energy savings from reference [5] 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 CO2/MWh as reported by eGRID 2012. [102]

not necessarily translate directly to the best opportunity for energy savings. Energy saving opportunities depends not only on the number of installations, but also on the number of hours of operation and the energy efficiency improvement that LEDs offer over competing technologies. [37]

For all of these reasons, DOE and many in the lighting industry are looking toward potential energy savings in the commercial and industrial sectors offered by replacing fluorescent overhead lighting most commonly found in offices and manufacturing facilities. Energy impacts in these applications are disproportionately high in relation to LED penetration 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. In 2015, LEDs in typical commercial and industrial lighting fixtures contributed 20% of the LED-enabled energy savings, despite representing only 3% of their respective market, and are expected to contribute about 30% of the total energy savings from LEDs in 2035. [37]

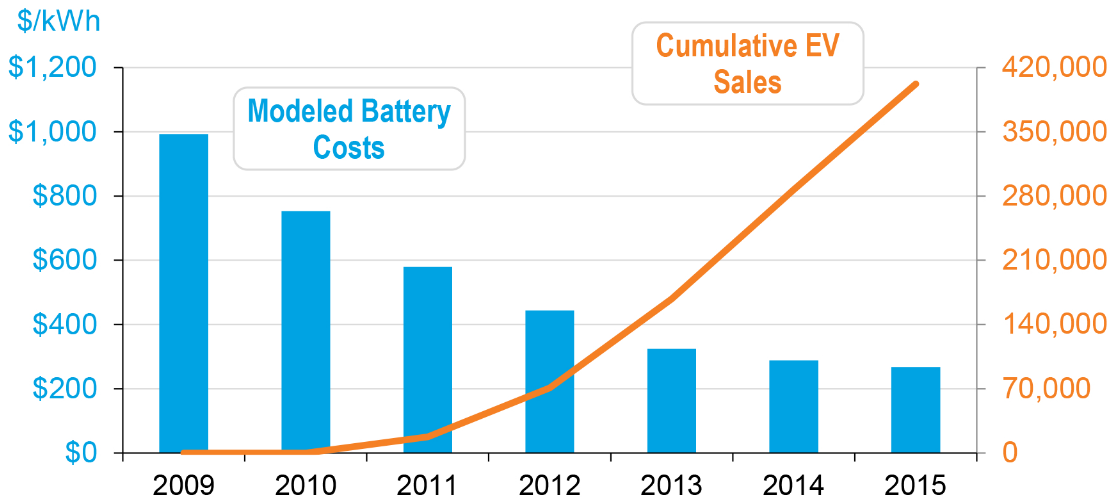
Achieving the greatest possible market adoption and energy savings from LED products will require ongoing technology R&D improvements. Unlike conventional lighting sources, LED technology has significant headroom for additional technological advancements. DOE is committed to working with industry to 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 more than doubled, from the current 95 lumens per watt to 218 lumens per watt. [5]

A Bright Idea

Fully capitalizing on the promise of LED technology will catapult our nation toward creating a clean energy future. Energy-efficient technologies like LED lighting not only reduce the consumption of fossil fuels, they also go hand-in-hand with effectively using renewable energy. For example, further cost reductions in LED lighting will make it far more affordable and practical to construct zero-energy buildings. These buildings are so energy efficient that renewable energy systems can help to 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. Developing this technology domestically also allows American manufacturers to benefit from exporting LEDs to rapidly developing nations while enabling those countries to save money and cut emissions by leapfrogging over less efficient lighting technologies.

LEDs are projected to make up over 85% of the nation's lighting installations by 2035, driven by performance increases and cost savings relative to conventional lighting. If DOE's Solid State Lighting Program targets for LEDs are met, the market penetration of LEDs is projected to drive a 75% reduction in annual lighting energy consumption by 2035 over a scenario without LEDs. This would result in total annual energy savings nearly equivalent to the energy consumed by 45 million American homes. The cumulative savings from 2015 through 2035 would save Americans nearly $630 billion in avoided energy costs, illuminating the potential of LEDs to save energy, save money, and enable a clean energy future. [37]

Electric Vehicles



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 in reference [38]. "EVs" include all plug-in hybrid and battery plug-in vehicles.

Electrifying Success

Americans bought over 115,000 electric vehicles (EVs) in 2015, more than double the number purchased in 2012 despite sustained low gasoline prices. This brought the total number of EVs on the U.S. roads to over 400,000 by the end of 2015. Sales were represented by over 20 EV model types available from over 15 different brands. [38] EV deployments continue to expand with cumulative sales topping 490,000 as of August 2016. [7] Today, EVs are helping to support America's energy and climate goals and are providing an opportunity for domestic manufacturers to remain globally competitive in the 21st century.

This is good news for our climate, our health, and our economy. With fewer to no 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, an EV on average reduces greenhouse gas emissions by 58%, compared to a gasoline fueled car.[13] EVs also will become cleaner as the nation's electricity supply is projected to continue to move to lower-emitting energy sources. [23] The development and production of EVs is also contributing to the economy – the United States is the largest market for automotive lithium-ion batteries and lithium ion battery manufacturing has added about $400 million in value to the nation's economy in 2014. [8]

This continued growth is the direct result of combined federal, state, and industry efforts to bring down the cost of EVs through research and better battery development, drivetrain improvements, promoting consumer adoption through tax credits and other incentives, and supporting public and private investments in domestic EV manufacturing capacity. DOE's utility partnership agreements with Edison Electric Institute and the American Public Power Association are intended to pick up this pace. DOE is also developing plans to collaborate with utilities to accelerate EV and charging infrastructure deployment. [39] The 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.

13 EV emissions are highly sensitive to geographic location; this number is based on the emissions associated with the national electricity generation fuel mix as reported in reference [103].

Charging Ahead

The increase in EV sales in recent years has been enabled by the development of lower-cost lithium-ion batteries. DOE estimates the cost of EV batteries produced at high volume has fallen by an astounding 73% since 2009.[14]

The cost and performance of batteries are key factors 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 in battery R&D, which advanced the state-of-the-art by six years and created $3.5 billion worth of economic value.[15] This investment continues to pay off as battery costs may be as low as $200/kWh by 2020. [40] Looking ahead, DOE will work with industry, academia, and its national laboratories toward achieving an even more aggressive goal of $125/kWh modeled production costs by 2022. [41]

We can already see firsthand the results of advanced research in EV batteries as it makes its way into the market. For example, improvements in battery energy density enabled by DOE funded research has allowed the energy storage capacity of the second-generation Chevrolet Volt battery to be increased by 15% compared to the previous generation. [42] In general, optimization of cell chemistry, design, and performance decreases the mass of battery packs, allowing EVs to travel farther with full performance. 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. [43] As EVs accounted for 1.5% of all passenger cars sold in 2015,[16] the potential for the next generation of EVs to impact transportation is significant.

Power Up

Improved and expanded charging infrastructure will also maintain the momentum for EVs. There are now more than 35,000 public and private EV charging outlets in the United States. Of those, there were over 4,000 DC fast chargers, which allow drivers to charge up to 100 miles of range in as little as 20 minutes.[44, 45]

In 2015, the DOE Workplace Charging Challenge had 605 workplaces from partner organizations that have committed to providing EV charging for employees, increasing range confidence for potential EV owners. [46] This effort has shown increased deployment as employees of challenge partners were six times more likely to drive an EV than the average worker. [46] EV owners with access to workplace charging also drive 23-26% more electric-powered miles than those that do not. [47] Moving forward workplace charging while increasing EV infrastructure is key to enabling future EV deployment and emissions reductions. Recent analyses of workplace charging show that in some areas, charging during the workday reduces EV emissions. [48]

Road to the Future

Driven by reduced battery and vehicle costs, as well as an expanded charging network, EVs are continuing to attract new consumers and provide environmental and economic benefits.

Looking ahead, continued cost reductions and performance improvements of EVs coupled with new technologies, such as wireless charging, will increase the performance and attractiveness of EVs. With over 490,000 EVs deployed as of August 2016, [7] the half-million EV milestone will certainly be passed before the end of the year. America is one of the largest EV markets in the world, and more Americans are powering their cars with affordable, clean, and secure energy.

14 Estimated costs are modeled and validated through applied research, and represent calculated high-volume commercial production costs, rather than market price.

15 Inflation adjusted to 2015 dollars using U.S. Bureau of Economic Analysis GDP budget deflator. Data from reference [104].

16 115,262 EVs sold in 2015 as reported in reference [38] as compared to 7,525,023 passenger cars sold in 2015 as reported by Ward's Auto in reference [105].

Revolution Next

The technologies highlighted in the first section of this report have already made a big impact and are easily visible in our daily lives. Wind towers dot the landscape, solar panels sprout on rooftops, LEDs are on shelves in every hardware store, and the latest EV models drive through neighborhood streets.

Other emerging technologies have not quite reached the same wide-scale deployment, or are impacting our energy use in ways that are not as visible in our daily lives. Yet in each case, deployment has begun to accelerate, costs have started falling, and large-scale deployment could transform portions of the energy sector.

Last year, this report highlighted fuel-efficient technologies for heavy trucks, smart building controls, and vehicle lightweighting. Along with updates in these areas, this report will look to highlight the accomplishments and potential of fuel cells, industrial energy management, grid-scale batteries, and big area additive manufacturing.

The technologies we discuss from this point forward are what we believe we should keep an eye on over the next five to 10 years.

Super Trucks

The SuperTruck Initiative — a DOE program to increase long-haul 18 wheeler truck fuel efficiency by 50% over 2009 levels — has been incredibly successful. All of the teams will exceed this goal by the end of 2016, with one team achieving a 115% increase in fuel efficiency. The success of the initiative has already encouraged participating companies to commercialize technologies from SuperTruck. For example, Volvo has commercialized tractor aerodynamic improvements in its 2016 highway trucks [49] and several engine improvements will be commercialized for 2017. [50, 51] Peterbilt used its aerodynamics work in SuperTruck to develop a high-efficiency truck package for its Model 579 tractor. [52] Their work was commercialized in 2014 and has been continually refined since then. It includes extensive aerodynamic features such as tractor side fairings that close gaps between the fender and front steer wheels, a front air dam to prevent air from flowing under the truck, and fairings that extend down the side of the tractor nearly to the ground, to direct airflow away from the underside of the truck. Overall the participating teams have already successfully commercialized 21 technologies to date, including advances in engine and drivetrain integration and in aerodynamics. An additional 26 technologies are estimated to be commercialized in the next two to four years, and 13 more in the five to 10 year timeframe, highlighting the potential of these technologies to impact fuel use in heavy-duty vehicles. [53]

Building on the success of the SuperTruck I initiative, in August of 2016, DOE announced a follow-on SuperTruck II $80 million program for research, development and demonstration of long-haul tractor-trailer truck technology. These projects will research, develop, and demonstrate technologies to improve heavy-truck freight efficiency by more than 100 percent, relative to a manufacturer's best-in-class 2009 truck, with an emphasis on technology cost-effectiveness and performance. DOE has made four selections under this opportunity Cummins, Inc. with Peterbilt Trucks as a partner; Daimler Trucks North America LLC; Navistar, Inc.; and Volvo Technology of America LLC. [54] Another $12 million supported projects on the research, development, and demonstration of plug-in electric powertrain technologies for medium- and heavy-duty vehicles. [55]

Smart Buildings

Buildings are full of hidden energy savings potential that are easy to overlook because they are housed in familiar technologies, such as heating, ventilation, and air conditioning equipment. However, with sophisticated software and advanced data and analysis being applied to everyday building operations, building owners can leverage the more than 58.5 million smart meters installed in the nation to realize the cost-saving benefits of analytics. [56]

Recently, the Energy Department launched the Smart Energy Analytics Campaign to provide technical support and recognition for owners in their use of a wide variety of commercially available Energy Management and Information Systems (EMIS) technologies. [57] Paired with ongoing monitoring practices, these technologies help identify energy-saving opportunities and improve building performance for the long run. The potential for EMIS to save energy is also sizable: as much as 10-20% energy savings is possible in a single building, and if EMIS best practices were adopted by all target buildings in the U.S. commercial sector, over $4 billion in cost savings could be achieved. [58] From single buildings to large portfolios, owners are moving building energy and operations into the age of smart, ongoing, data-centered analytics.

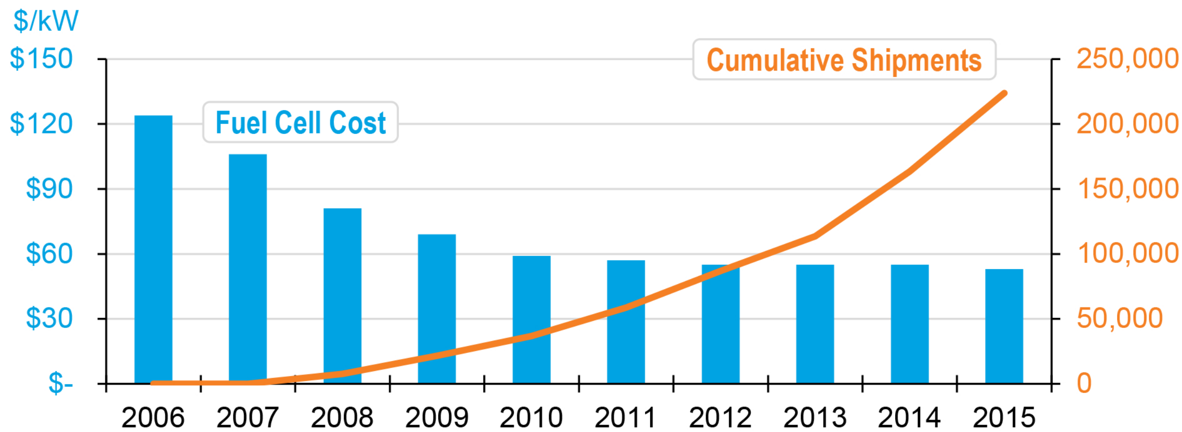
Lightweighting Materials

The development and use of lightweighting materials, such as high strength steel, aluminum, and carbon fiber, has the potential to reduce total mass of a vehicle, increase its fuel efficiency, while maintaining or evening improving vehicle safety. [59] For example, a 10% reduction in vehicle weight can result in a 6-8% improvement in fuel economy, and can also allow electric powered vehicles to go further on a single charge. [60] Using lightweight components is also beneficial because it means vehicles can carry additional advanced emission control systems, safety devices, and integrated electronic systems to increase functionality, safety, and performance without increasing the overall weight of the vehicle.

Overall the use of lightweight materials in vehicles is on the rise. The average amount of regular steel in a vehicle was reduced by over 200 lbs since 1995, while average amount of high and medium strength steel used per vehicle increased by 325 lbs. Similarly the amount of plastics and composites used per vehicle increased by 40% since 1995. This trend continues — in addition to the 2016 Ford F-150 that used aluminum to shed nearly 700 lbs, the 2017 Chrysler Pacifica minivan was reengineered with a new body and vehicle platform to reduce weight and improve vehicle fuel economy. The Pacifica is 250 lbs lighter than the Town & Country – the previous minivan offering from Chrysler. Part of this weight reduction comes from use of lightweight magnesium in place of steel in the rear liftgate. This reduced the liftgate weight by 22 lbs all while maintaining crash safety performance. [61]

Through industry, academia, and national laboratories, the Department of Energy continues to invest in technologies to spur the development and commercialization of lightweight materials. The recently completed Multi-Material Lightweight Vehicle (MMLV) project demonstrated the ability to combine several advanced lightweight materials, resulting in a vehicle that is 23.5% lighter than a similar mid-sized sedan. This prototype vehicle passed several major safety tests and has already led to several of these technologies being used in vehicles on the market. [62] Built by Vehma International and Ford, with support from DOE's Vehicle Technologies Office, the MMLV demonstrated the feasibility of integrating lightweight materials and joining technologies into current production vehicles. The MMLV and the technologies used in it offer the potential to make our vehicles lighter and more efficient for generations to come.

Stacked for Success: Fuel Cells



Cost data is modeled fuel cell cost at high volume in nominal dollars from reference [63] . Deployment data is global fuel cell shipments for stationary, portable, and transportation uses from reference [64].

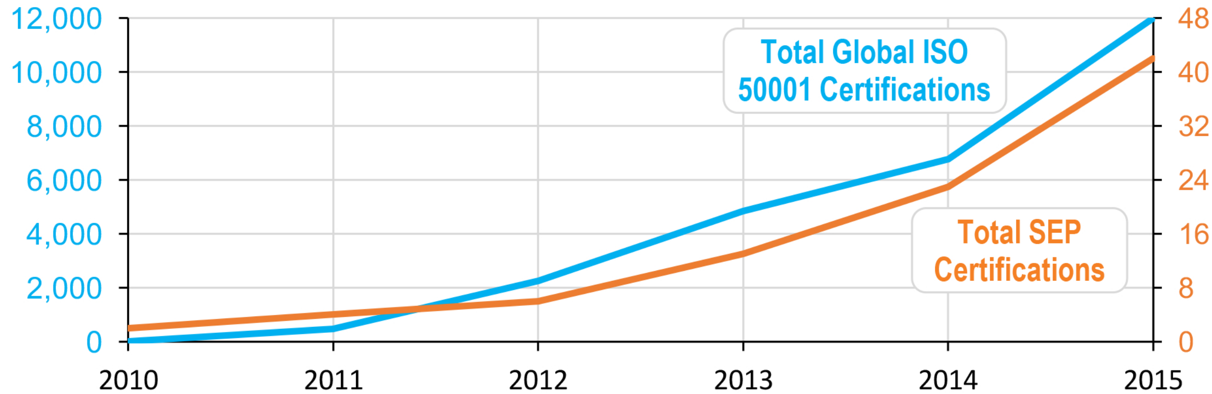
Fuel cells convert the chemical energy from fuel directly into electricity, without the need for combustion, thereby generating power at high efficiencies and with low or even zero emissions. They can use diverse domestic resources for fuel and because they're scalable, they can be small enough to power a vehicle and large enough to support power plants.

For the first time in history, automakers have introduced commercial fuel cell electric vehicles (FCEVs) that regular consumers can purchase or lease. These cars run on hydrogen, produce zero pollution from the tailpipe, can be fueled in just a few minutes, and can travel more than 300 miles on a single fill. Toyota is currently selling the Mirai and Hyundai is leasing its SUV, the Tucson, in California. [38] In addition, the Honda Clarity will be available in late 2016, while Daimler, General Motors, BMW, and others plan to bring FCEVs to market soon. [65-68] There are also several hydrogen-fueled medium and heavy vehicles - including transit buses - available on the market today. [38] These FCEVs can already cut total greenhouse gas emissions by 50% compared to today's conventional cars, even if hydrogen is produced from natural gas. When hydrogen is produced from renewables or low carbon sources, greenhouse gas emissions can be reduced more than 90%. [69]

DOE has funded research enabling significant improvements in the technology: platinum is the most expensive material used in fuel cells, and the amount needed was cut by five-fold enabling a 50% reduction in costs since 2007 while quadrupling durability. [70] DOE has validated more than 200 FCEVs driving over 6 million miles, demonstrating cutting edge advances under real world conditions. In addition, Recovery Act funds helped cost share 1,600 fuel cells that enabled 18,000 more used in forklifts and backup power units. [72, 73] In 2015, commercial fuel cell shipments surpassed 60,000 units worldwide, demonstrating growing traction in the marketplace. [64]

As fuel cells gain traction, more work is underway to further reduce platinum metals, cut costs, and improve durability. While today millions of tons of hydrogen is produced from cheap natural gas, R&D is focused on low-cost hydrogen produced from fully carbon-free pathways. Continued innovation in production, delivery, and storage will drive wider deployment of clean fuel cell technologies.

ISO 50001 and the Superior Energy Performance Program in the Manufacturing Sector



Data for global ISO 50001 certifications from reference [74]; SEP certifications provided by SEP program manager.

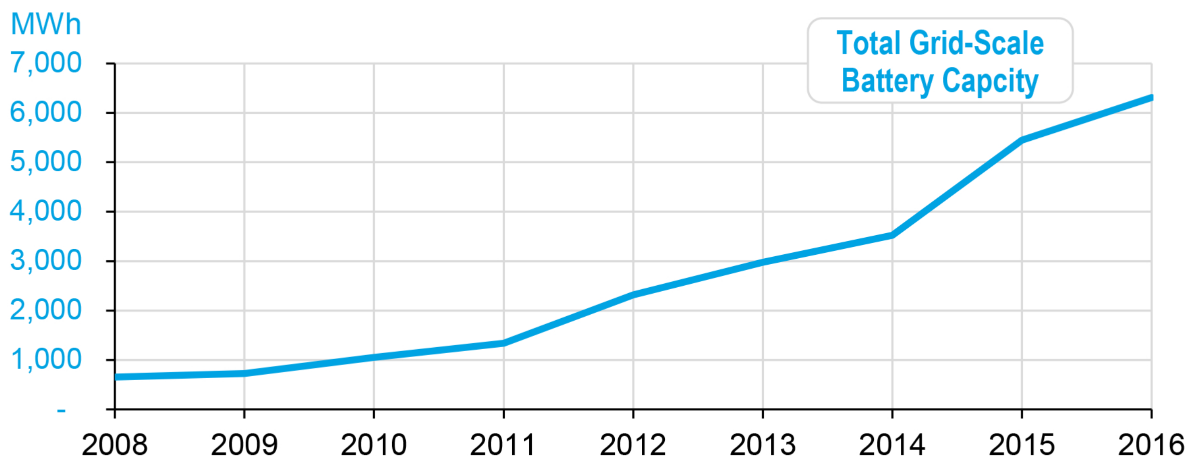
The industrial sector currently consumes 32% of all energy consumed in the country. [18] Capital funded energy efficiency projects do result in savings but experience has shown that the energy performance gains from these various one-off energy efficiency projects do not deliver sustained energy performance improvements due to a lack of continual post implementation monitoring and optimization. [75, 76] In order to ensure sustained energy performance gains, energy should not be considered a fixed operational expense but managed just as carefully done for production, quality, and safety. [78]

The International Organization of Standardization (ISO) has developed ISO 50001, a data driven management system standard that provides a flexible framework for organizations to implement an energy management system (EnMS) that can integrate with existing business practices. An EnMS achieves energy savings through a systematic evaluation of significant energy uses, review of operations, and maintenance and performance of each system. Conformance with ISO 50001 requires continual improvement to both the management system and energy performance improvement. DOE's Superior Energy Performance (SEP) program provides additional guidance, tools, and protocols to drive deeper, more sustained savings from ISO 50001.

ISO 50001 and the SEP program achieve significant energy and CO_2 emission savings results – all through better management of energy across facilities and organizations. In many cases, the improvements are achieved with no or low cost actions which existing facility staff can implement. Today, SEP certified facilities have achieved a 12% reduction in energy expenditures within 15 months of implementation of ISO 50001, equating to an annual savings of $36,000 to $938,000 using no-cost or low-cost operational measures. [78] More broadly, facilities with annual energy costs greater than $2 million can expect investment payback on ISO 50001 in less than 1.5 years. [79]

The potential for energy management through ISO 50001 to impact energy use and emissions is enormous – broad global deployment could save over $600 billion in energy costs, and 6,500 million tons of CO_2 by 2030. This is equivalent to removing the annual emissions of 215 million passenger vehicles. [80] A new global campaign announced at the 2015 Clean Energy Ministerial aims for 50,001 certifications by 2020, [81] highlighting the universal opportunity for economies around the world to realize energy savings, cost savings, and move the world towards a clean energy future.

Supercharging the Grid with Batteries



Battery capacity data from DOE Energy Storage Database, [82] showing only domestic electrochemical projects listed as "operational" by year project was commissioned.

As variable renewable generation from wind and solar continues to increase, the electricity grid needs more flexibility – making it better able to support variable generation and to respond to the complex needs of our electricity system. Specialized batteries are one technology that can provide this type of flexibility which can significantly improve the operating capabilities to the grid. Their ability to store electricity produced at one time for use at another time is key, allowing them to support deployment of renewable generation like wind and solar, as well as improving the overall efficiency and quality of the power grid. Batteries can also be sized and located in local communities or at a customer's location making them invaluable for emergency preparedness and resiliency in case of grid disruptions due to severe weather or other events. [83, 84]

The capacity of these grid-scale batteries has increased nearly 10-fold since 2008, [83] and they are already enhancing the capabilities of the grid. The lithium-ion battery packs used in the majority of grid-connected batteries have declined in cost by about 60% between 2007 and 2014 [40] and analysts expect both utility and consumer scale batteries to decline in cost by another 20-27% in just the next two years. [85] With these cost reductions and further deployment the total domestic energy storage market could be worth $2.9 billion by 2021, as compared to $350 million in 2015. [85]

DOE continues to support innovative energy storage solutions in a number of avenues, such as R&D in the Office of Electricity Delivery and Energy Reliability's Energy Storage program [86] and through the Advanced Research Projects Agency - Energy (ARPA-E) Grid-scale Rampable Intermittent Distpatchable Storage (GRIDS) program area. [87] More recently DOE's SunShot program awarded $18 million in 2016 to develop energy storage solutions for solar power using battery and other technologies, with the goal of developing projects to enable essentially "on-demand" solar power. [88] Continued innovation and deployment of grid scale batteries on the grid will provide added flexibility to help support the evolving of a clean energy electricity system.

Big Area Additive Manufacturing

Manufacturing is a key sector of the economy that will both enable a clean energy future and present opportunities for further energy savings. The manufacture of specific complex parts has traditionally relied on "subtractive" processes—taking solid blocks of metal and cutting away the unnecessary parts to sculpt the final products. Additive manufacturing (AM)—also known as 3-D printing—turns this process on its head by building items using advanced techniques that add raw material only where needed. While AM provides energy savings through reduced amounts of material needed and reducing the number of production steps, it has the potential to unlock significant energy savings through unprecedented design flexibility that is unavailable to conventional manufacturing techniques. [89, 90]

New advances in technology are literally expanding the potential of AM by increasing the size of components that can be manufactured. Big Area Additive Manufacturing (BAAM) – developed in partnership with Cincinnati Incorporated, the Department of Energy, and Oak Ridge National Lab – can construct items up to 10 times larger. [91] These items can also be produced at nearly 99% less energy per unit of mass as compared to other commonly used but smaller industrial AM techniques and even uses less energy than common conventional manufacturing processes like polymer injection molding. The lower energy intensity of BAAM arises because BAAM does not heat an oven during manufacturing, and generally operates at lower temperatures and pressures.

In addition to being less energy intensive and faster than conventional methods, BAAM is enabling the next-generation of design and manufacturing for other clean energy technologies. For example, creating molds for advanced wind turbine blades are complex, energy-intensive, and time-consuming. BAAM can produce these molds 500 to 1000 times faster than other industrial additive techniques, and overall can simplify the manufacturing of molds for turbine blades. This would reduce the costs and amount of time required for blade manufacture, as well enabling further and more rapid innovation in blade design. [91, 92] BAAM was also a key element in the Additive Manufacturing Integrated Energy demonstration projection, showcasing how rapid design and prototyping can enable new innovations in the buildings, transportation, and renewable sectors. [93]

The aerospace sector also holds a large potential for BAAM to revolutionize manufacturing while saving energy. BAAM was recently used by Oak Ridge National Laboratory to produce a tool used by Boeing for use in the manufacture of airplane wings, which secured a spot in the Guinness Book of World Records as the world's largest 3D-printed object. [94] The tool was produced in significantly less time and at lower cost than by conventional techniques, and will be used by Boeing in the production of their new 777X aircraft. This exemplifies how the widespread adoption of BAAM and other AM techniques in the aerospace sector could result in 92.1–215.0 million metric tons of avoided CO_2 emissions. [95]

Though the aerospace sector could be a likely first adopter for AM technologies, the broader manufacturing sector will also benefit as cost and performance improve. Any product with complex, highly customized, lightweight, or hard to manufacture components may stand to benefit from AM, especially when considering the reduced time to market, quick prototyping, waste minimization, on-site production, and on-demand manufacturing benefits that come along with the techniques. [90] DOE is particularly focused on applications in clean energy manufacturing such as metal and composite tooling and molding, lightweight automotive components, renewable and efficient energy generation systems, materials for extreme environments in industrial processes, and in buildings technologies. BAAM exemplifies the potential future of advanced manufacturing, allowing us to innovate and manufacture things bigger, stronger, faster, and with less waste, to enable a clean energy future.

Conclusion

The clean energy technologies highlighted here are transforming how our nation produces and uses energy. While challenges exist for these technologies, it is clear they are not long-term opportunities, but a significant part of the energy landscape right now. We can and should plan on using them to clean our air, drive energy independence, and help build an economy that is more competitive and more efficient, all while reducing carbon pollution.

There are even more technologies that are just on the horizon that will be every bit as important to the future clean energy economy. DOE will continue to encourage these innovations by providing support for R&D, policy development 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.

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