

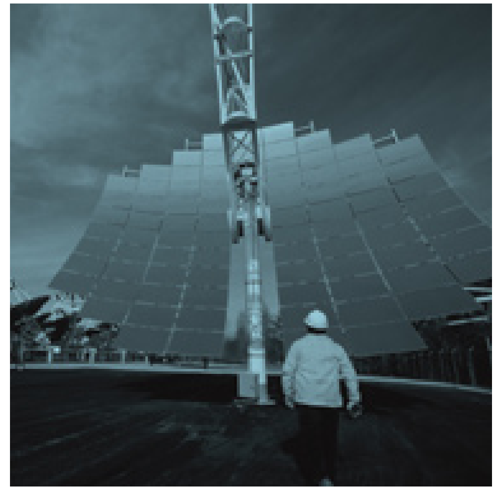




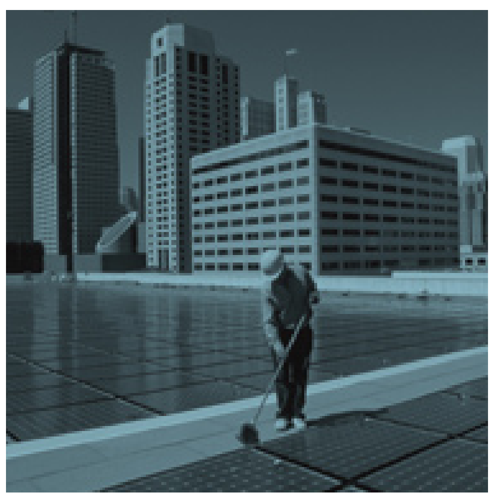


GIGATON THROWDOWN

Redefining What's Possible for Clean Energy by 2020

Job Growth
Energy Security
Climate Change Solutions

FULL REPORT
JUNE 2009

GIGATON THROWDOWN

Go to gigatonthrowdown.org for report downloads, supplemental material, and discussion.

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A Letter from the Cleantech Community

Dear Colleagues:

Out of our garages came the innovations that launched the information technology and biotech revolutions. From those beginnings, we have built a trillion-dollar IT economy and a biotech industry. As investors, entrepreneurs, and business leaders, we recognize a similar economic opportunity in clean energy technology. And this prospect isn't just about economic growth. Our security and prosperity and that of future generations depend on energy independence and a stable climate, which clean technology can ensure.

FOR THE FIRST TIME, WE HAVE A ROADMAP OF HOW TO SCALE CLEAN ENERGY TO HAVE MAJOR IMPACT BY 2020

As this report shows, clean energy can reduce greenhouse gas emissions by the gigatons required to address climate change over the next 20 years. For an entrepreneur, what can be imagined sets the bounds for what can become real. We can now imagine gigaton scale for clean energy technologies, and entrepreneurs can starting building the leading clean energy companies of tomorrow.

ACCELERATION WILL REQUIRE POLICY ENGAGEMENT

All of the technologies that can make major carbon dioxide emissions reductions — energy, buildings, transportation, forestry, and agriculture — have historically had market rules established by local, regional, national and international policy decisions. The future will be no different.

FOR INNOVATION TO FLOURISH, POLICYMAKERS MUST LAY OUT FAIR AND STABLE RULES OF THE ROAD

Scaling up clean energy industries requires coordinated action by the entire supply chain. Companies will expand capacity only when there are clear market signals for expected growth. Such signals are also required to increase demand for renewable energy and low-carbon alternatives.

The energy and carbon policies being decided now in the U.S. Congress and in December at the 15th Conference of the Parties (COP-15) in Copenhagen can lay the foundations for decades of massive innovation and growth in clean energy. The central reform must be a comprehensive carbon policy that puts a price on carbon for the long term. Without such a policy, cleantech energy pathways will grow slowly and in most cases fail to affect climate change. With such a policy, we can achieve gigaton scale by 2020, stabilize the climate, and create a new industry.

While we did not prepare this report, we agree with its basic findings and encourage our colleagues to use it as a framework for thinking about how to achieve scale in cleantech energy industries. We encourage policymakers to take to heart its central conclusions.

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Executive Overview

Introduction

The Gigaton Throwdown Initiative Team has spent the past 18 months evaluating what it would take to scale up clean energy aggressively so that it has a major impact on job growth, energy independence, and climate change during the next 10 years. We now see two possible worlds for 2020 and beyond.

In one world, clean energy markets expand dramatically. Private investment in renewable energy and energy efficiency more than triples, revitalizing the economy with green jobs in manufacturing, construction, and technology. Our energy economy becomes a source of investment in science, engineering, and technology, all of which drive national economic growth. Simultaneously, our investments deliver energy security and address climate change.

In the other world, clean energy markets remain a polite concession to the sustainability movement. Demand for renewable energy grows at the modest rate of 7% annually that many national agencies forecast. At this growth rate, these technologies will meet less than 2% of total global energy demand in 2020. Some jobs will be created, but the opportunity to build a global industry and advance U.S. leadership in technology will be lost. Meanwhile, the U.S. will remain dependent on imported oil and other fossil fuels, and climate change will continue unchecked.

The pace of innovation and private investment in clean energy is now making it possible to envision the first world. On the current trajectory, however, we end up in the second. The U.S. will miss a huge economic opportunity and squander the chance to address the climate problem and deliver jobs, economic growth, and energy security.

Key Findings

1. **The clean energy sector is growing rapidly but could grow significantly faster and sustain this growth for decades.**

2. **An aggressive scale-up is needed for clean energy technologies to fulfill the promise of economic and job growth, energy security and independence, and solutions to the climate problem.**

3. **Clean energy technologies could add 5 million direct jobs to the global economy, strengthen energy security by reducing dependence on foreign oil, and abate more than the total carbon dioxide equivalent (CO_2e) emissions currently projected to be necessary for 2020 climate stabilization goals.**

4. **Immediate, stable policies and increased investment are needed to support the necessary, aggressive scale up in clean energy.** Annual private investment must grow by more than 3X in the next 10 years to scale up renewable energy technologies to meet climate stabilization goals. This level of growth is feasible, but policy action is needed immediately to support it.

5. **Sound, stable policy is needed to guide investment:**
   - The supply chains for clean energy technology take years to ramp up capacity and require clear policy signals to attract investment today.
   - Past experience shows that investment in efficiency — the cheapest form of energy savings — requires policy action.
   - Stable policy that establishes a meaningful price on carbon is the single most important action that will encourage investment across the clean energy sector and ensure that capital flows to the most cost-effective technologies. Although clean energy is already providing solutions and attracting significant investment — private investment totaled more than $450 billion during the past 5 years with $135 billion invested in 2008 — a large amount of private capital remains on the sidelines or is currently diverted to supply fossil fuel energy.

Gigaton Throwdown Initiative

The Gigaton Throwdown Initiative was launched to educate and inspire investors, entrepreneurs, business leaders, and policy makers to "think big" and understand what it would take to scale up clean energy massively over the next 10 years. A unique group from the business community — investors, entrepreneurs, and executives — teamed up with leading academics for the throwdown. The team investigated what it would take to reach gigaton scale for 9 technologies currently attractive to investors.

To attain gigaton scale, a single technology must reduce annual emissions of carbon dioxide and equivalent greenhouse gases (CO_2e) by at least 1 billion metric tons — a gigaton — by 2020. For an electricity generation technology, this is equivalent to an installed capacity of 205 gigawatts (GW) of carbon-free energy (at 100% capacity) in 2020.

The 9 technologies we analyzed are examples of the potential to scale up clean energy technology:

- **Biofuels**
- **Building efficiency**
- **Concentrating solar power**
- **Construction materials**
- **Geothermal**
- **Nuclear**
- **Plug-in hybrid electric vehicles**
- **Solar photovoltaics**
- **Wind**

Gigaton Scale is Attainable in the Next 10 Years

We found that 8 of the 9 clean energy technologies we analyzed can each feasibly reach gigaton scale in the next decade. Together they would abate a total of more than 8 gigatons of dioxide equivalent (CO_2e) emissions in 2020. Of these 9 technologies, 7 are ready to scale up aggressively today: building efficiency, concentrating solar power, construction materials, nuclear, biofuels, solar photovoltaics, and wind. One technology, geothermal, needs an intense period of research, development, and deployment of pilot plants for new enhanced geothermal systems (EGS) in order to reach gigaton scale. Combined, these 8 technologies can meet more than 60% of new global energy demand during the next 10 years with reliable, clean, low-carbon sources.

Although continued investment in plug-in hybrid electric vehicles (PHEVs) is important for emissions reductions beyond 2020, achieving growth in PHEVs sufficient to reach the gigaton target faces serious challenges. To reach the gigaton goal, the industry would need an estimated 300 million PHEVs on the road in 2020. This is equivalent to the total number of new cars to be added to the fleet worldwide in the next 10 years. Although this might be feasible technically, the disruption to current operations, junking of existing vehicles, and sheer amount of capital needed for this transition make this pathway infeasible by 2020 in the estimation of the Gigaton Throwdown Team. Therefore, we do not include PHEVs in our gigaton projections.

One of the technologies, wind, is already growing fast enough to achieve gigaton scale by 2020. The wind industry has been growing at an annual rate of 28% over the past decade and will soon reach 150 gigawatts (GW) of installed capacity globally. At currently projected growth rates, it will exceed half a terawatt (TW) of installed capacity by 2020 and deliver close to 1.5 gigatons of CO_2e emissions reductions. Building efficiency technologies, solar, biofuels, and nuclear have all been tested and deployed and can scale more rapidly than their current projections. These are not laboratory curiosities. They are active technologies that are supplying power in multiple markets. With sound policy support, they will do much more.

In addition to the technologies analyzed in this report, others, from carbon dioxide sequestration to novel enzymes, to fuel-switching have the potential to achieve gigaton scale. With the right policies, many other businesses that have gigaton-scale ambitions can flourish.

Gigaton-Scale Clean Energy Can Drive Economic Growth and Create Millions of Jobs

Growth in clean energy is already stimulating regional U.S. economies and adding manufacturing, construction, and technology jobs.

JOBS: Number of Jobs Created to Supply 60% of Projected New Annual Energy Demand in 2020

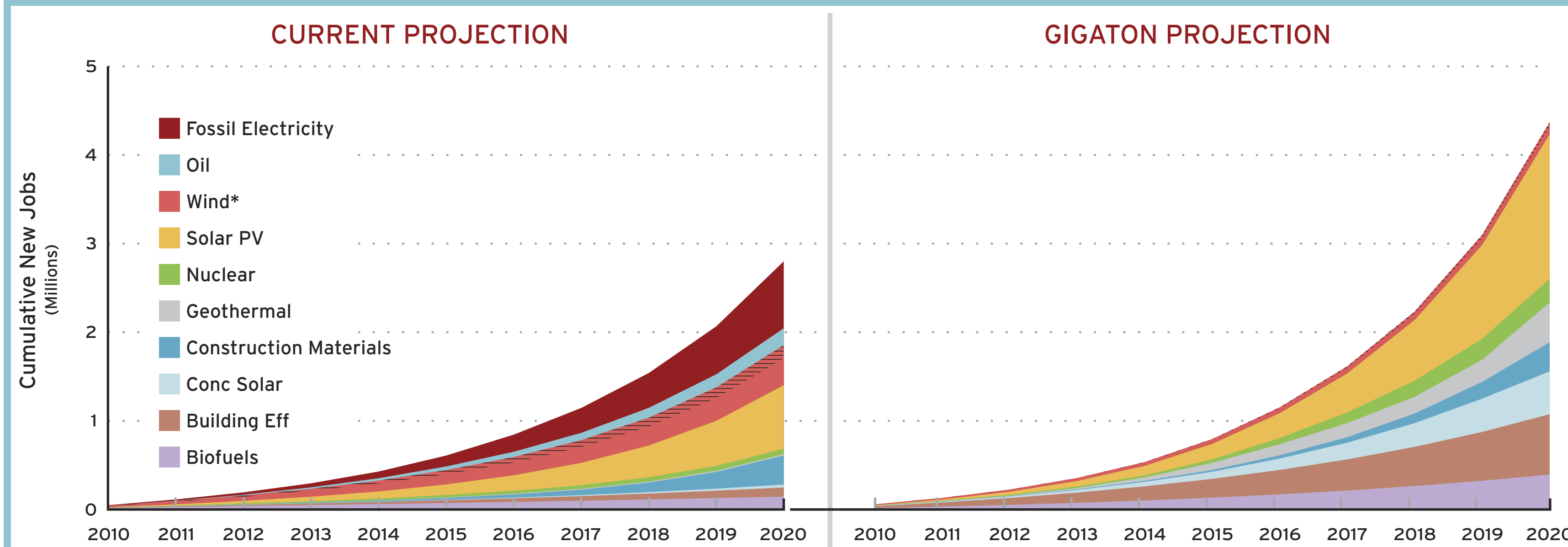

FIGURE 1. Expanding these 8 clean energy technologies to gigaton scale to meet new energy demand would create close to 4.5 million direct jobs, compared to fewer than 3 million under current projections. Both projections (current and gigaton) show jobs created for the same amount of energy (55 quads in 2020, which is approximately 60% of new global annual energy demand). Under current projections, the majority of new energy demand is met by fossil-fuel-based generation and adds significantly fewer jobs. Source of jobs data: Engel and Kammen, 2009.[1]

* Wind is currently projected to exceed gigaton scale and add approximately half a million direct jobs.

Clean energy has the potential to add several million new jobs over the next 10 years.[2]

The ethanol industry, for example, has created tens of thousands of jobs across the U.S., in Nebraska, Iowa, Illinois, and Michigan. In 2004, ethanol production generated more than 150,000 jobs. For every billion gallons of production, the industry adds between 10,000 and 20,000 new jobs in the U.S. This sector alone has the potential to create 1 million jobs in the next 10 years.

Other renewable-energy technologies are also strong jobs providers. Wind-industry jobs in the U.S. took off in 2006 and grew until late 2008 when the credit crisis struck and stalled wind developments. Industry-wide, wind energy employment is at 85,000, with 35,000 jobs added in the past year. A third sector — building efficiency — has the potential to add jobs in all 50 states. Based on past increases in jobs attributable to the building efficiency sector in California, for each 1% annual gain in efficiency, approximately 400,000 jobs are created. Similarly, the solar installation and utility business has added substantial numbers of jobs in a number of states, including Arizona, California, Nevada, and New York.

Clean energy sectors are typically more labor intensive than traditional fossil-based sectors, so gigaton-scale deployment would accelerate job growth around the world. Figure 1 shows the jobs created, over the next decade, by the 8 feasible technologies analyzed in this report.

Gigaton-Scale Clean Energy Can Meet 2020 Climate Stabilization Targets

In early 2009, both the Intergovernmental Panel on Climate Change (IPCC) and McKinsey reported that significant emissions cuts are needed in the next 10 years if the world is to have a chance of stabilizing the climate.[3,4] For the stabilization target of 450 parts per million (ppm) of CO_2e that is the focus of current U.S. legislative discussion, this amounts to reducing

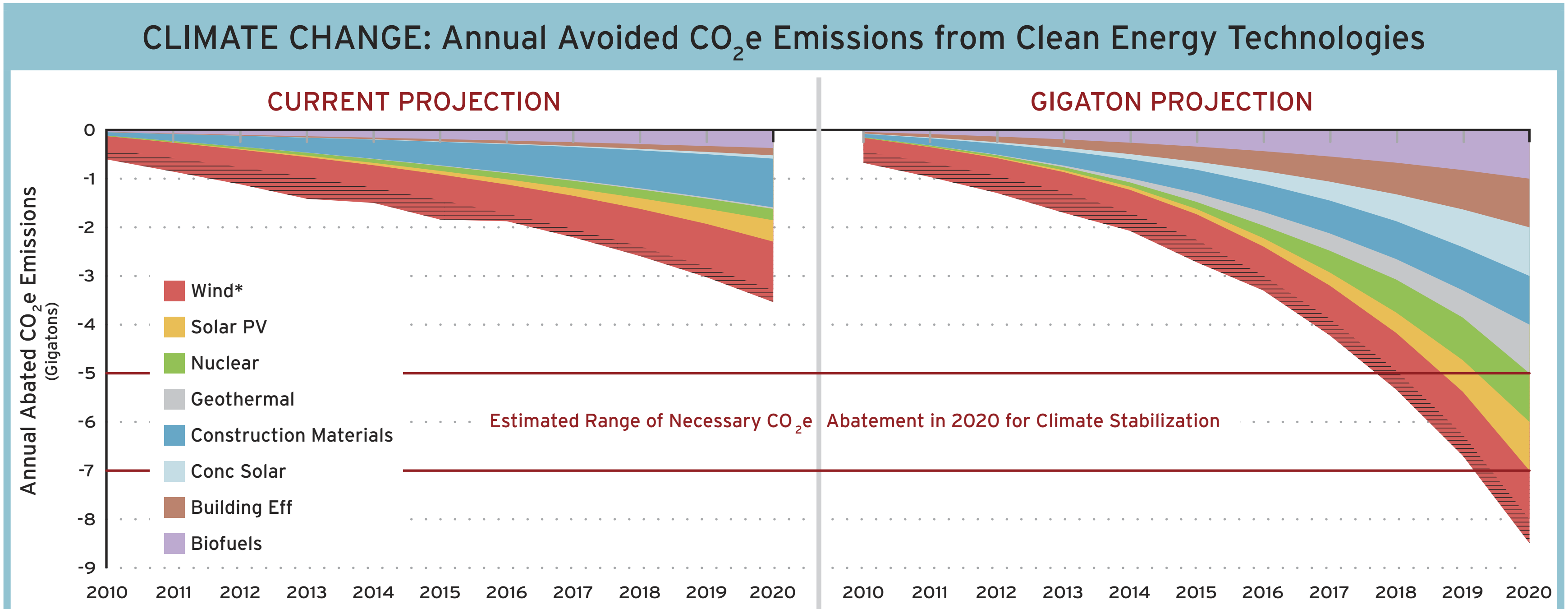

FIGURE 2. At gigaton scale, these 8 technologies could provide CO_2e reductions in excess of the 5 to 7 gigatons needed to hit 2020 climate stabilization targets, compared to the current projections that show these technologies falling short.[5] Under current projections, these 8 technologies abate close to 3.5 gigatons of CO_2e, with the bulk of the contribution from one technology, wind. (See report chapters for details on the current projections for each technology.)

* Wind is currently projected to exceed gigaton scale and abate 1.5 gigatons of CO_2e.

emissions from the global energy sector by an estimated 5 to 7 gigatons of CO_2e in 2020. Scaling the 8 feasible technologies by 2020 would more than meet this climate stabilization target (See Figure 2). Given that several technologies have the potential to deliver more than 1 gigaton of CO_2e reduction, the 450 ppm climate stabilization goal looks well within reach.

Gigaton-Scale Clean Energy Can Help Ensure Energy Independence and Security

Scaling up clean energy technologies to avoid 1 gigaton of CO_2e emissions has major implications for U.S. national security by reducing dependence on foreign oil as well as mitigating climate change and the associated social instability.

Reduced oil use through efficiency measures and scale-up of biofuels, for example, can put the U.S. on a pathway to energy independence. The U.S. imports a majority of the oil it uses, much of which comes from politically unstable regions. In February 2009, the U.S. consumed 524 million barrels of oil, of which it imported 60%. In periods of higher demand, imports account for an even greater percentage of consumption. A gigaton scale-up of biofuel production can reduce U.S. reliance on oil imports by as much as 25% in the next 10 years (See Figure 3). Distributed energy resources, e.g., small solar and wind installations, can also enhance energy security by reducing vulnerability to major power disruptions whether from oil shortages, natural causes, or terrorism.

Oil is currently such an essential ingredient in the U.S. economy that without it the nation would come to a virtual standstill. The dependence on oil leaves the U.S. vulnerable to price shocks when supply constricts, and sudden price increases harm consumers and can destabilize the economy. Even without price shocks, U.S. citizens pay for the costs of government and military activities to protect U.S. oil interests abroad. The nation is vulnerable to all disruptions in its supply, whether from piracy, terrorist attacks, or acts of war at key choke points for oil processing and transportation. In light of these vulnerabilities, the 2007 Energy Independence & Security Act recognized a decrease in oil dependence as a clear security objective.

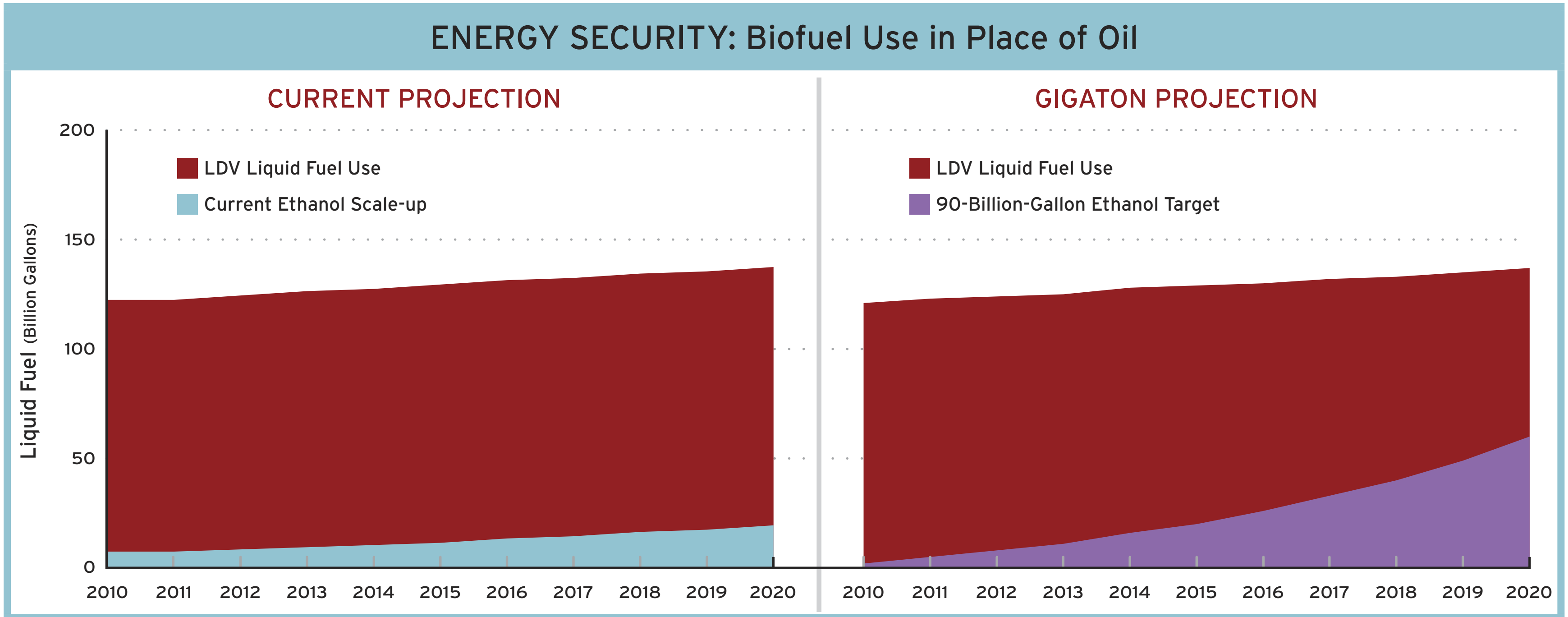

FIGURE 3. Gigaton-scale biofuel production in the U.S. can have a major impact on foreign oil dependence. An expansion of biofuel production to reach 90-billion-gallons in 2020 could displace close to half of the oil demand in the light duty vehicle (LDV) sector. The LDV sector is the largest oil-consuming sector in the U.S.

Climate change is the second threat to U.S. security that is addressed by scale-up of clean energy. Climate change poses a severe threat to global stability, with both direct and indirect implications for U.S. security. Unchecked, climate change is likely to create refugee crises worldwide as large populations are displaced by rising sea levels, increasingly intense storm patterns, prolonged drought, and resource scarcity leading to intense struggles for water and food and contributing to social instability. Conflict, loss of human life, and disruptions in trade could all have a significant impact on the U.S. The nation risks both needing to mount a humanitarian response and being drawn into conflict in order to protect national interests abroad as instabilities develop.

Gigaton-Scale Clean Energy Requires a 3X Expansion in the Current Rate of Investment

Deploying all 8 of the feasible gigaton-scale technologies in this report would require a significant increase in worldwide investment to $500 to $800 billion per year. At this scale, clean energy investments would be in line with fossil-fuel investments. Current global investment plans for maintaining and expanding energy infrastructure are on the order of $13 trillion globally over the next 10 years. In the U.S. alone, current planned investment is projected to be close to $1 trillion.

Shifting investment to the clean energy sector will not only benefit jobs, energy security, and climate change, but will create a new global industry. Twenty years ago, the U.S. had an information technology (IT) sector and a tiny internet and mobile phone sector. The nation developed these sectors by investing in technology and creating a marketplace where it could prosper. The IT sector has been propelled by more than $680 billion in direct investment in wired and wireless infrastructure between 1997 and 2008. Facilitated by stable and supportive government policy, this trillion-dollar sector now employs more than 1 million people directly in the U.S. and supports millions of additional service jobs. The investment oppor-

INVESTMENT: Global Annual Investment to Scale Up Clean Energy Technologies

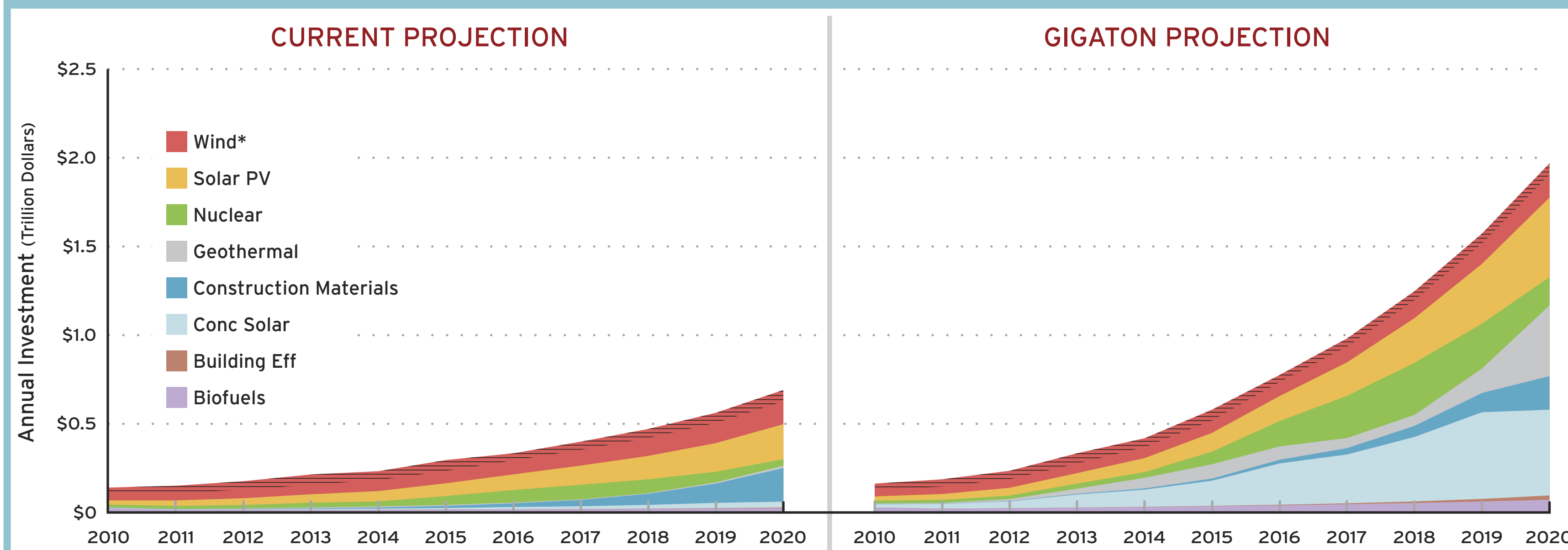

FIGURE 4. Private investment needs to accelerate by 3X for technologies to achieve gigaton scale over the next 10 years. The cumulative 10-year investment for gigaton scale-up of all 8 feasible technologies is $8.41 trillion, compared to currently projected investments in these technologies of $3.67 trillion. In 2020, annual investment levels reach $2 trillion (compared to $135 billion today), indicating a significant market opportunity.

* Wind is currently projected to exceed gigaton scale and attract $1.38 trillion in investment.

SPOTLIGHT: Companies with Gigaton Goals

Novozymes

Setting out an ambitious but achievable goal has a way of sparking creativity and new ways to solve a problem. Novozymes, an industrial biotechnology company, is an example of that creativity.

"We have set out as a corporate objective to enable our customers to reduce their CO_2 emissions by 75 million tons by 2015 through the application of our products," says CEO Steen Riisgaard.

Novozymes' carbon reductions come from the use of enzymes. "Enzymes are nature's engines of efficiency," says Riisgaard, "We apply them to industrial processes to increase efficiency and reduce greenhouse gases as well."

Novozymes sells more than 700 types of enzymes and microorganisms to the nearly $3 billion enzyme market. The company is one of the largest biotechnology and enzyme companies in the world with revenue of $1.5 billion in 2008.

The types of products Novozymes sells are as wide ranging as the industries they service. Paper pulp processing is only one example of the 40 different industries Novozymes serves. Less than half a kilogram of a particular enzyme can separate the fibers of more than 1 ton of wood pulp, saving energy and CO_2. If all thermo-mechanical pulp used this enzyme, the industry could eliminate 3 megatons of CO_2e per year.

Serious Materials

Two of the technology pathways reviewed in this report achieve significant CO_2e reductions by focusing on the built environment – building efficiency and construction materials. California-based Serious Materials, with manufacturing facilities across the U.S., recognizes both the immense business opportunity and potential environmental and social benefits of these two sectors.

CEO Kevin Surace observes, "The opportunity here is immense. Many building materials and technologies have not seen any innovation in the last century."

Serious Materials currently focuses on improving windows and drywall for energy efficiency, thereby reducing carbon emissions in two main ways: by developing and manufacturing building materials that are less energy intensive to make, which reduces up-front carbon emissions compared to other products by up to 80%, and by improving operating energy efficiency for buildings, thus continuing to reduce carbon emissions by up to 50% or more during a building's lifetime.

"Indeed, the environmental benefits of energy-efficient building materials are quite compelling, but the fact is that energy efficiency saves consumers money on their electricity bills and creates new domestic manufacturing jobs," says Surace. "We believe that scaling up our operations to reduce a gigaton of carbon emissions is not only feasible but can help the U.S. take the lead in an important and growing sector."

tunity in clean energy is much larger given the more than $4-trillion energy market.

The 8 renewable energy technologies that this study finds can feasibly achieve gigaton scale represent an investment opportunity of more than $8 trillion over the next 10 years, as shown in Figure 4. At this scale, clean energy — including efficiency improvements — would meet close to 60% of new global energy capacity requirements by 2020. The magnitude of investment needed to achieve gigaton scale varies by technology. The most capital-intensive technology we analyzed was PHEVs. The least capital-intensive technologies capable of gigaton scale include building efficiency, construction materials, and biofuels. Of particular note, the capital intensity of the building efficiency gigaton-scale pathway is 10 times less than for any of the generation pathways.

Expansion of clean energy in the developing world could benefit from accelerated U.S. investment to scale technology. The promise of inexpensive electricity and fuels has already encouraged venture capitalists in the U.S. to fund hundreds of clean energy start-ups; some of these companies could scale up over the coming decade to become large global suppliers. If the U.S. creates large, well-structured markets at home, these companies can continue to advance their technologies and reduce costs so that they can compete with fossil fuels even in the developing world.

Policy Action is Needed to Achieve Gigaton-Scale Clean Energy

To support the potential of gigaton-scale clean energy, the U.S. must enact and sustain policies to catalyze private investment, expand markets, and align incentives to produce society-wide benefits. Current policy does not take into account the negative effects of fossil-fuel-based energy use, nor does it motivate efficient energy use.

The three categories of policy important to achieving gigaton scale are: financial incentives, regulatory structure, and infrastructure development. In addition, the U.S. government should continue support for research and development (R&D) and lead the international community to create a global policy framework.

Policies must be stable if renewable energy technologies are to achieve gigaton scale. A carbon policy, for example, will not attract investment capital if the policy is subject to political manipulation in the short term or risks being revoked by a future congress or administration. No matter how robust a policy, investors are reluctant to bet on the staying power of a single policy by a single government because a shift in that policy can be catastrophic. The revoking of wind subsidies by California in the early 1990s, for example, caused the bankruptcy of almost every wind turbine start-up company in the U.S. and many around the world. The U.S. is no longer the world leader in wind technology largely as a result of such unstable policies. In short, unpredictable policy causes capital to flee; investors avoid categories of risk that they can't predict or understand. Investors and entrepreneurs are accustomed to analyzing uncertainty based on markets but are wary of uncertainty based on politics.

Financial Incentives

- **Carbon policy.** The single most important policy needed to support gigaton scale is a carbon pricing regime. A meaningful price on carbon emissions will drive investment into supply chains and spur innovation. The timing of this action is critical. It is needed now. Investment will lag the increase in potential market size. Supply chain ramp-up is particularly time sensitive. It can take 3 to 5 years for market opportunity to flow through to capacity investment, so the right signals must be given to private investors today if clean energy technologies are to achieve gigaton scale by 2020. Many innovations that could result in fast, cost-effective paths to gigaton scale will emerge rapidly with appropriate policies and investment.

- **Loan guarantees, early deployment, and tax credits.** These financial policies are important for the short term both because of the current shortage of capital and because of the special role of capital for clean energy. The cost of capital has a bigger impact on the price of clean energy sources than on the price of fossil-fuel sources. In general, clean energy has higher up-front costs and lower operating costs than traditional energy sources, and the "fuel" for clean energy is typically a free (renewable) source (e.g., sunshine or wind). Higher up-front costs make clean energy more sensitive to financing costs. Traditional lenders need examples of successful renewable energy plants operating at scale to provide favorable rates comparable to what is offered to fossil-fuel industries. Eventually these financial incentive programs can be phased out as clean energy ramps up and becomes more mainstream.

- **Government purchasing.** The government can be the market maker for early technologies as it has successfully done in the past. For example, federal purchases of buildings certified by Leadership in Energy and Environmental Design (LEED) helped pave the way for expansion of energy-efficient buildings.

- **Support for early scaling efforts.** A number of issues need to be resolved when a utility switches to a renewable energy source, including integration related to the timing of power supplies because many renewable resources produce electricity intermittently. Government should fund utility-scale pilot projects to test higher penetration of renewables.

Regulatory Policy

- **Decoupling.** Most utilities are regulated in a way that couples revenues and earnings. This gives utilities an incentive to increase the volume of electricity sales, which simultaneously increases revenues and earnings. In other words, regulation in this case dissuades utilities from pursuing or promoting efficiency. This is one of a set of market failures associated with overconsumption of energy in buildings. Decoupling of revenues and earnings for California utilities has enabled those utilities to increase support of efficiency programs.

- **Renewable Electricity Standards (RESs).** Requiring a utility to incorporate a minimum amount of renewable energy into its electricity mix guarantees a market for clean energy, which in turn stimulates investment. RESs are already in place in 49 jurisdictions (countries and U.S. states) around the world, but our findings indicate that more aggressive standards are needed to facilitate gigaton scale.

- **Fuel standards.** Standards and minimum production levels for low-carbon fuels can play an important role in reducing oil dependence and addressing climate change. These fuels are not necessarily more expensive, but without standards there is limited incentive for investment in new fuel infrastructure.

- **Efficiency standards.** As illustrated in the McKinsey 2007 report, efficiency is the lowest-cost pathway to energy and carbon savings.[6] Because developers are not responsible for a building's utility payments, and car owners don't own vehicles long enough to benefit from higher mileage, these market participants have limited incentive to surpass current standards. Energy-efficiency upgrades in buildings are often inexpensive but may require training and restructuring on the part of industry. Efficiency standards can align incentives to help surmount these obstacles. New building standards can encourage fast-payback upgrades, and vehicle efficiency standards are a proven way to reduce energy dependence and limit CO_2e emissions. Regulatory intervention is needed to align incentives in the buildings and vehicle sectors.

- **Demand-side management support.** Managing when consumers use electricity, not just the quantity they use, is an important step to improving market functioning. Giving consumers options to shift the timing of their power consumption can relieve peak demand and lower electricity system expenses. Power costs more to produce during peak-use times. With modern information technology, it is possible to use price signals to shift consumption. As an example, time-of-use pricing gives consumers a true price signal so that they can opt to shift power consumption to lower-cost (non-peak) times. Employing time-of-use rates would open up a much larger market for technologies that provide intermittent or peak power such as wind and solar.

Infrastructure Policy

- **Transmission regulation.** Electricity grid enhancement will support all of the gigaton-scale generation technologies. Both long-haul transmission and local grids need enhancement. Prime renewable energy resources (wind, solar, geothermal, and biofuels) are mostly located in areas not connected to the grid; therefore, investment in infrastructure is needed to bring them to the power transmission network. Infrastructure build-out will enable long-distance electricity transmission that taps inexpensive sources of clean power. Investment is also required to improve grid intelligence. "Smart grid" enhancements enable distributed sources of power like rooftop solar, fuel cells, and small-scale wind and make the grid more efficient and resilient. The cost of grid enhancement is small compared to the cost of new generation capacity.

R&D and Education

The energy crisis of the 1970s sparked clean energy R&D in the U.S. and other countries. Many of the innovations developed and enhanced during that era are just now reaching utility scale. Future innovations can move more quickly to market with appropriate policies. Moreover, emissions cuts beyond the gigaton target will be necessary after the year 2020; continued R&D can smooth the way to those reductions and reduce their cost. R&D funding also supports training for the technicians, engineers, and scientists necessary to accelerate scaling of energy technology.

All of the gigaton-scale technologies produce jobs. In some categories, such as nuclear and solar, the Gigaton Throwdown Team identified a shortage of trained personnel, which might constrain gigaton-scale expansion. Government support of training and education can be a major help in providing the human resources necessary to scale up clean energy aggressively.

International Engagement

The bulk of growth in energy demand is occurring in countries outside the Organization for Economic Cooperation and Development (OECD), with more than 40% coming from China alone. The technology choices that OECD countries make will determine global energy markets and significantly affect future global CO_2e emissions. U.S. policy engagement and technology innovation can influence these choices. U.S. leadership can also ensure the competitiveness of innovative clean energy companies as they expand beyond the U.S. and OECD markets. First, the U.S. can serve as a receptive market to reduce the cost of these new technologies. Second, the U.S. can encourage adoption of similar policies in the developing world and other countries. Creation of a global carbon market would expand the opportunity for U.S. businesses that develop their technologies under a U.S. carbon regime.

Pathway Findings

Biofuels

- Biofuels can achieve gigaton scale by 2020 for an investment of $383 billion, creating 394 thousand direct new jobs and enhancing energy security by displacing foreign oil imports.
- Corn ethanol cannot deliver 1 gigaton of CO_2e reductions because of massive land-use requirements; next-generation biofuels (e.g., cellulosic ethanol) can scale to 1 gigaton.
- Biofuels are widely seen as a low-cost and rapidly deployable alternative for the transportation sector.

Building Efficiency

- Building efficiency can achieve gigaton scale by 2020 for an investment of $61 billion, creating 681 thousand direct new jobs.
- Building efficiency is the lowest-cost pathway (of the 9 in this report) to achieve 1-gigaton CO_2e reduction by 2020.
- New energy-efficient building designs show little to no up-front cost and more than 30% energy savings.

Concentrating Solar Power

- Concentrating solar power can achieve gigaton scale by 2020 for an investment of $2.24 trillion, creating 484 thousand direct new jobs.
- Solar resources are abundant in the U.S. and globally to meet new energy demand, and concentrating solar power is ideally situated to remote, high-insolation desert areas, so new transmission build-out is needed to bring CSP to high-population areas.
- Solar thermal systems with storage can provide consistent power and thus are attractive relative to intermittent power sources, e.g., solar photovoltaics and wind.
- Tested technology has been supplying cost-competitive solar thermal power in southern California for the past 20 years.

Construction Materials

- Construction materials can achieve gigaton scale by 2020 for an investment of $445 billion, creating 328 thousand direct new jobs.*
- Multiple gigaton-scale pathways exist in the construction materials sector; the biggest single opportunity for CO_2e reduction is low-carbon cement.
- No single country's building sector can achieve gigaton scale alone, with the possible exception of China if that country shifted to low-carbon cement production.

* *Jobs and investment numbers based on transformation of the cement industry.*

Geothermal

- Geothermal can achieve gigaton scale by 2020 – contingent on development of Enhanced Geothermal Systems (EGS) – for an investment of $919 billion, creating 448 thousand new jobs.
- EGS development will require an estimated $1 billion in R&D to be market ready.
- Major areas for technology support include transmission, drilling, reservoir stimulation, downhole pumps, energy conversion, and exploration.
- Geothermal will ramp slowly; each project requires roughly 5-7 years.

Nuclear

- Nuclear can increase by gigaton scale by 2020 for an investment of $1.27 trilllion, creating 269 thousand direct new jobs; this pathway faces major build out challenges.
- Nuclear power already displaces more than 1 gigaton of CO_2e annually.
- Major technical challenges to scaling nuclear include rapid expansion of the supply chain, including the build-out of large steel forges, and expansion of the workforce.
- Concerns surrounding weapons proliferation, waste disposal, and safety make nuclear uniquely challenging.

Plug-In Hybrid Electric Vehicles

- PHEVs cannot achieve gigaton scale by 2020; starting in 2010, every new car would have to be a PHEV to meet the gigaton goal by 2020, making this pathway all but impossible.
- An aggressive scale-up to 5 million PHEVs would create more than 204 thousand jobs in the battery industry, for an investment of $1.9 trillion.
- Innovations that reduce the cost of batteries and of vehicle retrofits would have a major impact on this pathway, as would business models to finance up-front costs of vehicles.

- The vehicle sector in general is by far the most capital-intensive sector of those examined in this report; it is also a source of major job creation.

Solar PV

- Solar PV can achieve gigaton scale by 2020 for an investment of $1.71 trillion, creating 1.63 million direct new jobs and enhancing energy security through distributed power generation.
- At current growth rates solar PV is on track to abate half a gigaton CO_2e by 2020 and be cost competitive with current electricity prices within the next 5 years.
- Solar PV is already price competitive for peak power rates in a number of markets.
- Successful policies, grid integration, and storage are critical to scaling PV.

Wind

- Wind is on a pathway to exceed gigaton scale by 2020 and attract $1.38 trillion in investment, creating 452 thousand direct new jobs.
- Current projections show wind delivering close to 1.5 gigatons of CO_2e reductions in 2020.
- There is enough wind resource available for more than 4 times projected annual global energy consumption in 2010.

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GIGATON
THROWDOWN

Introduction

Background

The two most recent technology revolutions — information technology (IT) and biotech — have generated trillion dollar sectors and changed the world as we know it. A similar, even-larger-scale technology revolution is under way today: the clean energy revolution has the potential to transform the multi-trillion-dollar energy market and to meaningfully impact economic and job growth, energy security, and climate change.

The Gigaton Throwdown Team has spent the past 18 months analyzing the potential for 9 clean energy technologies — biofuels, building efficiency, concentrating solar power, construction materials, geothermal, nuclear, plug-in hybrid electric vehicles, solar photovoltaics (PV), and wind — to have this impact. Specifically, we asked what it would take to aggressively scale up these technologies by 2020 to each provide the equivalent of 8% of projected new global energy demand and each abate 1 gigaton (1 billion metric tons) of carbon dioxide equivalent (CO_2e) emissions.

We found that 7 of the 9 technologies analyzed in the report have the potential today to scale up rapidly and massively by 2020, and an eighth, geothermal, could scale up after additional research and development and deployment of enhanced geothermal systems (egs). The technology that in our assessment cannot achieve gigaton scale by 2020 is plug-in hybrid electric vehicles (PHEVs). The Gigaton Throwdown target would require 300 million PHEVs on the road in 2020, which is equivalent to the total number of vehicles to be added to the fleet between now and then. Such a complete transformation within a decade would be infeasible.

Scaled up, the 8 feasible pathways could collectively offset more than 8 billion tons (gigatons) of CO_2e annually in 2020 and supply the equivalent of 55 quads (billion British thermal units [Btus])of power annually, more than achieving current climate stabilization targets as well as meeting up to 50% of new energy demand worldwide.[1,2] This exceeds by a factor of 5 current projections, which show clean energy technologies meeting less than 10% of new global energy demand in 2020.[3] Under the Gigaton Throwdown scenario, clean energy technologies would add an estimated 4.5 million direct jobs to the economy and many more indirect jobs.

Of the 8 technologies, only one, wind power, is currently growing fast enough to achieve gigaton scale. By 2020, wind is projected to have an installed based of more than 852 gigawatts, avoiding more than 1.5 gigatons of CO_2e emissions annually. The other 7 technologies are not scaling up fast enough in our assessment.

The rate of scale-up can be significantly influenced by policy action today. Just as policymakers laid the foundation for the high-tech revolution with telecommunications reforms in the 1990s, action is again required to accelerate clean energy technology and spur innovation and investment to achieve what we now know is possible in a trillion-dollar sector that is already providing millions of jobs.

Gigaton Throwdown Initiative

The Gigaton Throwdown Initiative brought together a unique group of investors, entrepreneurs, business leaders, and academics interested in answering the question: *What would it take to scale up clean energy technology ("cleantech") to make a difference?*

This challenge was first posed at an informal gathering of policy wonks, investors, and entrepreneurs in late 2007, one of whom made the following casual observation:

"You cleantech guys could all make a bunch of money and not a bit of difference."

The Gigaton Throwdown Team responded by investigating what it would take for cleantech to make a difference. We defined as our target: 1 billion tons of CO_2e abated per technology in a 10-year time frame.

Gigaton scale: *Scale at which a single technology reduces annual carbon dioxide equivalent (CO_2e) emissions by 1 billion metric tons – 1 gigaton.*

Note: Global CO_2e emissions are currently more than 50 gigatons.[4] Abating a gigaton reduces projected global emissions by roughly 2%, a meaningful contribution.

Gigaton scale is also about energy provision or savings. At gigaton scale, a clean energy technology has an installed capacity equivalent to approximately 205 gigawatts (GW), assuming 100% capacity for the technology, which provides enough energy to meet approximately 5% of total U.S. energy demand.

The 9 clean energy technologies we analyzed are currently operational and attracting investment. Many more clean energy technologies, from carbon sequestration to novel enzymes to fuel-switching, have the potential to scale up; we invite similar analysis of those.

Ten-year Time Frame

For our analysis we adopted a short time frame: 10 years, from 2010 to 2020. This time frame is relevant to businesses, leaders, and individuals — long enough to allow industries to scale but short enough that leaders and individuals can take credit for actions and be held accountable for them. Much analysis of energy alternatives to date has focused on a longer time horizon, 2030 or 2050. Although this time frame is relevant for scientific research and development, by then most of today's entrepreneurs, investors, business leaders, and policymakers will be retired or dead. Recent studies by the Intergovernmental Panel on Climate Change (IPCC) and McKinsey also emphasize the importance of deploying technology to reduce CO_2e emissions in the next 10 years to stabilize the climate.[5,6]

Achieving Gigaton Scale

The Gigaton Throwdown Team developed a set of criteria for a technology to achieve gigaton scale:

- A technology must attack a segment of CO_2e emissions that is large and growing, within a market that is also large and growing. In this study we look at energy generation, buildings, and passenger vehicles because each represents significant portions of the total anthropogenic (man-made) greenhouse gas (GHG) emissions.
- A technology must have the prospect of being cost competitive with fossil-fuel alternatives. All of the technologies we examine have that possibility.
- A technology must have the capacity to ramp up jobs, training, and supply chains, and a receptive market that can accommodate the increased production.
- There cannot be a fundamental constraint — such as land use or a limited natural resource — that prevents the technology from achieving scale.
- The technology must pass a complete life-cycle assessment, ensuring that its manu-

facture and build-out does not release carbon emissions in excess of its savings. Although more difficult to assess, indirect effects of technology scale-up should also be taken into account.

Implications of Gigaton Scale

At gigaton scale, a technology is supplying a meaningful amount of energy, and the industry is directly employing hundreds of thousands to millions of workers.

Economic and Jobs Growth

A gigaton scale-up of clean energy presents a major opportunity for economic growth and job creation. The clean energy sector is generally more labor intensive than the fossil-fuel-based energy sector, and as noted earlier, scale-up of the 8 feasible gigaton technologies would create an estimated 4.5 million direct jobs in the clean energy industry and millions more indirect jobs.[7]

Clean energy has already created jobs across the U.S. The ethanol industry, for example, generated more than 150,000 jobs in 2004, many of them in Nebraska, Illinois, Iowa, and Michigan. For every billion gallons of production, the industry adds between 10,000 and 20,000 new jobs in the U.S. This sector alone has the potential to create 1 million jobs in the next 10 years. Wind energy also provides tens of thousands of U.S. jobs with industry-wide employment at 85,000 in 2009 and 35,000 jobs added in the past year. Building efficiency has the potential to add jobs in all 50 states. Data on jobs attributable to the building efficiency sector in California show that, for each 1% annual gain in efficiency, approximately 400,000 jobs are created. Similarly, the solar installation and utility business has added substantial numbers of jobs in a number of states, including Arizona, California, Nevada, and New York.

The scale-up of a new industry not only generates additional jobs, it generates new types of jobs that require education and training. A new industry also engenders innovation and promotes investment in engineering, science, and technology to advance and take advantage of new market opportunities. Private investors are already backing a number of young and growing companies in the clean energy sector in the U.S. With additional investment, these companies could become global energy market suppliers, and a shift toward more clean energy can advance U.S. technology competitiveness.

Our research found that the opportunity is already here for fast growth that can be sustained for years in the clean energy sector.

GLOBAL ENERGY DEMAND IS GROWING – THE QUESTION IS HOW WE MEET IT

The global energy market is approximately 508 quads and is continuing to grow. Global energy demand is projected to increase by nearly 17% in the next 10 years.[8] This new energy demand can be met using traditional fossil-fuel-based energy sources, or it can be met using clean, low-carbon energy sources. As noted above, meeting global demand with clean energy creates a market opportunity larger than the IT and biotech markets and provides more than energy: it provides job growth, spurs innovation, and offers solutions for climate change.

SEVERAL CLEAN ENERGY SOURCES ARE ALREADY COST COMPETITIVE WITH FOSSIL FUELS, AND EVEN MORE WILL BE BY 2020

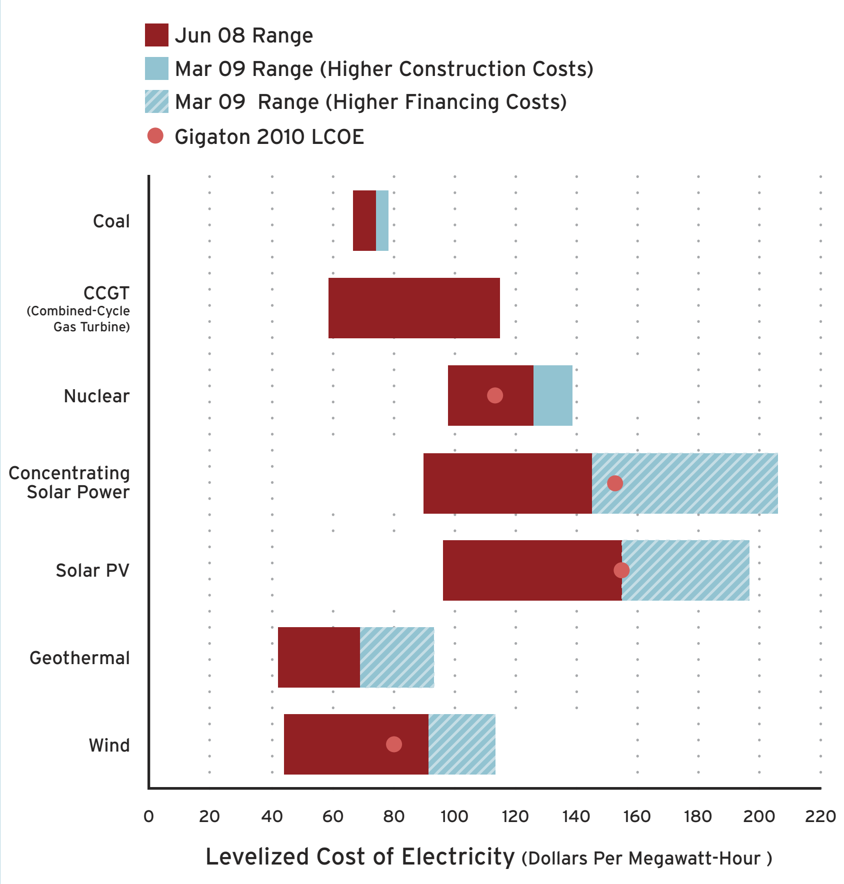
Clean energy sources including wind, geothermal, and solar power already compete with the price of natural gas as an electricity source in some cases, especially where grid infrastructure is available. As shown in Figure 1, wind and geothermal are cost competitive today with new coal-fired generation.[9]

Solar power is competitive at peak prices in states where electricity is costly, e.g. in California. In the next 5 years, several clean energy sources are projected to become cost competitive with traditional sources across the board. Figure 2 shows how dramatically the price of solar is projected to fall during the next several years. In 2020, several sources of clean energy (wind, geothermal, solar, and nuclear) are cost competitive with natural-gas and coal generation.

When making decisions about new generation, the relevant cost comparison for clean energy versus fossil-fuel-based energy is the cost of new —not existing — generation. Although coal-based electricity generated from existing plants sells for as little as $40 per megawatt-hour (MWh), new plants will be considerably more expensive than those built 40 years ago, resulting in higher electricity costs.[12] Construction costs for coal plants escalated more than 60% between 2005 and 2008, driven by increased worldwide demand for power plant construction materials and tight labor markets.[13]

The levelized cost of electricity (LCOE) includes financing costs and is therefore

LEVELIZED COST OF ELECTRICITY COMPARISON FOR NEW GENERATION



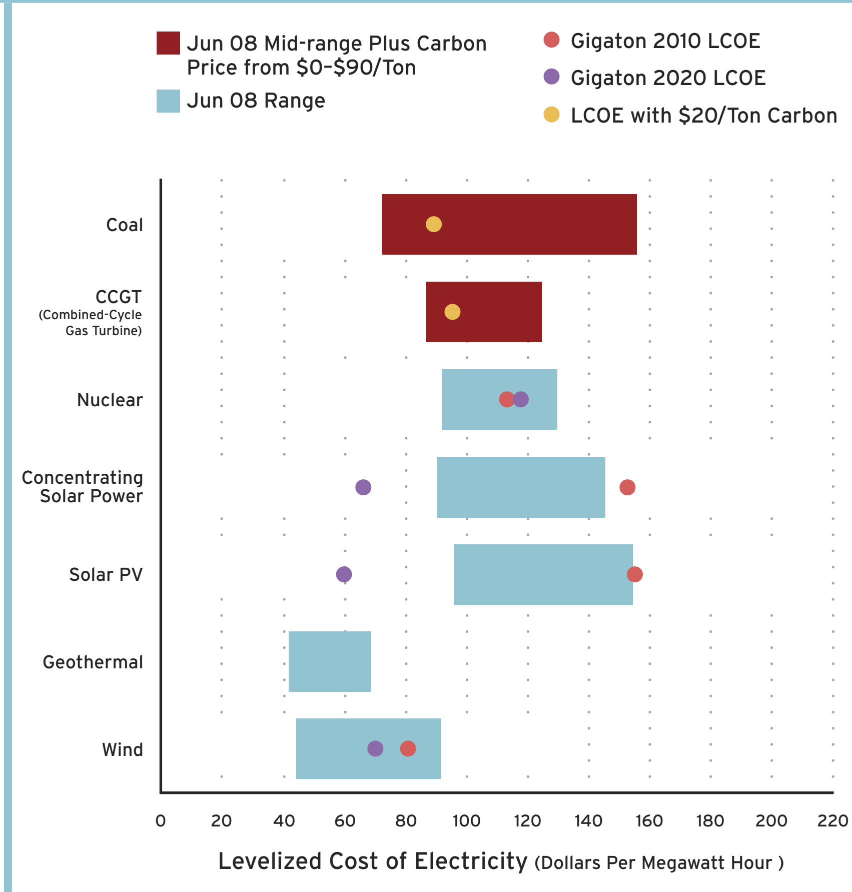


FIGURE 1. Levelized Cost of Electricity (LCOE) for New Clean Energy Generation vs. New Fossil-Fuel-Based Generation Today in the U.S. The LCOE for new clean energy generation is already competitive with new fossil-fuel-based generation in many cases. Notably, an increase in financing costs for clean energy technologies in the 2009 economic slowdown is making them less competitive. However, at 2008 levels, which are likely more reflective of the long-term outlook, geothermal and wind could compete with the cost of new coal; nuclear, concentrating solar, and solar PV are competitive with natural gas once financing conditions return to normal. Source: Lazard, June 2008, March 2009.[10] Note: Coal and natural gas (combined-cycle gas turbine) prices are for newly built generation; coal and natural gas ranges reflect sensitivity to fuel costs.

FIGURE 2. Levelized Cost of Electricity (LCOE) of New Clean Energy Generation Today and in 2020 vs. Fossil-Fuel-Based Generation with a Carbon Price in the U.S. Several clean energy technologies are projected to be cheaper than coal and natural gas in 2020. With a carbon price of $20/ton, concentrating solar and solar PV become competitive at today's prices; wind and geothermal are already competitive. With a carbon price of $90/ton, all clean energy is price competitive with new fossil-based generation at today's prices, even at the high end of the cost ranges. Source: Lazard, June 2008, Mar 2009.[11] Note: Gigaton concentrating solar power (CSP) LCOE assumes trough technology with storage at constant capacity factor across time, cost reduction is primarily capital expenditure for components; Gigaton 2010 concentrating solar includes 30% investment tax credit (ITC), 2020 includes 10% ITC.

sensitive to the cost of capital. Clean energy technologies are disproportionately affected by increases in financing rates for two reasons. First, they have higher capital costs than traditional fuels but lower fuel costs over their life cycle. (The fuel is generally free: wind, sunshine.) Second, they typically rely on relatively more expensive, equity-based financing structures. The economic crisis of 2009 has increased financing costs, which has escalated the cost of clean energy projects. The recessionary impact on the cost of capital, as estimated in March 2009, showed the levelized costs for clean energy technologies to be up to 30 to 40% higher than the pre-recessionary 2008 estimates.[14] While we view it as unlikely that 2009 conditions will persist in the long term, the 2009 economic downturn draws attention to the important role the government can play in putting these capital-intensive technologies on equal footing with fossil-based-generation through loan guarantees and tax support. With guaranteed financing, the LCOE of clean energy generation would look even more competitive.

In general, the costs of newer clean energy technologies such as solar PV and concentrating solar power are more variable than the costs of mature technologies like coal-fired generation. Part of the variability in Figure 1 and 2 stems from technology choice, e.g., for solar, crystalline silicon PV versus thin-film technology. The other contributor to variability is technological uncertainty. In terms of technology scale-up, the factors that affect the cost uncertainty need to be well understood so that trade-offs can be made. For example, the cost of wind energy is highly sensitive to the quality of the specific wind site and the resulting capacity factor. This clearly affects siting decisions. The advantage of most clean energy sources, in terms of uncertainty, is the elimination of fuel costs. The cost of natural gas generation, in comparison, depends almost entirely on the price of natural gas fuel, which has historically been highly variable. The elimination of fuel cost risk is another aspect of scaling up clean energy that should be taken into account when valuing these technologies.

Finally, although it is true that projections show most clean energy sources to be competitive with coal even without a carbon price by 2020, such dramatic cost reductions require rapid investment and build-out today. This reality will not materialize without the right incentives. The effect of a carbon price on fossil-fuel-based energy prices is shown in Figure 2. Based on the Lazard analysis shown in Figure 2, at $20 per ton of carbon, wind and geothermal look more competitive, and concentrating solar power and solar PV begin to be competitive with fossil-fuel-based alternatives at the low end of their cost ranges. Nuclear is not competitive unless carbon is at least $30 per ton. At a much higher rate of $90 per ton of carbon, all clean energy sources out-compete coal and natural-gas generation today. A meaningful carbon price will shift decision-making at the utility and consumer level.

RAPID SCALE-UP IS ATTAINABLE; HISTORY PROVIDES EXAMPLES

The build-out of natural gas in the U.S. in the 10-year period between 1997 and 2007 is an example of how rapidly an energy source can scale up. The natural gas industry added nearly 217 GW of capacity during that decade.[15,16] For most of the technologies examined in this report, 217 GW represents a substantial percentage of the total installed capacity needed to reach gigaton scale. Moreover, the gigaton scale-up under consideration here would be global, making technology expansion even more feasible.

INVESTMENT IN CLEAN ENERGY ENHANCES COMPETITIVENESS

If the U.S. fails to act, other countries will continue investing in clean energy, and the nation will be left behind, remaining reliant on foreign technology (or oil). There is, instead, an opportunity for the U.S. to lead. With more than 140 funded solar start-ups and numerous start-ups in all of the other clean energy categories, these technologies could flourish in the U.S., given the right policy support. Rather than importing energy sources, the U.S. could be in a position to export to other countries with burgeoning energy markets.

WITH 60% OF NEW DEMAND MET BY CLEAN ENERGY SOURCES, ELECTRICITY PRICES WOULD BE LOWER THAN IN 2008

The Energy Information Administration (EIA) projects that, in light of 2009 economic stimulus activity, a projected 60% of new energy demand in the U.S. (330 GW) will be met with renewable energy generation.[17] With this energy mix, the price of electricity over the next 10 years is projected to be lower than 2008 prices across sectors. (See Figure 3.) The basic finding is that increased renewable energy dependence is not substantially increasing rates. In general, the cost of new generation has been increasing, leading to some increases in electricity rates. The addition of renewable

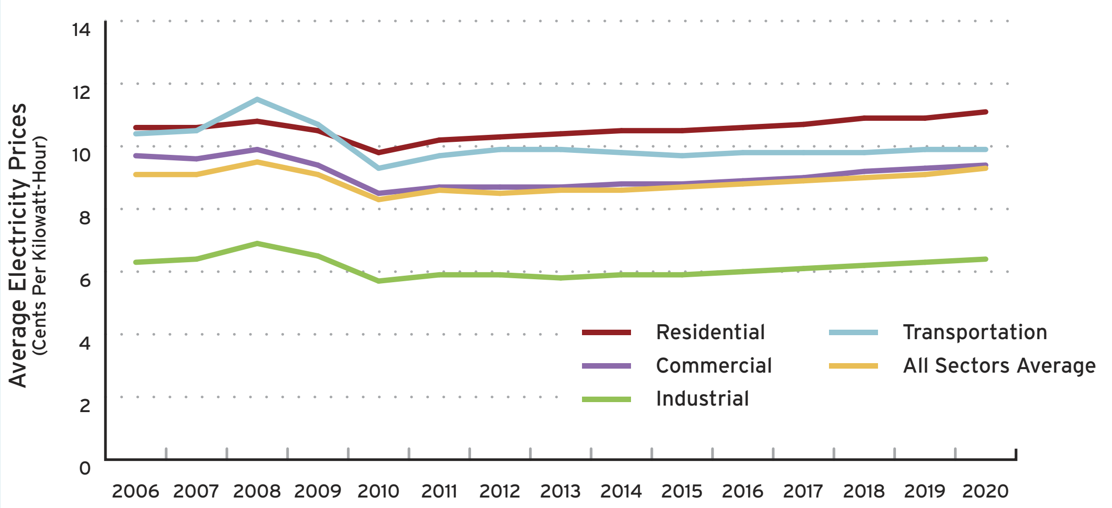


FIGURE 3. Electricity Price Projections Through 2020. Source: EIA, 2009[18]

energy is not projected to cause major price impacts or spikes.

EFFICIENCY MEASURES PROVIDE REAL COST SAVINGS AND ARE THE CHEAPEST NEW ENERGY GENERATION AVAILABLE

Public awareness, incentives, and higher energy costs can all spur investments in energy efficient buildings. With short payback periods, efficiency provides significant near-term cost savings. Design examples of building energy-efficiency retrofits have demonstrated more than 30% reductions in energy consumption. New energy-efficient designs can likewise reduce energy use by 30% to 40% and even achieve net-zero energy use, at negligible up-front costs for efficiency measures.

Energy Independence and Security

The structure of our current energy system directly undermines a number of U.S. security interests. Oil dependence leaves the nation vulnerable to supply shocks and in a defensive position globally. Exclusive reliance on centralized power instead of distributed generation leaves important facilities such as hospitals — as well as homes and businesses — vulnerable to power disruptions. Finally, the security threat posed by climate change is real, substantial, and exacerbated by continued use of fossil-fuel-based energy.

Clean energy technology is much more strongly aligned with national security interests, and the pursuit of gigaton scale addresses global and national energy supply concerns and promotes national security. Gigaton pathways diversify energy supply and displace oil demand and thus reduce dependence on foreign oil imports, hedge against fuel price shocks, and reduce the need to maintain an active deployed military presence to protect access to finite fossil-fuel resources. Furthermore, aggressive CO_2e reductions are a sound preventative measure in view of the projected global security threats of climate change, including global political instabilities caused by displaced populations and increased competition for strained resources. Climate change also threatens national security as a result of the risks to coastal areas from sea level rise, intensified storms, water supply shortages, and the widespread risks of increased wildfires and desertification of land leading to food shortages. These are just some of the anticipated consequences of global warming.

REDUCING FOREIGN OIL DEPENDENCE INCREASES NATIONAL SECURITY

Gigaton-scale adoption of biofuels could displace up to 40% (60 billion gallons) of U.S. oil use in the nation's largest oil-consuming sector, light-duty vehicles (LDVs). Increased use of PHEVs would also decrease national oil dependence. These efforts would be furthered by stringent fuel efficiency policies and standards. In particular, efficiency gains by the military and other emergency responders directly increase their mission effectiveness, as these gains allow scarce dollars to be diverted to other critical needs. The military is an ideal early adopter for fuel and efficiency technology because the fully burdened cost of delivering fuel for military operations can be measured both in dollars and lives. All of these actions are in alignment with stated U.S. security objectives to increase energy independence.

DISTRIBUTED GENERATION CAN PROTECT CRITICAL FACILITIES AND RELIEVE GRID VULNERABILITIES

Through the combined use of distributed (on-site) clean energy generation such as solar PV, enhanced efficiency in buildings, and energy storage systems, critical facilities can be self-reliant during power outages. Electricity produced independent of the centralized grid can power communication systems, hospitals, police stations, military bases, and fire departments to respond effectively during crises. Ensuring electricity supply during emergencies is critical to protecting public health and safety, justifying economic costs associated with distributed generation systems and making the military, hospitals, and other emergency response entities ideal early technology adopters and test cases. Distributed energy that can operate either connected to or in isolation from the power grid can both provide reliable electricity to facilities when there are problems on the central grid and contribute to meeting grid energy demand by selling back excess power during non-emergency times.

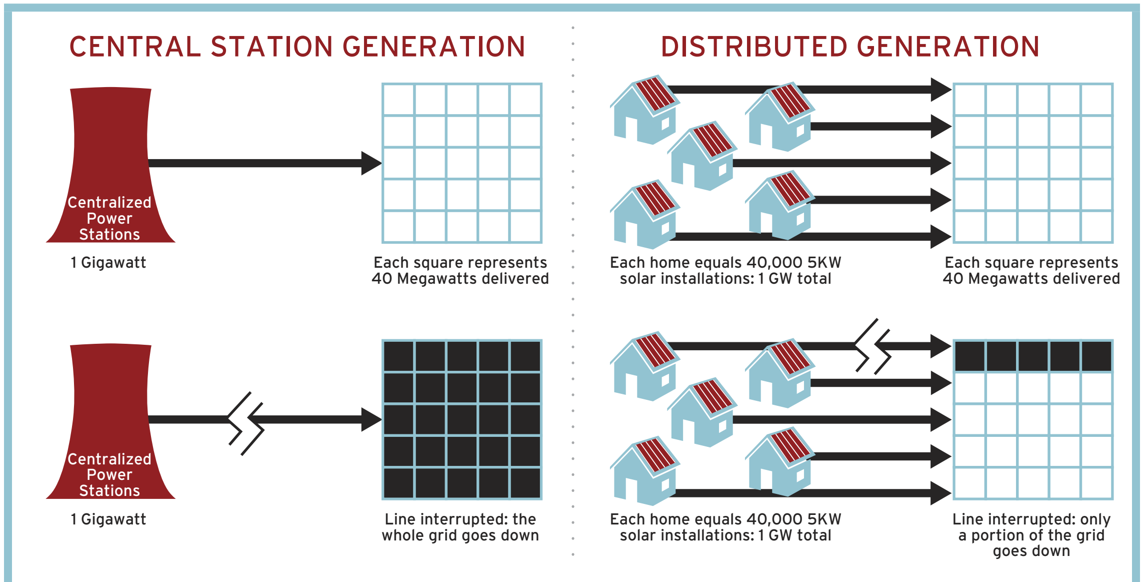


FIGURE 4. Effect of a Power Outage Under Centralized Generation Versus Distributed Generation. Distributed generation helps avoid widespread power outages.

Figure 4 illustrates the difference between centralized and distributed generation in a power outage.

SCALING TECHNOLOGY POSES SOME SECURITY CONCERNS

The national security benefits of clean energy are compelling, but some issues related to scale could, if not addressed, exacerbate existing security concerns.

One security concern is raised by increasing reliance on nuclear energy. Although civilian use of nuclear energy is a key component of the Nuclear Non-Proliferation Treaty (NPT), expanding nuclear generation increases the importance of strict oversight of radioactive fuel and waste management. If nuclear facilities and their byproducts are to be more widely distributed, signatories to the NPT must renew their commitments to working with the International Atomic Energy Agency (IAEA) to ensure stringent management systems and IAEA oversight.

Another concern raised by the scaling of nuclear, concentrating solar power, and most of the geothermal and wind technologies analyzed in this report is perpetuating reliance on a centralized power grid. Although solar PV and some wind technology can support distributed generation and thereby enhance energy security, these clean energy technologies in this report can contribute to continued reliance on the centralized station model of electrical generation and distribution, which is the dominant model in the U.S. This model creates significant vulnerability as it requires distribution through unprotected transmission lines. Transmission redundancies are expensive but clearly needed to ensure uninterrupted distribution of electricity. Lawmakers, the Federal Energy Regulatory Commission, and the Department of Homeland Security perceive that the threat of cyber attacks on the electricity grid will become more pervasive and accordingly the U.S. will need to ensure that National Institute of Standards and Technology smart grid standards ensure protection against cyber breaches.

Climate Change Solutions

Currently under discussion both nationally and internationally is how to reduce CO_2e emissions to avoid dangerous climate change. The target of 450 parts per million (ppm) concentration of CO_2e in the atmosphere has been identified as significantly decreasing the risk of large-scale global temperature change.[19] Although the time frame for stabilization extends beyond 2020, it is important to start now — particularly because CO_2e emissions released today will remain in the atmosphere for years to come.

Risks Associated with the Energy Status Quo

Even though ensuring uninterrupted flow of energy to U.S. citizens and the economy is a critical national security concern, the country's short- and long-term energy supply is precarious, and current policies increasingly place the U.S. at risk.

RISKS FROM FOREIGN OIL DEPENDENCE

Oil more than any other fossil fuel is regionally concentrated and subject to supply disruption. The world oil supply passes through numerous "choke points" vulnerable to attack and seizure, including, but not limited to, the Straits of Hormuz, the passageway for 40% of the world's seaborne oil, and the Malacca Straits. (See Figure 5.) At these key locations, terrorists and pirates could, even with ill-equipped forces, have a large impact on another country without attacking its military directly. By consuming 25% of the world's daily oil demand while controlling less than 3% of its reserves, the U.S. is particularly exposed to the risks inherent in the fossil-fuel infrastructure as well as the conflicts that could arise as resource competition increases.

Researchers disagree on specifics but agree that oil production cannot sustainably keep up with demand. The competition for this finite resource contributes to volatility as profit-seekers and countries attempt to secure access to these assets. China is keenly aware of the oil and other natural resources needed to fuel its tremendous growth; accordingly, Chinese oil companies have invested heavily in Africa, which is rich in resources and poor in capital and governance. Approximately 70% of China's infrastructure spending is concentrated in oil-rich Angola, Nigeria, Ethiopia and Sudan.[a] Similarly, Russia has shown interest in pursuing energy and resource assets in an increasingly exposed Arctic. Increased wealth without stable government can breed discontent, instability, and terrorism.

The concentration of energy and the threat of disruption have given tremendous wealth and geopolitical power to oil exporters. For example, Russia, which provides the European Union (EU) with 44% of its natural gas and 18% of its oil, has in the past cut the Ukraine's gas supplies as a political gesture.

ELECTRICITY INFRASTRUCTURE RISKS

The vast majority of the U.S. electricity system is vulnerable to disruption. Malevolent attacks on the electricity grid can be both physical and, as has been demonstrated by recent reports by the Central Intelligence Agency and Department of Homeland Security, via the internet.[b] The Department of Energy projects that these so-called "Aurora threats" (cyber attacks that disrupt the electricity grid), will become frequent and increasingly sophisticated. This issue will not go away with increased dependence on clean energy sources that require long-distance transmission, e.g., concentrating solar power and large-scale wind, but it can be partially ameliorated by increased deployment of distributed renewables, such as solar photovoltaics and small-scale wind.

Communications and emergency management systems require electric power to operate effectively in crises. As our civilian sector has become increasingly digitized and

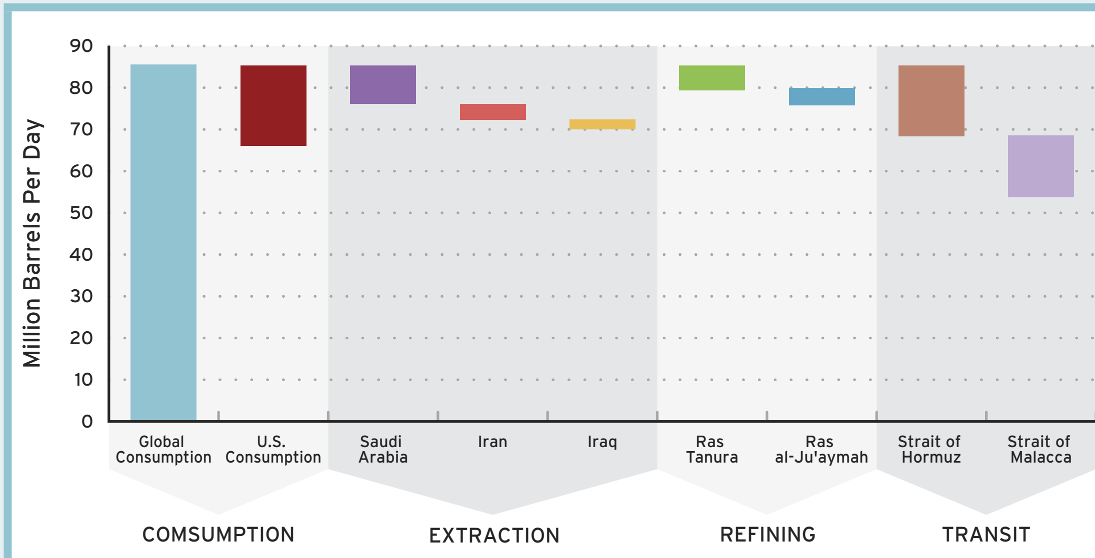


FIGURE 5. Origin and Routing of Global Oil. Oil passes through a number of choke points on its way to its final destination.

electrified, ensuring electricity supply during crises is also critical to emergency response. Ensuring that essential emergency response assets can rely on locally generated renewable resources during a catastrophe reduces exposure to disruption of diesel supplies on which emergency back-up generators typically depend. Furthermore, unlike generators, most distributed generation assets are solid state and can produce electricity during non-emergencies without significant operating costs.

SECURITY RISKS FROM CLIMATE CHANGE

Global warming poses a considerable national security challenge that multiplies the threats of volatility and vulnerability already described above. Major geopolitical instabilities are likely to result from shifts in climate patterns that disrupt food and water systems, displace large populations, and intensify storms and wildfires.

Water shortages not only stimulate migration, they precede food shortages – particularly in the developing world where more than 70% of available fresh water is used in agriculture. Crop ecologists estimate a drop of 10% for every 1.8° F rise in temperature above historical norms; this is particularly concerning given that food requirements, particularly in developing countries, are increasing, which could lead to forced migration.[c] Desertification alone is having profound effects on what was once sub-Saharan Africa.

The ethnic and religious tensions resulting from displacement of Africans have been felt beyond Africa, as seen during the civil unrest of the 2005 Paris riots.

The chaos associated with global warming will compromise military effectiveness as will increasing demands on the military for both humanitarian missions and to protect U.S. interests abroad if geopolitical instabilities unfold. Attending to these situations will degrade the readiness of military assets in affected regions, undermining their ability to react to civilian threats and protect the nation and its interests internationally. Coastal disruptions will threaten Naval bases along the U.S. eastern seaboard and bases in the Indian Ocean and the Pacific. The effect on the Navy is potentially significant as it is the military branch that will likely have to address threats associated with patrolling emerging sea lanes and the competition for natural resources in an increasingly exposed Arctic Circle.

a. Congressional Research Service. February 29, 2009. *China's Foreign Aid Activities in Africa, Latin America, and South East Asia* http://www.CRS.gov

b. Kevin Kolevar, Assistant Secretary of Department of Energy (DOE). 2008. Testimony: House Subcommittee on Energy and Air Quality. September.

c. Center for Naval Intelligence. 2007. *National Security and the Threat of Climate Change.* http://securityandclimate.cna.org

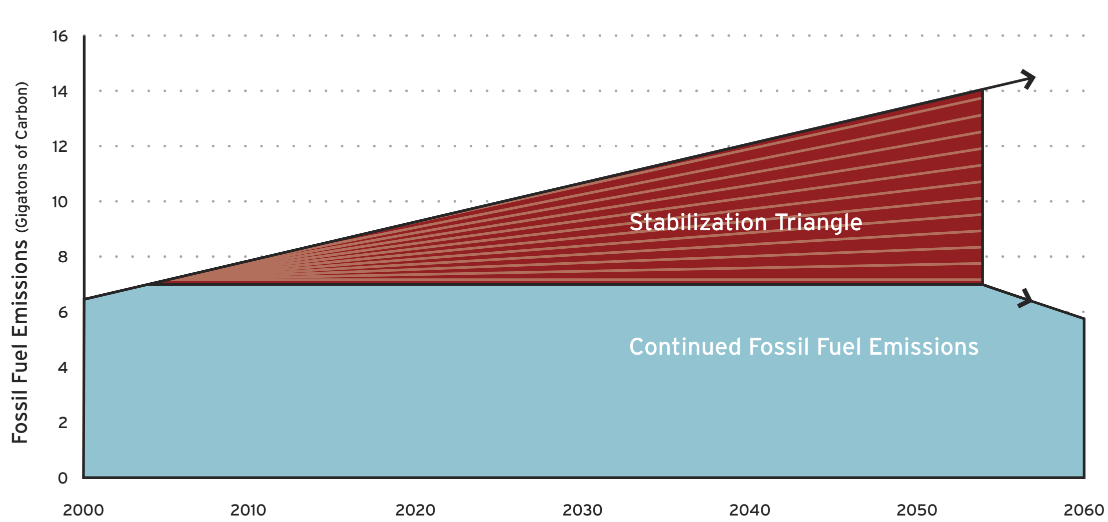


FIGURE 6. Stabilization Triangle Illustrating Emissions that Must be Avoided Annually to Prevent Global Temperature Rise. Note: 1 gigaton of carbon equals 3.76 gigatons of CO_2e. Source: Pacala and Socolow, 2004.[22]

The IPCC calls for emissions reductions of 25% to 40% below 1990 levels by 2020 to achieve 450 to 550 ppm of atmospheric CO_2e and stabilize the climate.[20] To achieve 450 ppm, businesses worldwide will need to reduce emissions by an estimated 5 to 7 gigatons of CO_2e by 2020.[21] As shown in Figure 6, emissions are increasing, so reduction strategies must offset the projected emissions increase from growth in energy use worldwide.

The 8 feasible technologies in our analysis can each be scaled to deliver at least 1 gigaton of CO_2e reductions each by 2020, more than meeting the global target of 7 gigatons to stabilize the climate. Wind is on a growth trajectory to abate more than 1 gigaton.

Challenges of Gigaton Scale

The rapid scale-up of any new technology poses some concerns. Our chief concern with regard to the scale-up of clean energy technology is life-cycle emissions. If the aim is to reduce CO_2e emissions, then the CO_2e associated with the entire life-cycle of a technology must be taken into account — as well as possible indirect effects, which are much more difficult to quantify (see, for example, the discussion of displacing food production in the biofuels chapter). A second concern relates to land-use policy. Land requirements to scale up the new clean energy technologies in this report are not prohibitive but will require sound planning to ensure that environmental impacts and conflicts with existing uses are resolved. Both of these challenges can be addressed through sensible policy and should not ultimately impede scale-up.

Gigaton Analysis

Of the pathways we analyzed, 6 are new ways to make electricity or fuels that displace oil, natural gas, and coal (biofuels, solar PV, concentrating solar, wind, nuclear, and geothermal). Two improve the efficiencies of residential and commercial buildings, reducing the need to expand fossil fuel production. One, PHEVs, improves the efficiency of light-duty vehicles, which are responsible for the majority of the transportation sector's GHG emissions.

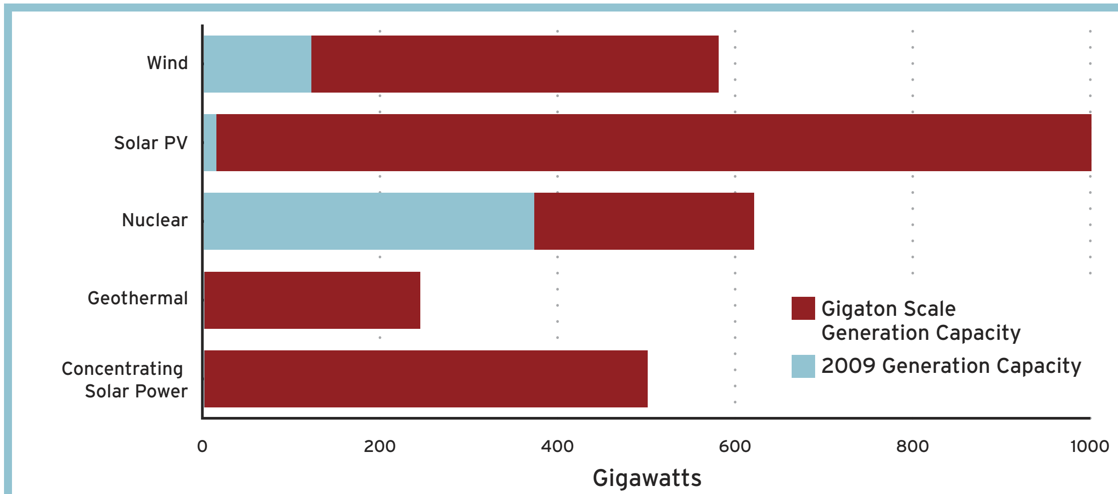


FIGURE 7. Scale-up for Gigaton Clean Energy Generation Technologies by 2020.

Our analysis focused not only on what's possible in the next 10 years but also on what's needed to achieve the possible.

Technical Scale-Up

The Gigaton Throwdown analysis focuses on what is required for each technology to achieve gigaton scale. Examining current projected growth rates in comparison to the growth rates necessary to achieve gigaton scale by 2020, we found that 8 of the 9 technologies would need to scale more rapidly than currently projected to hit the gigaton target. Wind is the exception, already growing rapidly enough to hit a gigaton by 2020. Figure 7 shows the expansion in installed capacity necessary for each of the generation technologies to get to gigaton scale.

The growth needed for gigaton scale depends on a number of assumptions. Most importantly, actual CO_2e emissions reductions depend on the carbon intensity of the electricity or fuel being displaced. For instance, displacement of coal has a larger impact than displacement of natural gas, and displacement of hydropower would have no effect on emissions. We used the average carbon intensity of the U.S. electricity grid (in 2020) as the basis for our calculations. Given that 40% of new energy demand is projected to come from China where clean energy technology is likely displacing coal (rather than natural gas), our estimate is likely conservative in terms of CO_2e offset globally. Clearly, the numbers are sensitive to both the geography of the build-out and the energy source displaced. Figure 8 shows general assumptions used in the gigaton analysis.

Embodied Carbon

Each energy generation technology inherently depends on industrial and related processes (e.g., manufacturing, mining, materials processing and transportation, and construction) for development and scale-up. Embodied in each of these processes are varying degrees of energy intensity; as the capacity of any technology to generate carbon-free electricity is built out, a certain amount of energy will be consumed to create the infrastructure necessary. The energy consumed to make a technology possible is referred to as "embodied energy." In short, it takes energy to make energy, and each clean energy technology will have an accompanying embodied energy, which is the amount of energy that the source (wind turbine, solar module, etc.) will need to produce to break even. Each technology will also have an associated energy payback period, the time that it will take to offset the embodied energy.

Related to the embodied energy is embodied carbon. Simply put, embodied carbon is a total amount of CO_2e emissions that result from the complete life cycle of the clean energy technology. The embodied carbon is not a fixed number but depends heavily on the energy generation mix used in the manufacturing and construction processes for a technology. Thus, a solar module factory that is powered by solar panels will have a fixed, positive inherent embodied energy cost (i.e., the embodied energy associated with the manufacture of the original solar panels), but the embodied carbon from the manufacturing phase at the factory going forward will be zero. Embodied carbon is an important statistic that must be taken into account when new energy generation technologies are being proposed, planned, and built; however, it is affected by current energy generation capacities and can be improved upon greatly as low-carbon energy is used in a given technology's supply chain.

Of the 5 direct electricity generation technologies discussed in this report (wind, solar PV, nuclear, geothermal, and concentrating solar), solar PV has the highest embodied energy because of the silicon in PV system semiconductors, which requires significant energy to be processed to the high quality necessary for the PV module technology that dominates today's market. A rapid scale-up of solar PV could "front load" the process with additional CO_2e emissions, affecting how and when global CO_2e levels stabilize and ultimately decline. Newer, thin-film technologies for solar PV have much lower associated embodied energy and offer a promising path forward. (See solar PV chapter for more details.) Although solar PV has the highest embodied carbon potential of the technologies analyzed in this report, other clean energy technologies also raise this issue; for example, the emissions savings from using green building materials such as bamboo flooring in the U.S. can be more than undone by the emissions associated with transporting the bamboo to the U.S. from its point of origin in Asia. Careful life-cycle analysis is needed account for the energy and CO_2e emissions consequences of scaling up any clean energy technology.

GENERAL ASSUMPTIONS					
Capacity Factor for Each Generation Technology	Concentrating Solar Power 0.41	Geothermal 0.84	Nuclear 0.83	Solar PV 0.21	Wind 0.35
Carbon Intensity of Displaced Electricity[23]	Average 2020 carbon intensity of the U.S. electricity grid (0.000558 megatons of CO_2e per kilowatt-hour)				
Carbon Intensity of Displaced Liquid Fuel[24]	Average carbon intensity of gasoline (96 grams of CO_2e per megajoule)				

FIGURE 8. Gigaton Analysis Assumptions.

Policy Support for Gigaton Scale

A foundational element of a massive scale-up of clean energy technology is policy action. Energy markets are highly regulated, and policy influences the actions of consumers, utilities, and investors in these markets. Policy determines the environment in which certain technologies can flourish and therefore attract private investment. Finally, policy can directly support the research, development, and deployment of early-stage technologies by signaling strong future demand for these technologies.

Effective policy to support clean energy scale-up will do three things. First, it will align marketplace incentives with U.S. goals and produce society-wide benefits. Second, it will expand markets for clean low-carbon energy. Third, it will catalyze private investment. Policy actions to support these objectives fall into three categories: financial incentives, regulatory structure, and infrastructure development. Our analysis examined a number of policy instruments in these categories and their effect on specific technologies:

FINANCIAL POLICIES

- Carbon price
- Loan guarantees and tax credits (investment tax credit, [ITC]; production tax credit [PTC])
- Government purchase
- Research, development, and deployment (RD&D)
- Workforce development

REGULATORY POLICIES

- Building codes
- Demand-side management (DSM) support
- Efficiency standards
- Feed-in tariffs
- Renewable Electricity Standards (RESs)
- Fuel standards
- Decoupling for utilities

INFRASTRUCTURE POLICIES

- Transmission

The cross-cutting nature of these different policies is shown in Figure 9. (Decoupling for utilities and fuel standards are omitted because these two policies primarily impact building efficiency and biofuels, respectively.) Each of the technology chapters discusses the impact of the relevant policies on technology scale-up.

The central policy that affects every clean energy technology is stable, consistent carbon pricing. The price on carbon should reflect the value of reducing CO_2e emissions to avoid dangerous climate change, which will align market incentives with U.S. goals and interests. A price on carbon does not select a single technology winner but rather spurs competition among low-carbon technologies. It sends a strong signal to investors and innovators that there is demand for low-carbon technology. Much like the design of regulatory policies for nitrogen oxides (NOx) and sulphur oxides (SOx), policy designed around carbon dioxide and equivalent GHG emissions (CO_2e) must be long term to be effective.

While carbon policy is a long-standing multi-decade commitment, other important policies can be in place over shorter time periods. These policies still require a multi-year stable commitment to be effective, but many will eventually be phased out as the innovation they support leads to price-competitive clean energy. An example is feed-in tariffs to encourage solar PV adoption. In the next 5 years, solar PV, which is already a competitive provider of peak electricity in expensive markets, is forecast to be cost competitive across markets. The price is projected to drop by more than 50%, at which point feed-in tariffs will no longer be needed.

Conclusions

We found that clean energy can feasibly scale to abate more than the amount of CO_2e emissions needed to achieve 2020 stabilization goals for a 450 ppm trajectory, drive economic and jobs growth and create a new industry, and enhance energy independence and security.

We identified a number of challenges to accelerating the growth of individual clean energy technologies to achieve gigaton scale. However, we see these challenges as surmountable. A more aggressive scale-up than currently projected will require policy support but is achievable over the next 10 years from 2010 to 2020. As noted above, a carbon policy will be essential to the scale-up of clean energy technologies.

This report highlights the possibilities for an alternative future. If the gigaton-scale vision is realized, the world in 2020 will be a different place, much less at risk of significant social and ecological destabilization.

	FINANCIAL					REGULATORY						INFRASTRUCTURE
Policy	Carbon Price	Loan Guarantees	Government Purchasing	RD&D	Work Force Development	Building Codes	DSM[a]	Efficiency Standards	Feed-in Tariffs	RES[b]	Tax Instruments: PTC, ITC, and Accelerated Depreciation[c]	Transmission
Biofuels	yes	yes	yes	yes	yes	no	no	yes	no	no	yes	yes
Building Efficiency	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	no
Concentrating Solar Power	yes	yes	yes	yes	yes	no	yes	no	yes	yes	yes	yes
Construction Materials	yes	yes	yes	yes	yes	yes	no	no	no	no	yes	no
Geothermal	yes	yes	yes	yes	yes	no	no	no	yes	yes	yes	yes
Nuclear	yes	yes	yes	no	yes	no	no	no	no	no	yes	yes
Plug-In Hybrid Vehicles	yes	yes	yes	no	yes	no	yes	yes	no	yes	yes	no
Solar PV	yes	yes	yes	yes	yes	yes	yes	no	yes	yes	yes	yes
Wind	yes	yes	yes	no	yes	no	yes	no	yes	yes	yes	yes

a. Demand side management
b. Renewable electricity standards
c. Production tax credit and investment tax credit

blue = yes
red = no

FIGURE 9. Policy Matrix

Notes and References

1. At gigaton scale, each generation technology is supplying energy output equivalent to a 205-GW facility (at 100% capacity factor).
2. According to the EIA 2009 Reference Case, new annual energy demand globally between 2010 and 2020 is 87 quads. Source: EIA. 2009. *International Energy Outlook.*
3. Energy Information Administration (EIA). 2009. See 2.
4. Rogner, H.-H., D. Zhou, R. Bradley. P. Crabbé, O. Edenhofer, B. Hare, L. Kuijpers, M. Yamaguchi. 2007. "Introduction," in *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*
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6. McKinsey & Company. 2007. *Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?* December.
7. Engel, D., D.M. Kammen. 2009. *Green Jobs and the Clean Energy Economy.* Copenhagen Climate Council Thought Leadership Series.
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9. LCOEs of clean energy technologies based on existing tax credit incentives, as extended by American Recovery and Reinvestment Act legislation.
10. Lazard. 2008. *Levelized Cost of Energy Analysis.* June; Lazard. 2009. *Levelized Cost of Energy Analysis.* March.
11. Lazard. 2008, 2009. See 10.
12. Federal Energy Regulatory Commission (FERC). http://www.ferc.gov. Accessed April 2009.
13. Electric Power Supply Association (EPSA). May 2008. *The Cost of New Generation Construction.* May. Note: With the current 2009 recessionary decrease in demand, it is reasonable to expect prices to come back down somewhat in the short term, but the expected growth and industrialization of China, India, and other developing countries makes it unlikely that commodity prices will ever be as low as they were when most existing coal plants were first built.
14. Lazard. 2009. See 10.
15. Blair, N. et al. 2006. *Concentrating Solar Deployment Systems: A New Model for Estimating U.S. Concentrating Solar Power Market Potential.* Prepared for National Renewable Energy Lab.
16. Energy Information Administration (EIA). 2009. *An Updated Annual Energy Outlook 2009 Reference Case Reflecting Provisions of the American Recovery and Reinvestment Act and Recent Changes in the Economic Outlook.* Table 8. http://www.eia.doe.gov/oiaf/servicerpt/stimulus/index.html
17. EIA. 2009. See. 16
18. EIA. 2009. See 16.
19. Intergovernmental Panel on Climate Change (IPCC). 2007. *Working Group 3 Report*, AR4. Box 13.7
20. IPCC. 2007. See 19.
21. The IPCC calls for reductions in CO_2e emissions of between 25% and 40% for Annex 1 countries by 2020 to achieve climate stabilization at 450 to 550 ppm. The reported emissions for 1990 according to United Nations Framework Convention on Climate Change (UNFCC) is 18.7 gigatons CO_2e. Hence the range of required reductions is 4.675 to 7.48 gigatons of CO_2e, with the high range more likely to achieve 450 ppm. Notably, this is slightly higher than the reductions that the IEA reports as necessary by 2020 for 450 ppm: 4 gigatons. The discrepancy stems from the assumption on timing for peak emissions. Under the UNFCC scenario, peak emissions occur in 2015. Under IEA, they occur in 2020, possibly 5 years too late to achieve the targeted stabilization. Sources: IPCC. 2007. (see 19) and UNFCCC. 2007. "National Greenhouse Gas Inventory Data for the Period 1990–2005." No.: F4C COCct/oSbBeIr/ 22000077/30 and IEA. 2008. *World Energy Outlook.* Key Graphs: Slide 11.
22. Pacala, S., R. Socolow. 2004. "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies." *Science.* Vol. 305. August 13.
23. EIA. 2007. *Annual Energy Outlook.* (Reference Case)
24. GREET Model. 2009.

Biofuels

MAIN POINTS

- Biofuels can achieve gigaton scale by 2020 for an investment of $383 billion and enhance energy security by displacing foreign oil imports.
- Corn ethanol cannot deliver 1 gigaton of CO_2e reductions because of massive land-use requirements; next-generation biofuels (e.g., cellulosic ethanol) can scale to 1 gigaton.
- Biofuels are widely seen as a low-cost and rapidly deployable alternative for the transportation sector.
- Increased reliance on waste streams for fuel generation and use of regionally appropriate feedstocks for biofuels can address land-use concerns.

Overview

Transportation has proven to be one of the hardest emission sources to address with low-carbon solutions. Sunk costs in existing infrastructure for fossil-fuel energy sources and consumer performance requirements have slowed the adoption of alternative fuels. Car manufacturers have had little incentive to offer alternative fuel-efficient vehicles, given consumer preferences and the high capital cost of change.

Biofuels blended with gasoline are one of the few alternatives that has not required significant new infrastructure or change on the part of consumers or auto manufacturers. As a result, biofuels are today the most widely deployed substitute for conventional fossil fuels in transportation. The scale-up of biofuels as a primary fuel in the transportation sector, not just a blending agent, would entail additional infrastructure investment but remains an attractive alternative.

The term biofuels encompasses two types of liquid fuels produced from biomass materials: ethanol, which is an alcohol produced when yeast ferments sugar from plant material such as corn or sugar cane, and biodiesel, which is made from plant oils, such as soy or canola (rapeseed), or animal fats. Ethanol production is significantly higher than biodiesel production globally; the main types of ethanol in production are corn ethanol and sugarcane ethanol. In the U.S., biofuels can currently be blended up to 10% (ethanol) and 20% (biodiesel) in every gallon of fuel, and an increasing number of vehicles can use blends of up to 85% ethanol. Biodiesel is an alternative for diesel vehicles. Although biodiesel is a promising low-carbon alternative for some transportation uses, it is a much smaller fraction of world production than ethanol and less commonly used in the light-duty vehicle (LDV) sector. In this chapter, we focus on the potential to scale up ethanol production to achieve the target of a 1-gigaton reduction of carbon dioxide equivalent (CO_2e) emissions in 2020 through displacement of gasoline in the LDV sector.

Ethanol can be produced from a number of feedstocks; in addition to corn and sugarcane, other feedstocks include switchgrass, woody biomass, agricultural residue, wood residue, and municipal solid waste (MSW). Ethanol derived from plant fiber cellulose (e.g., plant stalks, trees, MSW) is known as cellulosic ethanol, as distinct from ethanol derived from starch (e.g., corn). The actual carbon dioxide equivalent (CO_2e) savings from each of these feedstocks varies and depends, among other things, on land-use and agricultural practices and yields associated with a particular biomass material, use of fossil fuels in refining and transporting the biofuel, and the ability to "coproduce" electricity during refining.

Biofuels can achieve gigaton scale globally by 2020. The actual volume of biofuel production required to meet the gigaton target depends on the feedstock choice and the underlying technology used for production. For cellulosic ethanol, upwards of 150 billion gallons (550 billion liters) is needed for the various feedstocks, which include sugarcane, switchgrass, agricultural residues, and woody poplar (see Figure 3). The 150-billion-gallon level is used as a reference for gigaton scale throughout this chapter.

Because ethanol has a lower energy density than gasoline, 150 billion gallons of ethanol replaces approximately 100 billion gallons of gasoline, or roughly 5% of the world's projected liquid fuel demand in 2020. Factoring in the CO_2e savings from coproduction of electricity at biorefineries significantly lowers the volume of biofuel needed to achieve the gigaton target. For instance, use of switchgrass with an electricity coproduct requires only 76 billion gallons to reach gigaton scale.

The diversity of available feedstocks for biofuel production suggests that regionally tailored solutions can play a significant role in the short term. In the longer term, a number of technologies are evolving, such as algae-based biofuels, that promise to unlock even greater emissions reductions and more broadly adopted low-carbon-fuel solutions.

Challenges associated with biofuels include controversy over land-use and food-production impacts of growing biofuel energy crops and the varying feasibility of different feedstocks (e.g., corn ethanol is likely not feasible to meet the gigaton goal because of the large land area that would be required for growing). The land and water demands, and other challenges, associated with biofuels — and any alternative technology — need to be made integral, not peripheral, to the assessment of the transportation energy. The Low-Carbon Fuel Standard and Renewable Fuels Standards are two of a small set of implementation efforts in this vital area.

Other challenges include: the need to convert vehicles and gas stations to be compatible with biofuels; the need to build infrastructure including biorefineries, distribution facilities, and transportation networks for both the raw materials and the refined fuel; and the performance of biofuels whose use decreases gas mileage because they are less energy-dense than gasoline.

Biofuels are one of the least capital-intensive gigaton options; the estimated cost of scaling up biofuels to meet the gigaton target is $383 billion, although costs rapidly escalate if vehicles need to be converted after-market for ethanol compatibility. The cost of converting new vehicles, when manufactured, is a fraction of the cost of after-market conversions. Ensuring ethanol compatability in new vehicles would significantly decrease future investment costs for this pathway. Achieving gigaton scale with biofuels would create an estimated 200,000 new direct jobs in the industry.

Industry Background

Brazil and the U.S. are the major players in the biofuel industry. In 2008, the U.S. eclipsed Brazil as the largest producer of ethanol, generating 9 billion gallons (34.1 billion liters) while Brazil produced 6.5 billion gallons (24.6 billion liters).[1] The significant difference between these two countries is their choice of feedstock. The majority of ethanol produced in the U.S. is corn based. In Brazil, the exclusive feedstock is sugarcane. Figure 1 shows worldwide ethanol production by country.

Biofuel Industry

Ethanol produced from corn and sugarcane is a member of the first generation of biofuels, which also includes oilseed rape biodiesel produced primarily in Germany and palm oil biodiesel produced in Malaysia. The large land area required to scale corn ethanol and oilseed rape biodiesel and the forest-clearing practices that would accompany increased production of palm diesel make these pathways unattractive for substantial scale-up. Sugarcane ethanol is a notable exception in this category and appears to have potential to scale sustainably in appropriate areas, e.g., areas with tropical and subtropical weather and long growing seasons that allow for high-yield sugarcane cultivation.[3,4] Hopes for scaling biofuels elsewhere in the world have been pinned on second- and third-generation biofuels.

Second-generation biofuels utilize an array of different feedstocks with higher net energy yield and lower land-use requirements than first-generation feedstocks. Ethanol produced from cellulosic biomass is a major category of second-generation fuels. Cellulosic feedstocks include high-energy-density crops, such as switchgrass and woody biomass, and agricultural and wood residues left over from existing cultivation. A significant amount of biofuel can be produced globally by converting waste streams — agricultural and wood residues and MSW — into biofuels. These second-generation fuels still face a number of technological challenges. The construction of test facilities is an important step in scaling up production and is currently under way. Four mid-size cellulosic ethanol plants are under construction in the U.S.

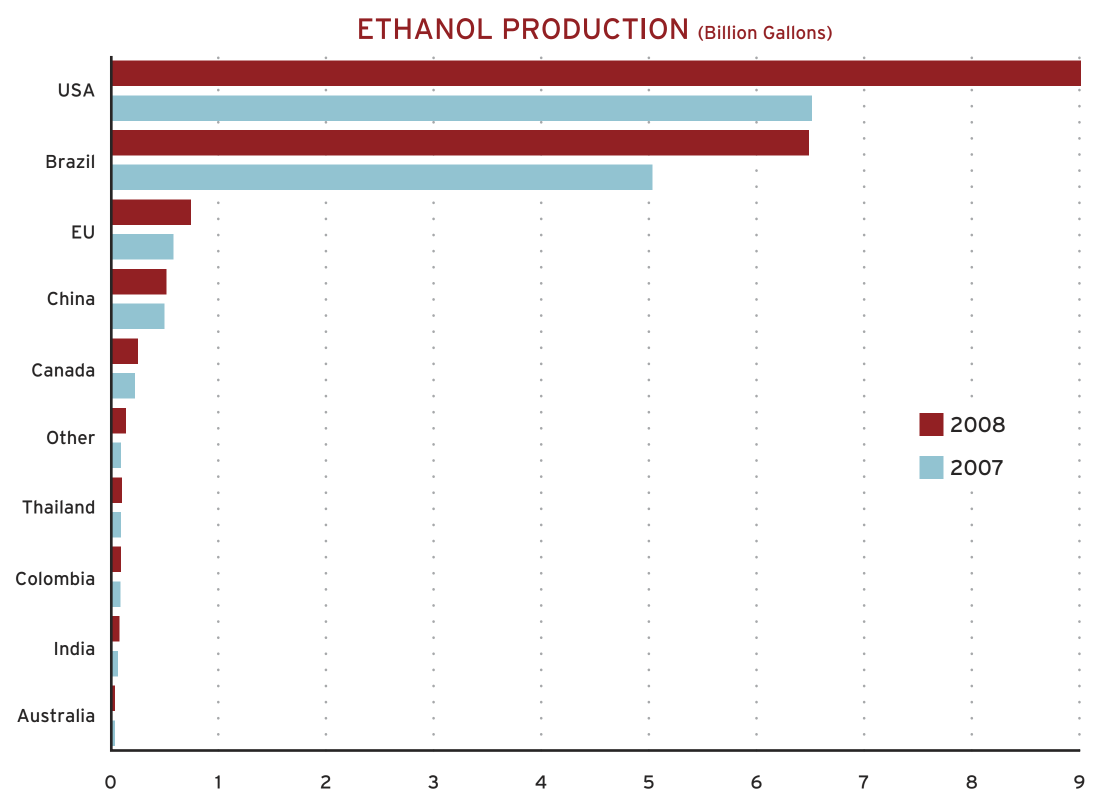

FIGURE 1. Ethanol Production by Country, 2007 and 2008. Total global ethanol production grew from 13.1 billion gallons in 2007 to 17.3 billion gallons in 2008. The U.S. surpassed Brazil as the largest producer in 2008. Source: F.O. Licht, 2008.[2]

Industry Growth

Strong growth in ethanol production reflects active government support and growing demand for alternative liquid fuels. The corn ethanol industry grew 32% between 2005 and 2008.[5] The mandates under the 2007 U.S. Energy Independence and Security Act (EISA) aim to increase ethanol production in the U.S. to 36 billion gallons by 2020. Of this quantity, more than half — 20 billion gallons — would be cellulosic ethanol.

Biodiesel production has also been increasing worldwide and was at 245 million gallons in 2005.[6] Although only a small fraction of total biofuel production, biodiesel has a large and growing potential market. Sectors of the liquid-fuel market for which there are currently not good electric-vehicle options, e.g., heavy freight and airline travel, are promising biodiesel markets. Germany is the chief producer of biodiesel today, followed by France, the U.S., Italy, and Austria. As noted above, this chapter focuses primarily on the LDV sector and therefore on the gigaton potential for ethanol.

Biofuel growth trends are highly sensitive to gasoline prices in various parts of the world. In general, accelerating the growth of biofuels will require public support in the short term. Brazil's experience demonstrates the potential of stable, multi-decade government policies to bring biofuel prices to a competitive level. As illustrated in Figure 2, sugarcane ethanol in Brazil is the only biofuel currently cost competitive with gasoline. There is large potential for biofuels in tropical countries with high crop yields to be price competitive with oil when oil prices are above $50/barrel. During the period of high oil prices in 2005 and 2006,

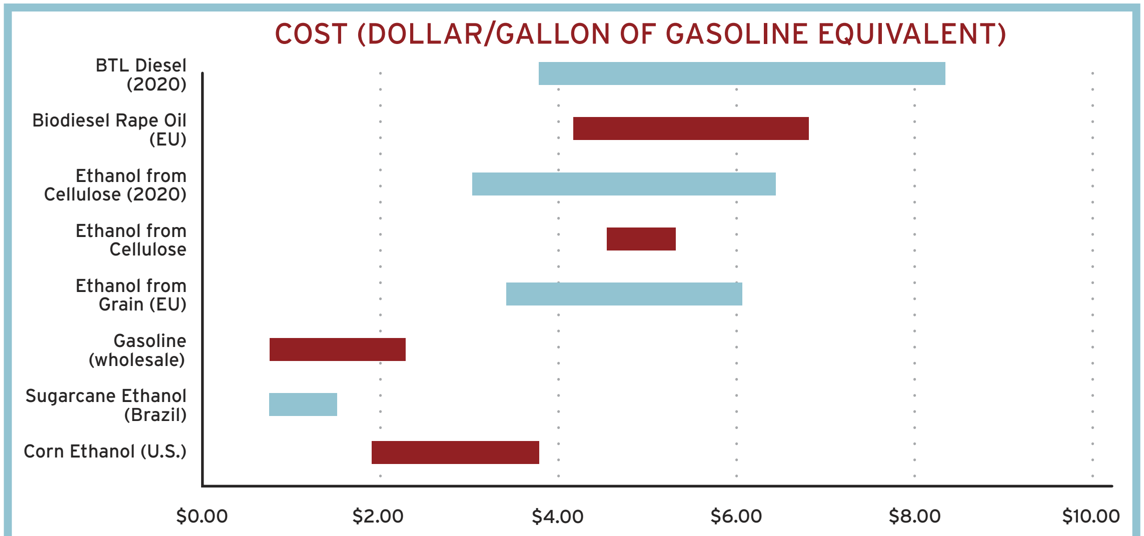

FIGURE 2. Cost of Biofuels, Current and 2020. Currently, sugarcane ethanol is competitive with gasoline. Cellulosic ethanol and biodiesel close in on current gasoline prices in 2020. Source: Worldwatch, 2006.[7]

sugarcane ethanol was significantly less expensive than oil. In general, ethanol production costs are expected to decline significantly with continued investment and government support, making ethanol competitive with gasoline in the near future.

The rising tide of liquid-fuel demand in many developing countries is a promising market opportunity that could buoy biofuel production. Africa's existing sugar industry is a large source of sugarcane bagasse (the fiber that remains after the juice has been extracted from sugarcane stalks) that is suitable for cellulosic ethanol production.[8] Cultivating additional sugarcane in Africa for direct use in biofuel production is another avenue for expansion. China has been expanding its ethanol production and is the third-largest producer in the world. Although China's first efforts focused on corn ethanol, a range of other first-generation feedstocks have been explored including cassava, sweet potato, and sugarcane. China's growing appetite for liquid fuels presents a massive market opportunity. In India, the economics of sugarcane ethanol production are becoming more favorable, and both India and Thailand have adopted pro-biofuel policies.[9]

Projections for global biofuel production vary significantly. The International Energy Agency (IEA) and the U.S. Office of Policy Analysis (OPA) present more conservative projections than gigaton scale. IEA forecasts that 10% of global fuels will be biofuels by 2030, and the OPA projects 54 billion gallons of biofuels production in 2020.[10,11] (See Figure 3.)

Achieving Gigaton Scale

The volume of ethanol required to reduce greenhouse gas (GHG) emissions from the LDV sector by 1 gigaton a year in 2020 depends on the choice of feedstock and biorefinery methods as well as the potential carbon credit received for coproduction of electricity at the biorefinery. Electricity coproduced with cellulosic biofuel at the biorefinery can displace fossil-fuel-generated electricity on the grid, providing an additional carbon benefit. The volume of biofuels needed to reach the gigaton target is halved when the additional carbon reduction from the coproduct electricity credits is taken into account, assuming the additional electricity produced is sold back to the grid.

Biofuel Potential and Scale-up

The CO_2e savings from different ethanol feedstocks varies. Figure 3 shows gigaton-scale production among ethanol feedstocks as well as the percent of U.S. and global liquid fuel demand that gigaton-scale production would supply, the amount of land needed for production as a percent of U.S. arable land, and the factors that affect the CO_2e emissions associated with each feedstock.

As the land area required for corn ethanol in Figure 3 suggests, achieving a 1-gigaton reduction in emissions using current corn ethanol technology would be a staggering undertaking. It would require production of more than 627 billion gallons (2,374 billion liters) on 1 million acres of land, which would be a challenge even on a global scale. Recent improvements in corn ethanol technology, including use of biomass in biorefinery boilers to reduce use of fossil-based fuel in the processing phase, have improved this fuel's carbon numbers, but carbon savings would still have to increase substantially for corn ethanol to compete with other biomass technologies on a global scale. Corn ethanol is, therefore, a transitional technology that will continue to

TECHNOLOGY	1-GT PRODUCTION LEVEL (BIL GAL)	PERCENTAGE U.S. LIQUID FUEL DEMAND	PERCENTAGE GLOBAL LIQUID FUEL DEMAND	PERCENTAGE U.S. ARABLE LAND	CARBON DRIVERS				
					Nitrogen fertilizer input	Transport distance	Indirect land-use effect	Biomass in boilers	Improved yield
Corn[a]	627	460%	35%	107%	↑	↑	↑	↓	↓
Sugarcane[b]	190	139%	11%	67%	↑	↑	↑	↓	↓
Switchgrass (SG)[c]	219	161%	12%	29%	↑	↑	↑	↓	↓
Agricultural Residue (AR)[d]	242	178%	14%	N/A	—	↑	—	↓	↓
Woody Poplar[e]	146	107%	8%	17%	↑	↑	↑		↓
AR with Elec Coproduct[f]	81	59%	5%	N/A	—	↑	—	—	↓
SG with Elec Coproduct[g]	76	56%	4%	10%	—	↑	—	—	↓
Algae (70% oil)[h]	—	100%	8%	2%	—	—	—	—	—
Algae (30% oil)[i]	—	100%	8%	5%	—	—	—	—	↓

EXPLANATION OF CARBON DRIVERS

Description	Explanation
Nitrogen fertilizer input	Nitrogen fertilizer contributes nitrous oxide emissions, which is a potent GHG. Hence, increased fertilizer use increases biofuel's carbon footprint.
Transport distance	The distance that the biomass and the biofuel end product need to be transported before use increases the carbon intensity.
Indirect land use effect	The indirect land-use is a measure of the carbon released when new land is brought into production to compensate for farm land taken out of food production and used for energy crop production.
Biomass in boilers	Biomass, such as corn stover, can be used to power the biorefinery, thereby reducing the use of fossil fuels and lowering the overall carbon footprint.
Improved yield	Improved crop yields and higher ethanol yields (from improved microorganisms and enzymes) lower the biomass, and land, intensity of biofuel production.

FIGURE 3. Comparison of Production Volumes and Land-area Requirements Across Feedstocks The production volumes required to meet the 1-gigaton target and the implied land-use requirements vary significantly among feedstocks. Sources: a. Searchinger, et al. 2008; b. Spatari, 2007; c. Spatari, 2007; d. Spatari, 2007; e. Industry data, 2008; f. Spatari, 2007; g. Spatari, 2007; h. Cristi, 2007 (70% oil [by wt.] in biomass); i. Cristi 2007 (30% oil [by wt.] in biomass).[12]

have some regional importance where appropriate. Detailed regional studies are important to further understand the role that corn ethanol can play. In a recent study, Liska et al. (2009) highlight the low-carbon potential of corn ethanol in certain U.S. regions.[13]

A number of carbon drivers, both positive and negative, are either uncertain at this time or highly case specific. These clearly affect the production levels needed for gigaton scale. Increasing crop and ethanol yields — the latter through new enzymes and microorganisms — can improve the carbon profile across feedstocks. Conversely, increases in transport distances — whether for the feedstock or for the distribution of ethanol — and intensive farming processes (including fertilizer use) detract from the carbon profile of biofuels. The key for Figure 3 describes the carbon drivers.

Electricity as a coproduct of biofuel production at the biorefinery also reduces carbon emissions associated with the fuel. In terms of scale, the lowest production volumes for the 1-gigaton target are obtained in scenarios where switchgrass or agricultural residues used for biofuel production also generate an electricity coproduct that provides additional carbon savings. Based on our assumption of U.S. average grid emissions, the volume of switchgrass ethanol needed to meet the 1-gigaton CO_2e reduction target fell from 219 to 76 billion gallons. The critical assumption is that the additional electricity generated at the cellulosic ethanol biorefinery can be sold back to the electricity grid, supplanting coal or natural-gas-based electricity generation. This requires a readily available grid hook-up. Currently, with only four cellulosic biorefineries under construction in the U.S., the actual infrastructure requirements and potential are unexplored. The use and potential sale of coproduct electricity can also improve the economics of the biorefinery.

Land Use for Different Feedstocks

The social and environmental implications of using larger volumes of biofuels have sparked active debate about land-use priorities, specifically indirect land-use change when new land must be brought into production to grow food because energy crops displace food crops. First-generation biofuels, mainly corn ethanol and soy biodiesel, have reduced CO_2e emissions compared to conventional petroleum according to accounting methods that include CO_2e emissions from direct land-use

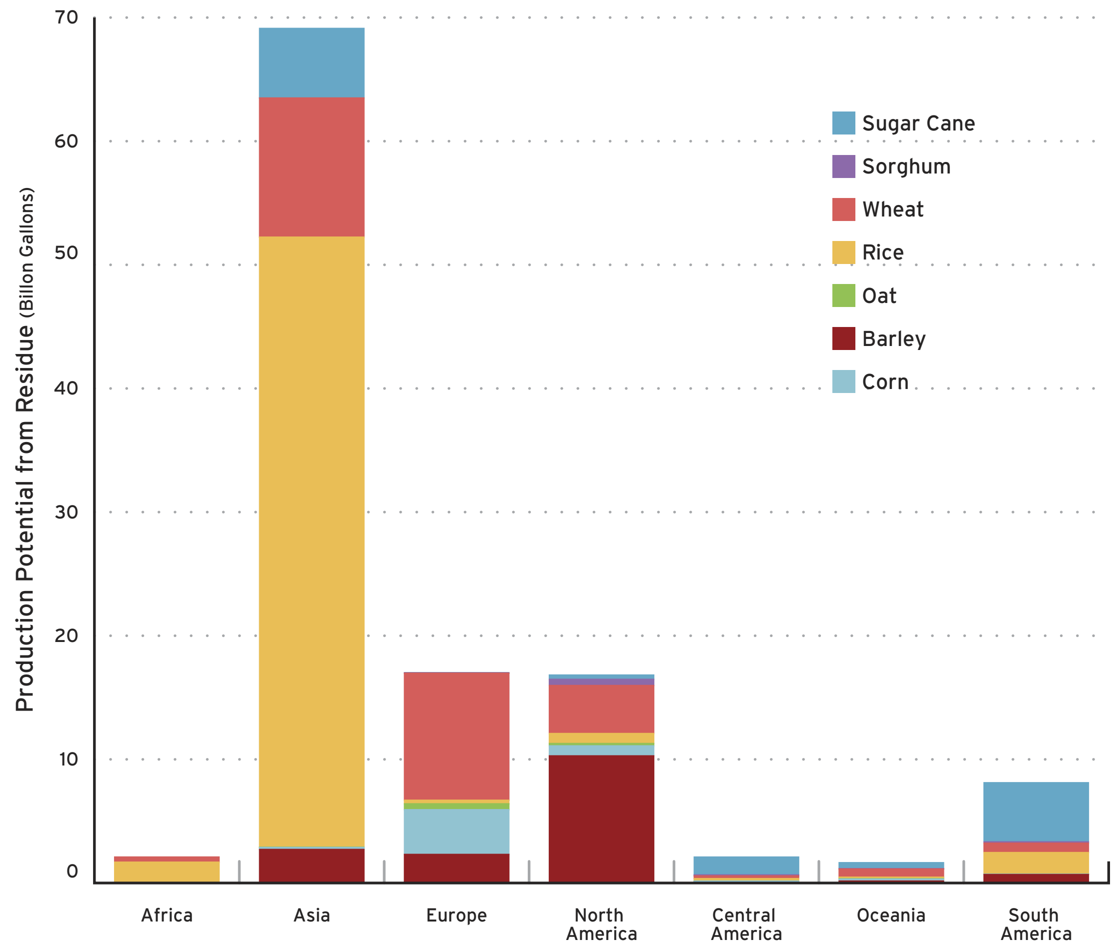

Figure 4. Global Availability of Agricultural Residues. Asia has the largest potential to produce ethanol from residues. The primary feedstock is rice straw, with a total potential to produce 187 billion liters of cellulosic ethanol. In North America, the potential is an estimated 63 billion liters, primarily from corn stover. Large amounts of sugarcane bagasse are already being used in Brazil; this is the primary feedstock available in South America. Source: Kim, S. Dale, B.E., 2004.[17]

conversion, i.e., land-use changes directly related to biofuel production. However, as the biofuel industry expands, food crops may be displaced, and indirect land-use change may become more significant. The land-use debate centers on how large the indirect carbon emissions from this conversion will be and how much these emissions should be attributed to the increase in arable land devoted to bioenergy production.[14] These debates have largely focused on corn ethanol, but they highlight a number of issues related to indirect effects that have yet to be fully resolved for the scale-up of any new technology pathway. Preliminary estimates of indirect effects have been generated for several different types of biofuels, but more work is needed to fully validate the assumptions. Next-generation biofuel technologies that utilize cellulosic and waste products as feedstocks promise significant improvements in both direct and indirect emissions compared to first-generation technologies.

The use of waste products as feedstocks to produce biofuels avoids the land-use issue. Waste products include agricultural residues, such as remnants of the corn plant (stover) and the sugarcane plant (bagasse), and woody residues, as well as MSW. From a carbon standpoint, using waste feedstocks is desir-

Direct and Indirect Land-Use Effects

A paper by Searchinger et al. (2008) stirred up much controversy about corn ethanol by suggesting that its production results in carbon emissions much greater than those from gasoline because of the "indirect land use change" (ILUC) effect.[a] ILUC refers to new land brought into production elsewhere in the world to compensate for lost food or animal feed grain production when land is converted to growing corn for ethanol. The new land brought into production to grow food could be rainforest that is cleared, which releases carbon when burned and also eliminates a major carbon sink, or other land that releases soil carbon when tilled. McKinsey (2009) reports the impact of land clearing on carbon emissions, with emissions from land use, land-use change, and forestry (primarily deforestation) contributed an estimated 7.4 gigatons CO_2e in 2007.[b] The model used by Searchinger et al. has come under criticism, and new calculations suggest that it overestimated the ILUC effect.[c,d] A recent paper by Hertel, et al. (2009) using the Global Trade Analysis Project (GTAP) model found that the land-use impact of 15 billion gallons of North American corn ethanol production was roughly ⅖ of the value estimated by Searchinger et al.[e] The ILUC effect debate is far from resolved. However, in general, bringing new land into agricultural production will result in an initial direct carbon increase and therefore have an associated "payback period" for carbon.[f] deGorter and Tsur (2009) report carbon payback periods of up to 15 years in the U.S. for new land brought into cultivation for crops in the U.S.[g] Kim et al. (2009) found that, with sustainable crop management practices such as no-till and no-till plus cover crop planting in the U.S., the carbon payback period can be reduced to 3 and 14 years for converted grasslands and forests, respectively. Cover crops can also improve water quality by preventing nutrient runoff.[h] Some promising marginal land in Brazil could be used to grow energy crops, for example, with a payback period of less than 4 years.[i] The bottom line is that the indirect effects of technology expansion must be carefully assessed. Biofuels are not alone in this area. Increased demand for transport, electricity, or land because of expansion of any renewable technology — including other transport solutions such as electric vehicles that can increase electricity demand — can have serious unintended consequences. In the case of biofuels, bringing new land into production requires careful assessment and the science of life-cycle emissions analysis requires further development.[j]

(a.) Searchinger, T., et al. 2008. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change." *Science.*

(b.) McKinsey. 2009. *Pathways to a Low Carbon Economy.*

(c.) Birur, D.K., T.W. Hertel, W.E. Tyner. 2008. "Impact of Biofuel Production on World Agricultural Markets: A Computable General Equilibrium Analysis." Department of Agricultural Economics. Purdue University. GTAP Working Paper No. 53.

(d.) Hertel, T.W., Golub, A.A., Jones, A.D., O'Hare, M.O., Plevin, R.J., Kammen, D.M. 2009. 'Global Land Use and Greenhouse Gas Emissions Impacts of Maize Ethanol: The role of Market-Mediated Responses", submitted to *Biosciences.*

(e.) Hertel, T., et al. 2009. "Comprehensive Global Trade Analysis Shows Significant Land Use Change GHG Emissions from U. S. Maize Ethanol Production," in press.

(f.) Fargione, J., et al. 2008. "Land Clearing and the Biofuel Carbon Debt." *Science,* p. 1152747.

(g.) deGorter, H., and Y. Tsur. 2008. "Towards a Genuine Sustainability Standard for Biofuel Production," in *Climate Change in Latin America: Impact and Policy Challenges. World Bank.*

(h.) Kim, H., S. Kim, B. Dale. 2009. "Biofuels, Land Use Change, and Greenhouse Gas Emissions: Some Unexplored Variables." *Environmental Science & Technology.* Vol. 43 No. 3. pp. 961—967.

(i.) deGorter, H., and Tsur, Y. 2008. See reference f.

(j.) Liska, A., R. Perrin. 2009. "Indirect Land Use Emissions in the Life Cycle of Biofuels: Regulations vs. Science." *Biofuels, Bioproducts, and Biorefining.*

able. However, it poses some challenges. The availability of residue supply for certain crops depends on the fraction of the residue that must be returned to the land to replace soil organic carbon and protect against erosion. In the case of corn stover, the recommended fraction returned to the soil can range from 20% to 50% based on estimates of 5 to 8 megagrams per hectare (Mg/ha).[15] The actual amount needed depends upon existing soil conditions, tillage, and management practices. Some argue that little or no residue should be removed from the field for corn because of the depletion of soil organic carbon associated with this crop; this is an important area of ongoing research.[16] Figure 4 presents a regional breakdown of agricultural residue availability; notably, corn crop residue is a small fraction. An estimated 100 billion gallons (390 billion liters) of ethanol could be produced from agricultural residues from corn, barley, wheat, oat, rice, sorghum, and sugarcane crops based on harvesting 40% for feedstock, enough to meet the gigaton CO_2e target.

For energy crops, the land-use requirement is a function of crop energy density. Woody poplar has the highest energy density of the feedstocks listed in Figure 3 and requires the least production land area among the energy crops. In addition, third-generation algae-based biofuels are projected to have much lower land-use requirements than current technologies. Algae-based fuels are some years off, however, and there are significant uncertainties related to cost and production scale for these fuels. Significant advantages of algal production include use of non-arable land for production facilities and use of waste CO_2 as a feedstock.

Regional Biomass Solutions

A single preferred feedstock for biofuel production has not emerged and is unlikely to do so over the next 10 years. Biomass is fundamentally local, and different solutions are appropriate in different regions. This helps explain why sugarcane is favored in Brazil, why pulp and paper mill wood residues provide 25% of Sweden's fuel, and why the U.S. focused initially on corn ethanol.

The appropriate choice of a regional biofuel solution clearly depends not only on feedstock or land availability but also on a number of other factors, including water availability and nearby demand centers. As regionally specific technologies advance, they may have more widespread appeal. In the short term, a portfolio approach to biofuels that supports the dual objectives of low carbon emissions and regional appropriateness could offer major CO_2e savings globally while increasing the chances of technological breakthrough by not prematurely selecting a winner.

Highlighting the regional nature of feedstock selection is not to suggest that one or more feedstocks may not achieve great scale. In particular, the high energy density of woody poplar, the availability of regional waste streams, and the rapid growth of sugarcane in tropical climates all suggest the potential to scale up.

U.S. Biofuel Potential

Achieving gigaton scale with ethanol in the U.S. by 2020 — i.e., 150 billion gallons of cellulosic ethanol (equivalent to 100 billion gallons of gasoline) — would stretch the bounds of possibility. Gasoline demand in the U.S. LDV sector is expected to reach 136 billion gallons by 2020; 150 billion gallons of ethanol would displace 100 billion gallons of this consumption and require conversion of ¾ of the LDV sector to ethanol.[18] This is far more ambitious than the aggressive 90-billion-gallon scale-up recently studied by Sandia Laboratory and found to be feasible for 2030.[19] Under the current Advanced U.S. Biofuels Mandate, the nation would use 36 billion gallons of biofuels (15 corn ethanol; 21 cellulosic ethanol) in 2022, around ⅕ of this amount.

The feasibility of a massive scale-up in a short time hinges on fundamental uncertainties about production and vehicle conversion.

The Brazilian Experience: Sugarcane Ethanol

Brazil supplies ethanol to more than 40% of its gasoline market and is the second-largest producer of ethanol worldwide. Significant carbon reductions are achieved from sugarcane ethanol, compared to corn or sugar beet ethanol, because of both the dramatic increase in sugarcane crop yields over the past 25 years and the use of sugarcane bagasse (burned to generate electricity) to power biorefineries.[a] The price of ethanol has come down over time and is now lower than gasoline, with these low prices driving widespread adoption. The Brazilian success story owes in large part to carefully crafted government policies that initially provided loans to sugarcane growers and ethanol producers and, simultaneously, regulated ethanol prices to ensure competitiveness with gasoline.

a. Wang, M. 2006. "Learning from the Brazilian Biofuel Experience." *Environmental Research Letters*.

There is technical uncertainty about cellulosic biorefinery operation. With just four pilot facilities in the construction phase in the U.S., the actual production costs and outputs are still unknown. There is also uncertainty about yields of crops grown on marginal lands and hence the total land needed for energy crops. Of the 150 billion gallons needed to reach gigaton scale, approximately 15 billion gallons could come from agricultural residues. Scaling up further would require reliance on energy crops such as switchgrass. This would in turn require careful assessment of the CO_2e impacts of bringing new land into production, even assuming the land used is marginal rather than prime agricultural land.

Finally, a very rapid scale-up would entail converting vehicles to be biofuel compatible. The number of conversions required to support a gigaton reduction depends on the pathway taken and the total number of gallons needed to meet the emissions reduction target. The vehicle-conversion assumption, in turn, has a significant impact on the estimated deployment costs to reach gigaton scale. On the low end, which assumes residues and purpose-grown crops are harnessed to produce ethanol in conjunction with electricity coproducts, 116 million flexible-fuel vehicles (FFVs) would be required. If flex-fuel capability were required of all new vehicles starting in 2012 at a cost of $70 per vehicle, 128 million new flex-fuel vehicles would be produced by 2020, and the total cost would be approximately $10 billion spread over 10 years. On the higher end, if less-efficient pathways were utilized, the number of FFVs required could be as high as 152 million, in which case the mandate would need to begin in 2010 or be augmented by after-market conversion of existing vehicles, which costs $1,300 per vehicle. To meet the lower 116-million-vehicle target using entirely the more expensive after-market conversions would increase total costs to nearly $200 billion. In either case, early action would ensure a range of options, significantly lower deployment costs, and encourage investment in next-generation solutions.

Scaling the Industry

Figure 5 illustrates the expansion pathway for the 150 billion gallon expansion scenario for cellulosic ethanol. The amount of ethanol required when the coproduction of electricity to offset CO_2e emissions is taken into account it significantly lower. The ranges of production for the gigaton target can go as high as 420 billion gallons, depending on the feedstock and the production technology. The requirements for this expansion are between 1 and 6 billion dry metric tons (tons) of biomass per year. The high estimate exceeds available supplies of agricultural residue biomass feedstock.[30] However, these production levels could be met using purpose-grown energy crops.

Capital Investment

Of the nine gigaton pathways analyzed in this report, biofuel scale-up, including infrastructure costs, is the third-least-capital-intensive option, after building efficiency and construction materials. Direct investment to scale up biofuel production would be needed in five key areas: 1) biorefineries, 2) regional distribution facilities (which collect, store, and ship ethanol), 3) transport infrastructure, 4) gas-station conversion, and 5) vehicle fleet conversion to flex fuel. Direct investment in biorefineries for a global 150-billion-gallon scenario is approximately $300 billion. Additional capital investment in distribution facilities, transport, and gas-station and vehicle conversions

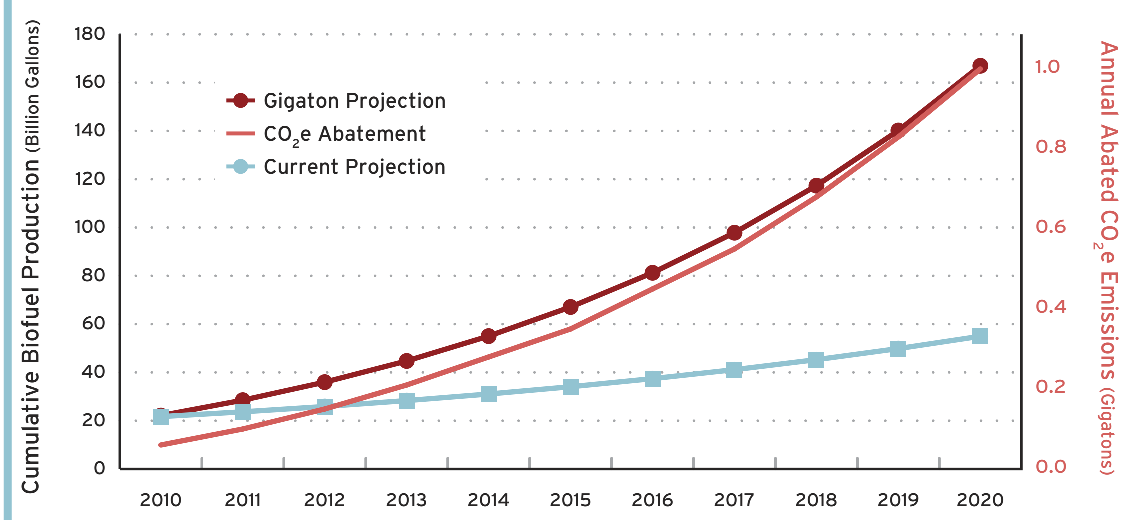

FIGURE 5. Required Growth in Biofuel Production to Achieve the Gigaton Target. A cumulative expansion in annual production capacity of 150 billion gallons is needed to achieve the gigaton target. Source of current projection: U.S. Office of Science and Policy, 2009.[31]

INFRASTRUCTURE	ESTIMATED INVESTMENT	EXPLANATION
Biorefineries	$307 billion	Approximately 2,143 biorefineries need to be built, assuming a 70-million-gallon annual capacity. NREL[a] specifies an average cost of $143.3 million per biorefinery.[20]
Regional Distribution Facilities (collection, storing, and shipping)	$12 billon	Estimate is based on new regional distribution facility in Manly IA, currently in first phase of development; cost of the project is an estimated $80 million.[21] When complete, the facility will have 20 million gallons in storage on site, 12 miles of rail, and could handle up to 1 billion gallons.[22,23] 150 facilities of this scale would be required. More likely, consolidation will take place, and there will be fewer, larger, facilities.
Transport Infrastructure (Rail)	$37.8 billion	USDA[b] estimates that the freight requirements for a 20-billion-gallon-a-year corn ethanol scenario are 400,000 carloads per year for ethanol, and 89,000 carloads for dry distiller grain and solubles, a coproduct from corn ethanol.[24] Based on these data, the 150-billion-gallon scenario would require more than 3.7 million carloads. The estimated rail expansion investment cost per carload is $10,000, based on AAR[c] data.[25]
Gas-Station Conversion	$7.3 billion	Estimate is based on the cost of converting all approximately 120,000 U.S. gas stations.[26] The median cost of a new tank for ethanol distribution at the pump is $60,000.[27]
After-market Vehicle Conversion	$351 billion	Current costs for after-market conversions are estimated at approximately $1,300 per vehicle.[28] The 150-billion-gallon ethanol scenario is ¾ of the U.S. fuel consumption in the LDV sector. A ¾ conversion of the U.S. vehicle fleet would be 270 million of 360 million vehicles.
New Vehicle Conversion	$18.9 billion	Converting new vehicles at the factory is much less expensive than performing after-market conversions. Estimated at-factory cost is approximately $70 per car.[29] An estimated 270 million vehicles would need to be converted.
TOTAL*	$383.10 billion	
* Based on only new vehicle conversions		a National Renewable Energy Laboratory b United States Department of Agriculture c Association of American Railroads

FIGURE 6. Infrastructure Investment to Support the 150-billion-gallon Ethanol Scenario.

totals an estimated $83 billion, assuming that vehicles are converted to ethanol-compatability at the factory. Costly after-market conversions of vehicles could add more than $200 billion to this price tag. Figure 6 shows the breakdown of direct capital investment by category for a 150-billion-gallon worldwide production scenario. Numbers are based on U.S. estimates and may differ significantly from country to country.

The estimated capital investment in delivery infrastructure includes investment in production of flex-fuel vehicles and is highly sensitive to the rate of new-vehicle versus after-market conversions. The total investment for conversions of 270 million new vehicles to support the 150-billion-gallon scenario is close to $20 billion. The investment for the same number of after-market conversions is more than $350 billion (see Figure 6). Because of the low cost of converting new vehicles ($70 per vehicle), new vehicle flex-fuel requirements would be the most economic strategy for ensuring flexible fuel options and driving private investment in infrastructure to support more widespread deployment of biofuels.

CAPITAL INVESTMENT IN NEW PLANTS

National Renewable Energy Laboratory (NREL) estimates the up-front capital investment per new biorefinery capacity to be approximately $143 million (based on an average plant capacity of 70 million gallons annually).[32] Estimates for the cost of scaling ethanol production from agricultural residues to achieve 1 gigaton CO_2e reduction are based on this NREL cost data. Figure 7 shows the capital costs for scaling lignocellulosic ethanol, but costs are expected to be comparable for other near-term biorefinery technologies, excluding

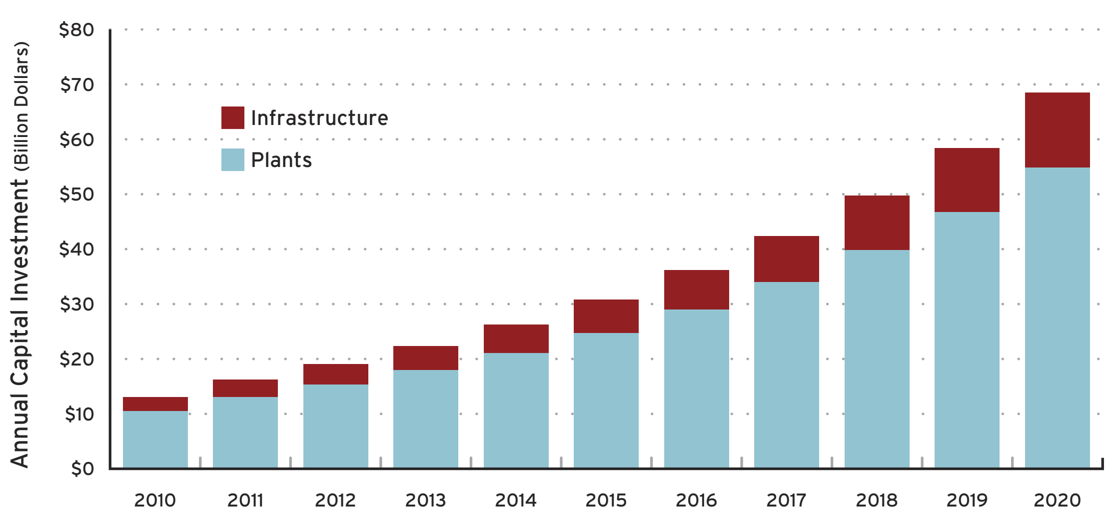

FIGURE 7. Annual Capital Investment in Biofuels Production. Investment in plants and infrastructure for gigaton scale totals $383 billion over 10 years.

consolidated bioprocessing (CBP); however, there are no actual industrial data, so this assumption remains uncertain. With electricity credits taken into account, expansion to 70 billion gallons of production by 2020 requires an estimated investment of $114 billion. Without coproduced electricity credits, the investment required for gigaton-scale biofuel production ranges from $143 billion to $458 billion dollars over a 10-year period.

CAPITAL INVESTMENT IN DELIVERY INFRASTRUCTURE

Cost estimates for delivered ethanol range from $0.29 to $0.62 per liter (l), depending on distance and transportation.[33] Transportation costs can double the delivered cost of fuel. The cost of delivering ethanol is currently an order of magnitude higher than the cost of delivering gasoline: approximately $0.02/l compared to gasoline at $0.003/l.[34] Pipeline distribution for ethanol could significantly lower this cost but requires large capital investment, estimated at between $200,000 and $500,000 per kilometer (km).[35] In some cases existing pipelines can be repurposed for ethanol distribution. In light of the high cost of transit and the associated carbon footprint, regionally based fuel strategies have been advocated for the U.S. to avoid long-distance transport of ethanol.[36]

For the 150-billion-gallon gigaton scenario, the total estimated investment in rail infrastructure would be $37.8 billion over 10 years. The total estimated investment in regional transport facilities would be on the order of $12 billion (see Figure 6).

CAPITAL INVESTMENT IN FLEX-FUEL VEHICLES

To support scale-up of ethanol production to the levels required to achieve 1 gigaton of avoided emissions in 2020, the vehicle fleet must support ethanol consumption. U.S. sales of FFVs rose by 20% between 2004 and 2007, and there are now approximately 7 million FFVs in the U.S.[37] As noted earlier, investment costs required for a scale-up vary significantly based on assumptions about the rate of new versus after-market conversions. If every new vehicle sold in the U.S. were converted starting in 2010, the total cost would be approximately $20 billion. If new FFV deployment continued at the current rate and the remaining demand was met via after-market conversions then the cost would escalate to close to $350 billion. This makes the case for early action and standards to ensure compatability, rather than relying on aftermarket conversions.

CAPITAL INVESTMENT IN THE BIOFUEL SUPPLY CHAIN

The entire biofuel supply chain would have to ramp up to support ethanol production expansion. If agricultural residues were used, feedstock delivery but not cultivation would have to ramp up. Feedstock costs can contribute between 25% and 50% of the total cost of production, depending on transport distances. The bulk of remaining costs are concentrated in the biorefining phase and include the cost of pre-treatment chemicals, enzymes, nutrients, and wastewater treatment for biochemical plants. For cellulosic biofuels, feedstock cultivation will have to increase. Industries supplying key inputs to ethanol conversion (pre-treated chemicals, enzymes, nutrients) will need to keep pace with new plant construction. Figure 8 shows cost concentrations in a biorefinery operation.

ELECTRICITY GENERATION

Production of 1 gallon of biofuel results in the coproduction of approximately 2.28 kWh electricity, 1.42 kWh of which is used for plant operations.[39] The remaining electricity can be sold to the grid. For the quantity of biofuel

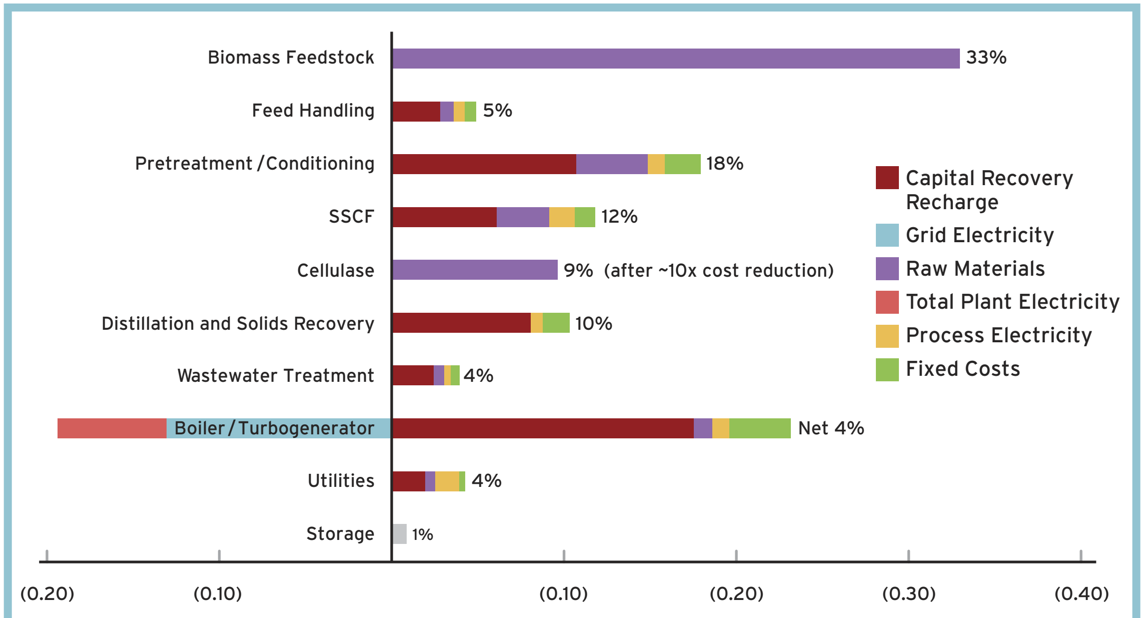

FIGURE 8. Cost Concentration for Biorefinery Operation. The feedstock accounts for 33% of the total cost. Source: Dale, 2008.[38]

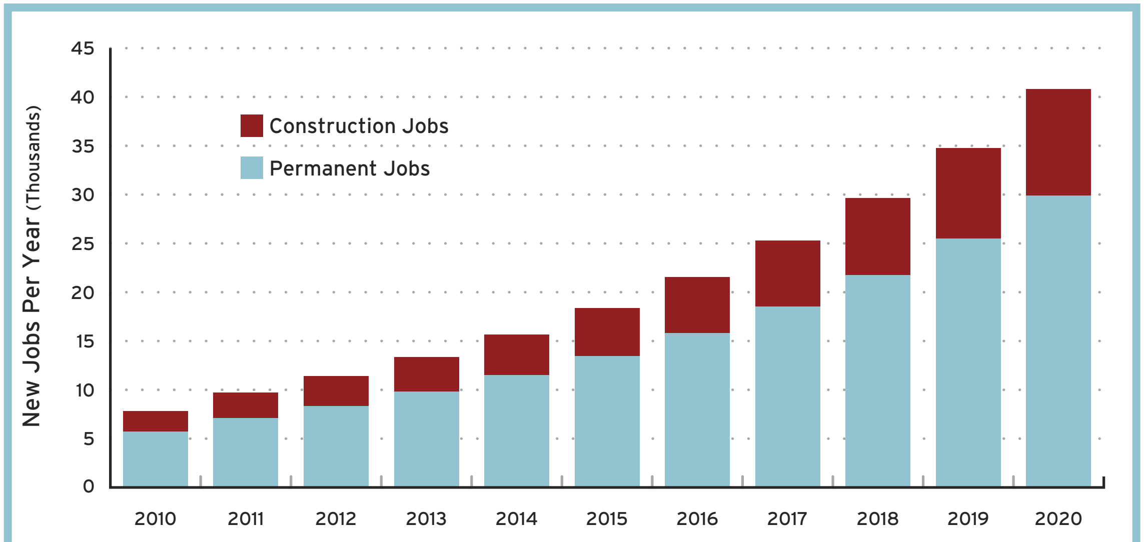

FIGURE 9. Jobs Created at Biofuel Production Facilities. More than 150,000 permanent new jobs would be created at biofuel production facilities over the 10-year gigaton expansion period. An additional 50,000 construction jobs would be generated, and jobs would also be added in distribution (freight and facilities operations) and trucking. Source of jobs data: Aden, et al., 2002.[40]

produced under the two scenarios — with and without electricity coproduction credits — revenues are between $19 and $27 billion dollars with electricity coproduction credits and between $69 and $91 billion dollars without electricity coproduction credits, where ethanol production is higher.

Jobs in the Biofuel Industry

A typical biofuel plant has roughly 5 managerial positions and approximately 70 employees ranging from shift operators to clerks, all of whom require minimal training. Thus, this pathway would require minimal investment in educational and training programs yet would provide an estimated 150,000 direct permanent jobs over the 10-year gigaton expansion period, as shown in Figure 9. An additional 50,000 construction jobs would be created.

Challenges to Accelerated Deployment

Deployment of pilot plants is critical for second-generation biofuels technologies to be able to scale over the next 10 years. There are currently four mid-size (>40 million liters a year) cellulosic ethanol plants under construction in the U.S. The construction of a large number of biorefineries would pose siting and distribution logistics challenges that may be best approached as an integrated task to ensure optimization of the distribution infrastructure. Other challenges to scaling are infrastructure expansion, including the FFV fleet and pipeline capacity, and up-front capital costs. Use of certain feedstocks can pose logistic challenges, and price fluctuations across feedstocks can disrupt local production.

COLLECTION, TRANSPORT, AND USE OF AGRICULTURAL RESIDUES AND WOODY RESIDUES

The use of agricultural resides as ethanol feedstock, which is desirable from a carbon standpoint, poses two challenges: collection and transport of raw materials.

Contracts must be established between biorefineries and existing farmers for residue collection. Competing uses for agricultural residues include animal bedding, hay, animal feed (silage), direct electricity production through incineration, conversion to pellets for use in district heating, electricity generation, and biomaterials, e.g. alternatives to plastics. This competition creates uncertainty about the actual availability and supply of residues and can slow down operations. It can also raise the price of agricultural residues, which could render a biorefinery uneconomic. All told, the issues related to collection of agricultural residues are an additional encumbrance to biorefinery owners and operators that may prevent expansion of residue use. This considerable risk could be addressed through vertical integration of the supply chain or long-run contracts.

Transport of residues is the second challenge. The use of agricultural residues is currently economically less attractive than the direct use of energy crops because collecting residues involves increased transportation distances. Agricultural residues are available in lower volumes per hectare than energy crops such as switchgrass because, as mentioned earlier, some portion of residues must be returned to the land. This means residues entail a larger collection area than purpose-grown crops, which increases the transportation distance and thus the total cost. The industry may resist policies mandating agricultural residue use because of the implied cost increase. Reducing the cost of agricultural residue transportation through efficiency gains in the trucking fleet or rail transport would help alleviate this opposition.

SUSTAINABLE BIOMASS

Producing biomass sustainably is a major challenge to accelerating the use of biofuels. Major issues with increased land use for biomass production include habitat loss, soil degradation and erosion, pollution from increased agricultural activity, and increased water use. As has been pointed out in the literature, shifting to low-carbon fuels without assessing water use among the impacts could create more problems than solutions.[41]

DISTRIBUTION INFRASTRUCTURE

Pipelines or new rail infrastructure will likely be needed to support ethanol distribution in the U.S. and other parts of the world. For an aggressive expansion to 150 billion gallons of ethanol, additional rail infrastructure would be required to support distribution. A related issue is the location of new ethanol biorefineries. Ideally, plant location and infrastructure planning would occur concomitantly, so refineries could be located near feedstock supply areas. Pipelines are likely to be constructed and operated by private firms if there are policy signals that ethanol demand will be stable over the long term.

VEHICLE FLEET

Historical production of FFVs in the U.S. has been mandated by the federal government. Similar policies in Brazil have ensured that there are vehicles compatible with ethanol to absorb production volumes. A large-scale expansion of ethanol production will require coordination with car manufacturers to expand the FFV fleet. Sales of LDVs in the U.S. were 16.1 million in 2007. It is unlikely that FFV deployment can be accomplished through pure consumer choice given the chicken-and-egg relationship between vehicle deployment and the need for sufficient density of vehicles to support private investment in fueling infrastructure. As noted previously, new vehicle flex-fuel requirements would be the most economic strategy for driving private investment in infrastructure to support more widespread deployment of biofuels. An additional challenge for scaling up ethanol is addressing consumer concern about the decreased mileage from ethanol in comparison to gasoline and the associated inconveniences, such as more frequent need to refuel.

RISING COMMODITY COSTS

The biofuel industry is exposed to commodity price fluctuation. In the plant construction phase, increases in the price of steel and steel-based equipment could add significantly to total plant cost. The increasing cost of crop inputs, including fertilizer, energy, and water, could decrease production and increase the price of feedstocks. Transportation of feedstocks and the ultimate end product (ethanol) is sensitive to oil prices. Some of this risk can be hedged on the commodity exchange. To mitigate the risks associated with large-scale expansion of the industry, vertically integrated biorefineries, with control over feedstocks, or long-term contracting options may be necessary.

BIOMASS AVAILABILITY AND LAND USE

Scaling the production of lignocellulosic biofuels in the U.S. to the levels called for in EISA requires technology advancement to increase conversion efficiencies, increase crop yields, and explore the potential of no- or low-land-use alternatives such as algal biofuels. With crop yield increases and the identification of land with low payback times, dedicated energy crops could be used. The expansion of dedicated energy crops poses a number of challenges that must be addressed in order to sustainably harvest feedstocks:

- Access to water
- Energy used in production and harvesting
- Design of plants to coproduce electricity and interconnect to the grid

Technology Innovation

Although bioalcohol (ethanol) production is essentially a variant of age-old brewery operations and has been practiced for decades, renewed interest and investment in biofuel technology is leading to rapid advances.

Game Changers

Several technological advances could change prospects for a biofuel economy. If agricultural and forest residues and MSW were used as feedstocks instead of purpose-grown crops, indirect land-use carbon emissions would be minimized. Different feedstock sources will likely require different fuel-conversion technologies. For example, softwood residues will most likely require thermochemical technologies because of complications with bioconversion and softwood lignin. Growing energy crops on marginal land could also avoid indirect land-use carbon emissions and might also conserve direct soil carbon emissions thanks to the deep-rooted structure of certain energy crops (e.g., switchgrass). We identify below several options for exceeding what is currently feasible for increasing the sustainable supply of biomass feedstocks as well as converting feedstocks.

NEW MORE PRODUCTIVE CROP HYBRIDS WITH HIGHER YIELDS AND HIGHER SUGAR/PROTEIN CONTENT

Improving crop yields on marginal land would decrease land requirements. Currently, for example, the yield of herbaceous crops such as switchgrass on marginal land is uncertain. In addition, developing crops with higher cellulose, hemicellulose, and lignin content (and therefore lower fractions of ash, acetate, and proteins) would increase ethanol yields as well as electricity coproduction. In general, increasing the density of biomass energy content is a key area for research.

IMPROVEMENTS IN BIOCONVERSION TECHNOLOGY

Today's projection of the enzyme performance needed for a cost-effective and low-carbon bioconversion process requires that enzyme-specific conversion activity be improved.[42] Developing enzyme cocktails at low cost with high specific activity to reduce loading requirements is a critical need for improving ethanol bioconversion costs. Because bioconversion of cellulose to ethanol is only now moving beyond laboratory and pilot projects to demonstration scale, experience gained over the next few years will be critical to move the technology to a mature industry. All major processes, including pre-treatment, hydrolysis, and fermentation, will need to develop and improve at industrial scale.

NEW BIOREFINERY MODELS

Bruce Dale at Michigan State University has proposed new biorefinery models that address the need to provide both fuel and animal feed on existing agricultural land, which is important for the U.S. where nearly 90% of agricultural land is used to produce animal feed.[43] This new biorefinery model projects a shift in cropping practices to incorporate grass cover crops in rotation with corn, wheat, rye, and oats, and the development of pretreatment enzymes to break down cellulose and hemicellulose in these grasses for combined fuel and feed production. Animal feed from switchgrass energy crops can be produced by separating the proteins in the feedstock. Feedstocks harvested in spring can have between 10% to 15% protein. The economics of this combined fuel/feed biorefinery model are favorable compared to a biorefinery only producing fuel.

VALUABLE COPRODUCTS

As biorefineries evolve and mature, continued research will be important for developing bio-based materials and chemicals from the lignin or the sugars generated from biomass feedstocks. As noted above, animal feed production is one valuable coproduct also important for the minimization of land use. Chemical products (from lignin) are also being researched and are recognized as important and valuable coproducts that would make the industry more attractive to investors.

SUSTAINABLE AGRICULTURAL BIOMASS PRODUCTION

Planting mixed native prairie grasses as a feedstock crop is one approach to sustainability, preserving biodiversity, reducing agrochemical runoff, and reducing GHG emissions from the life cycle of fuel products.[44] Lower yields than from other energy crops might make this option less attractive to farmers. Other ways of reducing GHG emissions from the biofuel production chain could involve using bioenergy all along the value chain: e.g., biofuels for farm operations and transport to ethanol conversion facilities.

USE OF FOREST AND MILL RESIDUES

As noted earlier, using feedstocks such as forest and mill residues avoids indirect land-use effects. A wider array of fuel conversion technologies, including bioconversion as well as thermochemical (e.g., Fischer-Tropsh synthesis) conversion would likely be necessary for converting woody biomass to fuel. Bioconversion can be used with hardwoods and feedstocks from dedicated crops such as hybrid poplar, but a thermochemical conversion process would likely be required for softwood residues, which are abundant in western Canada and the U.S. Thermochemical conversion technologies also open up the potential to synthesize a wider variety of fuels.

THIRD-GENERATION TECHNOLOGIES

Future biofuel technologies such as those using algae can improve bioenergy production with low or no substantial land-use requirements and likely without indirect land-use effects because these technologies do not need prime land for production. Algae-based fuels can also be produced with non-freshwater sources. Considerable scientific and engineering research, development, and deployment is needed prior to commercial- scale development. Figure 10 shows the status, GHG emissions, coproducts, and land requirements of second- and third-generation biofuel technologies.

TECHNOLOGY PLATFORM	FEEDSTOCK	TECHNOLOGY READINESS	GHG EMISSIONS	CO-PRODUCTS	LAND REQUIREMENTS
2ND-GENERATION:					
Bioconversion	Herbaceous crops, ag. residues, hardwood	Pilot phase: large-scale deployment	Low if sourced from feedstocks grown on marginal land and lignocellulosic waste	Electricity; animal feed; specialty chemicals	Medium-high
Thermochemical conversion	Forest and mill residues (softwoods and hardwoods)	Pilot phase: small-scale deployment			
Pyrolysis	Wastes (e.g., MSW)	Developing: small-scale		Biochar	
3RD-GENERATION:					
Algae technologies		In the lab	Very low		Very low

FIGURE 10. Fuel Option Matrix. Second and third generation technologies are still in pilot phase.

Public Policy

Stable multi-decade policy to ensure the competitiveness of ethanol with refined gasoline would support rapid industry expansion and attract private investment. This would be particularly challenging at a global level. Other important policy measures include standardizing the life-cycle analysis for biofuels, tying regulations to a standardized life-cycle analysis (LCA) to ensure carbon compliance, supporting the use of agricultural residues or sustainable energy crops, and investing in research and development (R&D) and infrastructure.

STABLE ENERGY PRICES

Ethanol is cost competitive at oil prices of between $70 and $120 per barrel, based on the following assumptions: 1) average conversion yield of 95 gallons per dry metric ton of biomass, 2) average conversion-plant capital expenditure of $3.50 per installed gallon of nameplate capacity, and 3) average farm-gate feedstock cost of $40 per dry ton.[45] Emerging technologies already promise significantly higher yields and lower capital expenditure requirements than conservatively assumed here and will likely make next-generation biofuels cost competitive at lower prices per barrel of oil. However, a carbon tax on oil or a floor on oil prices would help ensure biofuels' competitiveness and spur additional investment in next-generation technologies.

INVESTMENT IN R&D AND PILOT FACILITIES

Government support for R&D in a number of areas can help advance biofuels. Lynd et al. (2009) detail a number of areas for advancement to achieve cost-competitive mature technologies, focusing on process developments and laboratory work to enhance protein coproduct production and enzyme function.[46] Government investment in R&D in crops and algae biofuels is particularly important because of the long deployment times associated with these advances; long deployment times can dissuade private R&D investment. In addition to basic R&D funding, government funding for pilot facilities can accelerate deployment.

INVESTMENT IN INFRASTRUCTURE

Investment in rail, and possibly road, transport may be necessary to support ethanol distribution in the U.S. and globally. Incentives for car manufacturers and purchasers may also be needed to increase FFV production. Public policy has a potential role to play here in supporting regional fuel solutions to ensure that ethanol capability and distribution are developed where most economical.

STANDARDIZED LIFE-CYCLE ANALYSIS METHODOLOGY

During the past two years, the U.S., Canada, and many European countries have been developing renewable or low-carbon fuels policies.[47] One of the biggest challenges in implementing a low-carbon or renewable fuel policy is developing a robust verification system that can account for GHG emissions from both the biofuel supply chain and indirect (often referred to as "market-induced") effects of production. The large uncertainties and difficult-to-measure parameters related to CO_2e emissions from land-use change make developing plausible GHG intensity factors for different biofuel production pathways particularly challenging.

The ISO 14000 series is an existing international standard for LCA for biofuels. LCA tracks material and energy inputs and outputs. However, in general, using LCA approaches for technologies that have large-scale land impacts is challenging, and further research is needed in this area. Liska and Cassman (2008) draw attention to the need for a policy initiative related to life-cycle GHG accounting for biofuels: "There is a critical need for standardized life-cycle methods, metrics, and tools to evaluate biofuel systems based on performance of feedstock production and biofuel conversion at regional or national scales, as well as for estimating the net GHG mitigation of an individual biofuel production system to accommodate impending GHG-intensity regulations and GHG emissions trading."[48]

REGULATIONS BASED ON LIFE CYCLE

Policies to support carbon reductions in the transportation sector should be tied to comprehensive standardized life cycle-based methods like California's low-carbon fuel standard. There are also national standards, including EISA requirements for a 20% reduction in CO_2e for corn ethanol and a 60% CO_2e reduction for cellulosic ethanol over conventional gasoline. These two approaches need to be reconciled to ensure the development of the lowest-carbon solutions, whether that is feedstocks that actively sequester carbon or solutions that avoid arable land use altogether, such as algal biofuels or electric vehicle pathways. Of course the cost and timing of these pathways must also be taken into consideration. Globally, policies to identify promising areas for energy crop production, such as the Brazilian arid land identified by deGorter and Tsur (2009), are also needed.[49]

PROTECTION OF BIODIVERSITY

Ecologists have expressed concern about the expansion of the biofuel industry in the direction of monoculture cropping. In response to this concern, low-input, high-diversity mixed native grasses have been suggested as possible energy crops that would preserve biodiversity and avoid displacing food production because they can be grown on marginal land.[50] This option remains important for research on sustainable bio-feedstocks and cultivation practices. Growth of corn for corn ethanol competes with food for arable land and thus affects food prices; the expansion of corn-based ethanol production also induces indirect carbon emissions from land-use change and poses ecological problems including contribution to hypoxic zones in aquatic environments resulting from agrochemical runoff and farming of water-thirsty crops in water-scarce regions.[51]

Interactions with Other Gigaton Pathways

Transportation sector CO_2e emissions reductions could come from a number of technologies. Plug-in hybrid electric vehicles can reduce the demand for liquid fuels and, in areas where the grid is powered by renewables, can approach zero-carbon standards. Other strategies include improving fuel economy standards in the LDV and truck as well as heavy trucking sectors and reducing vehicle miles travelled (VMT). The recent increase in corporate average fuel economy (CAFE) standards recently passed by the U.S. Congress improves fuel economy in vehicles. However, it does not address VMT. Increases in gasoline prices, either through direct taxation or a carbon price, could reduce VMT. Implementing a carbon tax could encourage drivers to rely more heavily on public transit. In general, VMT can be reduced through better urban transportation design and a reinvestment in urban transportation and planning infrastructure.

The expansion of renewable electricity sources can improve the carbon profile of biofuels that rely on external electricity sources for heat for fermentation and distillation. This is the case for corn ethanol but not for cellulosic, which typically generates electricity for use in the refinery and for sale to the grid. In places where the grid is powered by renewables, there is no carbon credit available for biofuels that supply additional electricity. This would diminish the carbon savings from biofuels.

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Building Efficiency

MAIN POINTS

- Building efficiency can achieve gigaton scale by 2020 for an investment of $61 billion, creating 681 thousand direct new jobs, and enhancing energy security by reducing energy consumption.
- Building efficiency is the lowest-cost pathway (of the 9 in this report) to achieve 1-gigaton CO_2e reduction by 2020.
- New energy-efficient building designs show little to no up-front cost and more than 30% energy savings.
- Developers and homeowners both lack incentives and information to implement building efficiency.
- Multiple gigatons of CO_2e could be avoided with current building efficiency technology.

Overview

Our buildings are energy hogs. A typical residence uses up to 40% more energy than it needs to operate economically. Commercial and industrial buildings also consume much more energy than they need to provide equivalent levels of comfort and functionality. A collection of recent design examples of cost-saving retrofits proves that this is profligacy.[1] Retrofits of existing buildings and new building design can unlock massive energy and cost savings while reducing carbon dioxide equivalent (CO_2e) emissions.

New buildings can be designed to use ⅓ to ½ less energy than they use today, with little to no increase in the cost of construction.[2] Design examples include residences featured in the U.S. Green Buildings Council Leadership in Energy and Environmental Design (LEED) 2008 annual report.[3] There are also recent examples of “net-zero” energy use in new construction. Net-zero buildings pair energy-efficient design with distributed on-site generation, such as photovoltaic panels to reduce energy use — and utility bills — to zero. The additional cost of energy-efficient design and construction is small and continues to fall. Payback periods are generally less than 2 years. The lifetime energy savings can range from thousands to tens of thousands of dollars.

It is well understood that building efficiency is the low-hanging fruit in terms of dollar-per-ton of carbon reductions. The 2007 McKinsey study showed that carbon reductions through building efficiency measures actually saved money and did not cost money, thanks to energy savings.[4] A compelling finding of this study is that the investment required to achieve gigaton-scale energy provision and carbon reduction through building efficiency is a fraction of the investment required for new electricity generation. *The investment for gigaton-scale building efficiency is less than 1/10 the investment in any new generation pathway examined.* A kilowatt-hour saved is equivalent to a kilowatt-hour generated in terms of energy demand.

It is also increasingly understood that the savings opportunity in the building sector is immense. More than 25% of the total global CO_2e emissions projected in 2009 — an estimated 9.3 gigatons — will come from the building sector. Building-sector emissions have grown at approximately 2% a year during the past 30 years and at this rate are projected to reach more than 11 gigatons of CO_2e by 2020.[5] It is debatable exactly what fraction of emissions can be reduced cost effectively, but, based on estimates suggesting energy use could be halved economically, the savings could be upwards of 5 to 6 gigatons annually by 2020. Figure 1 shows that a 10% cut in total projected building energy use globally during the next 10 years would meet the gigaton goal.

Despite the potential to reduce energy use, cut energy-related costs, and deliver CO_2e savings, the efficiency industry hasn't taken hold. Less than 5% of homes in the U.S. have undergone an energy-efficiency retrofit. There are a number of explanations. An unwillingness to pay up-front investments in efficiency, the disaggregated benefits of energy efficiency, mismatched incentives, and a lack of consumer awareness all thwart adoption of efficiency technologies. Achieving gigaton-scale energy savings in buildings will require policy action, leadership in the building sector, and public awareness. Together these actions can shift incentives and deliver the energy and carbon savings currently locked up in this sector.

The biggest area for policy action is establishing new building codes for both new construction and resale. Comprehensive new efficiency standards are needed for this sector to deliver major carbon reductions. Even with major action in the private sector, adoption will likely be too slow to make a difference by 2020 without new codes. There is a compelling argument for immediate action in the new construction sector: failure to implement new standards for new construction locks society into wasteful energy use for decades to come. Asia is a key market for new construction standards, with more than half of new construction globally set to take place there in the next 10 years.

The first section of this chapter outlines four strategies for reducing energy use through new standards in the global building sector. Each strategy can deliver 1 gigaton of CO_2e reductions in the next 10 years. Each of the four strategies has large economic benefits related to both energy savings and the creation of several million jobs in the next 2 to 3 years. The retrofit of existing buildings and the construction and design of energy-efficient buildings are two labor-intensive processes. An estimated 1 million jobs would be added per year for construction workers, retrofitters, and other trained building professionals if the U.S. were to roll out a major efficiency program aimed at achieving gigaton scale in the building sector (Figure 2).

The second part of this chapter shifts focus to specific technologies and their potential to deliver gigaton-scale carbon reductions. Three building technologies are highlighted that can achieve major reductions of CO_2e: lighting, insulation, and windows. These three technologies fall into the category of negative cost.[6] That is, over the product lifetime, the (discounted) cost savings from energy reduction will exceed the up-front investment. The

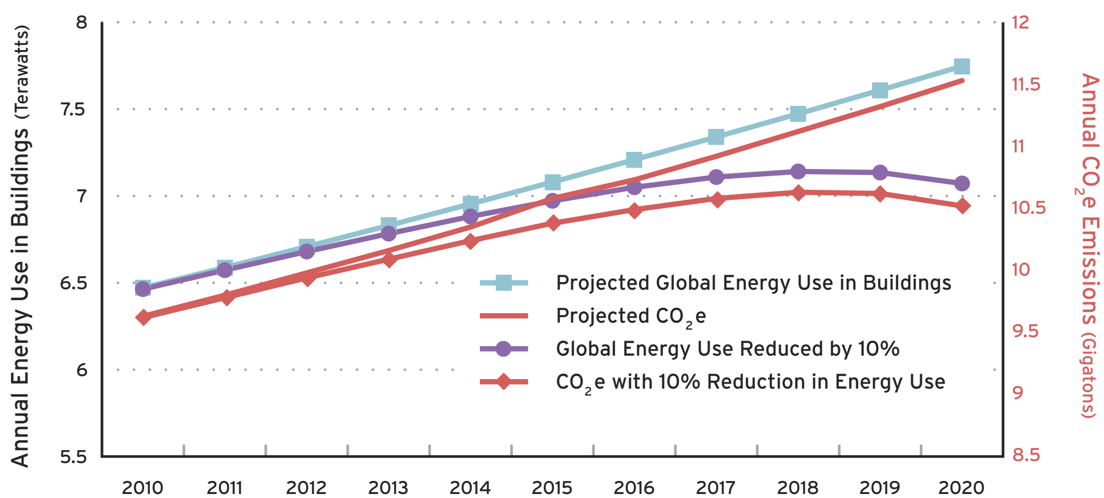

FIGURE 1. Impact of 10% Efficiency Gain on Energy Use and CO_2e Emissions in the Global Built Environment, 2010 to 2020. Building emissions will total an estimated 9.3 gigatons of CO_2e in 2009. Emissions in the building sector are projected to be growing by close to 2% annually. A cumulative 10% efficiency gain over the next 10 years would deliver 1 gigaton of CO_2e savings in 2020.

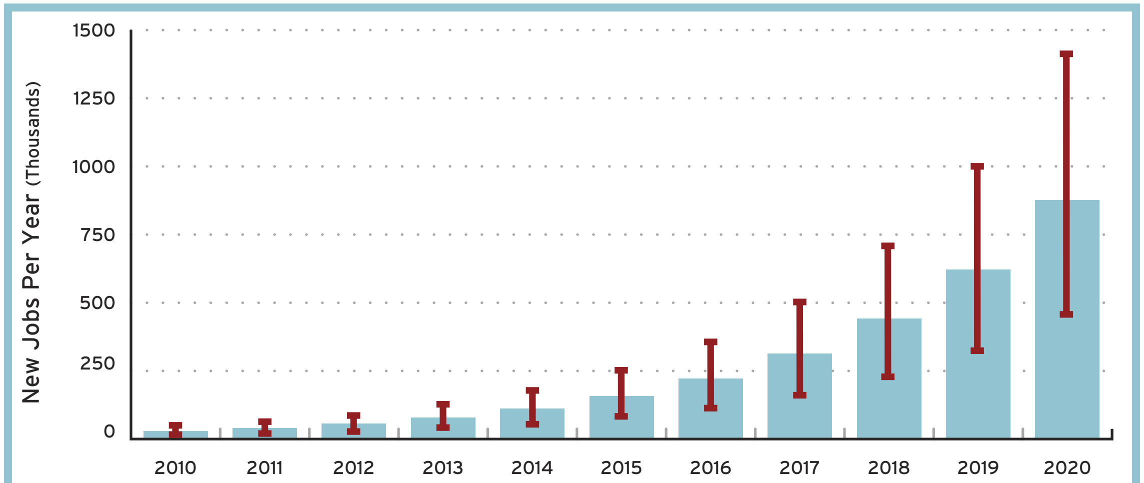

FIGURE 2. Jobs Created by an Efficiency Program that Reduces Energy Use in the Building Sector by 10% in 2020. Source of jobs data: ACEE 2007.[7,8,9]

three examples offer insight into how efficiency industries must scale to meet gigaton objectives.

Strategies for Building Efficiency

A number of strategies that reduce building energy use by 10% can deliver a 1-gigaton reduction in CO_2e in 2020. In general, the emissions reduction potential of efficient technologies involves an efficiency/adoption trade-off; the higher the efficiency of a technology, the lower the market penetration level required to reach the 1-gigaton goal.

Four possible strategies to reduce carbon emissions by 1 gigaton in 2020 are:

- Broadly deploying energy-efficiency measures over all sectors of the world's existing building stock
- Targeting climate zones, end uses, and industries with comparatively higher energy use
- Implementing a comprehensive overhaul of the U.S. building stock
- Converting new construction worldwide to net-zero energy use

STRATEGY 1 – BROAD ENERGY EFFICIENCY

A uniform 40% (or greater) improvement in energy efficiency in both new and existing buildings worldwide would reduce emissions by an estimated 4.4 gigatons CO_2e.[10] This 40% efficiency enhancement is obtainable using current technology, and, if deployed across ¼ of the world's building stock during the next 10 years would reach gigaton scale. Building shell improvements — enhanced insulation and new window technology — offer average efficiency gains of approximately 32% and 9%, respectively.[11] Lighting technology improvements promise building efficiency gains from 8 to 18% (using current compact fluorescent light [CFL] technology) to 10 to 20% (using current light-emitting diode [LED technology).[12] Coupling building shell enhancements — including insulation, windows, and roofing upgrades — with upgrades in lighting, appliances, and heating/cooling technology (e.g., heat pumps) achieves the required 40% savings. This strategy requires active retrofitting.

STRATEGY 2 – TARGETED ENERGY EFFICIENCY

A second gigaton strategy favors higher-efficiency regional upgrades over universal energy-efficiency upgrades. This strategy selects buildings based on climate zones (buildings in cooler climates typically use more energy, e.g., for heating, than buildings in milder zones) and rolls out industry-specific retrofit technology. In the U.S., approximately 45% of homes are expected to be in cold climate regions in 2020. Industries with high building energy intensity include health care and food and beverage. Targeting 12% of the highest-energy-intensity buildings (new and existing) globally with a high-efficiency strategy that nets upwards of a 75% efficiency gain could achieve a 1-gigaton reduction.[13]

STRATEGY 3 – ADVANCED U.S. BUILDINGS

A third approach implements a comprehensive strategy in the U.S. only, targeting all buildings (existing and new, residential and commercial). An estimated 2.4 gigatons of 2005 CO_2e emissions were attributable to building operations in the U.S.[14] Emissions are projected to increase to nearly 2.9 gigatons CO_2e in 2020. Almost 40% of total U.S. emissions and an estimated 9% of global emissions came from this sector in 2005. Halving current energy use in U.S. buildings by 2020 could eliminate more than a gigaton of emissions. This strategy would require an aggressive retrofitting strategy aimed at both residential and commercial buildings and paired with new low-energy standards for new construction. Building technologies that scale from the U.S. market to the global market would be critical for expansion of this emissions-reduction strategy beyond 2020.

STRATEGY 4 – GLOBAL NEW CONSTRUCTION

A fourth strategy targets new construction. A move to net-zero-energy-use ("net zero") construction in both the residential and commercial sectors, phased in over the next 2 to 3 years, could offset nearly 450 megatons of CO_2e in the U.S. by 2020 (158 megatons of CO_2e residential, 280 megatons of CO_2e commercial).[15] In comparison, new residential construction in China, estimated to be growing twice as fast as the U.S. (2.8%), has an estimated abatement potential of only 70 megatons of CO_2e because of much lower baseline usage associated with smaller houses and less consumptive lifestyles.[16] Globally, aggressive scaling of net-zero practices in the construction sector could avoid more than 2 gigatons of CO_2e.[17] Targeting adoption of net-zero practices in just two regions — North America (Canada and U.S.) and Centrally Planned Asia (predominantly China) — could deliver up to an estimated 890 megatons of CO_2e.[18] This strategy requires aggressive scaling of energy-efficient design and construction over the next several years. A strategy targeting two global regions, for example, would require universal adoption by 2010 of new net-zero standards for construction in those regions. The need to develop new green building technologies and sustainable design practices for post-2020 deployment elevates the importance of this strategy.

Industry Background

A building's carbon footprint can be traced through the three phases of the building's life cycle: construction, inhabitation, and deconstruction. The majority of emissions is energy-use related and accrues over the building's lifetime while the building is inhabited and in use. For a number of readily available efficiency measures, the cost savings from reduced energy consumption exceed the upfront purchase cost.

Energy Use by Buildings

Heating and cooling combined represent 43% of residential energy use and 27.3% of commercial energy use in the U.S. (see Figure 3) and account for approximately 660 megatons of CO_2e annually in the U.S. Heating and cooling energy use can be significantly reduced by installation of efficient heating/cooling systems and by enhanced building envelopes. Improperly installed and/or operated heating, ventilating, and air conditioning (HVAC) systems and outdated equipment can result in efficiency losses of 20 to 40%. A 30% efficiency gain from widespread repair/replacement of HVAC systems would lead to an estimated

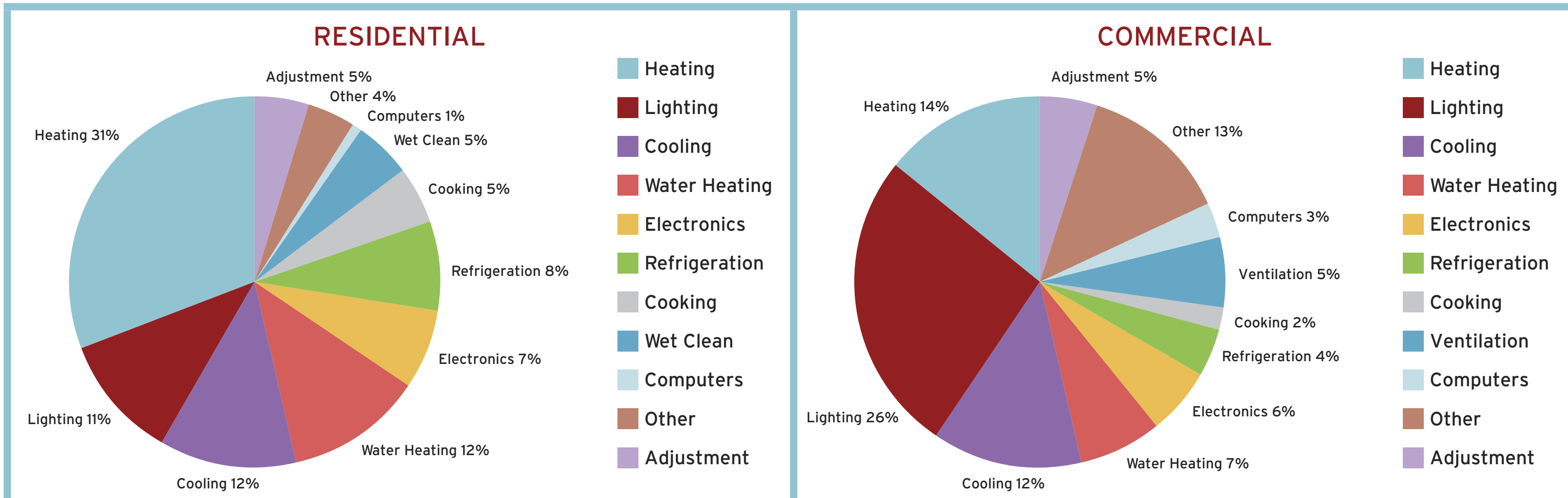

FIGURE 3. End-use Energy Consumption Percentages for Residential and Commercial Buildings in the U.S. Heating and cooling are the largest energy needs, followed by lighting. Source of data: DOE, 2008.[20]

carbon reduction of more than 400 megatons of CO_2e in the U.S. Use of ground source heat pumps could reduce building energy use by an estimated 35%. Widespread adoption of heat-pump technology in the U.S. could abate up to 450 megatons of CO_2e. Worldwide adoption could abate an estimated 1.2 gigatons of CO_2e.

Lighting accounts for 11% of residential energy use and 26% of commercial energy use in the U.S. and was responsible for an estimated 454 megatons of CO_2e emissions in the U.S. in 2008. Electric lighting is estimated to use 2,500 terrawatt hours (TWh) of energy per annum globally and to contribute 1.7 gigatons of CO_2e emissions.[19]

Figure 3 displays building energy end-use breakdowns in the two sectors. Energy for heating is a greater fraction of total energy use in the residential sector than in the commercial sector whereas lighting energy use is a larger fraction of total use in the commercial sector. Hot water and refrigeration use proportionally more energy in residential buildings; ventilation and computers account for a higher proportion of energy use in commercial buildings.

Energy-Efficiency Technologies for Buildings

Technologies that target heating/cooling/lighting will have the most dramatic effect in reducing energy use, with these end uses accounting for a combined 54% of building energy use in the U.S. residential sector and 53% in the U.S. commercial sector.

Air leaks in building walls, windows, roofs, and foundations (collectively, the building envelope) and high thermal conductance (low insulating value) can result in significant energy losses. Energy savings from upgrading insulation from current average levels to the U.S. Department of Energy (DOE)-recommended levels top 30%, based on average building data.[21] In the U.S., widespread building insulation upgrades to DOE-recommended levels could reduce energy-related emissions by an estimated 700 megatons of CO_2e ("widespread" means 75% adoption levels by 2020). The global carbon-reduction potential from efforts to build and retrofit well-insulated homes is estimated to be more than 3 gigatons of CO_2e.[22]

To reduce emissions by 1 gigaton in the U.S., a number of efficiency industries will need to be scaled simultaneously, including lighting, insulation, windows, and potentially the alternative heating (e.g., heat pump). Building retrofits and new construction would incorporate all of these efficient technologies. If scaled independently worldwide, the windows, lighting, and insulation industries could each deliver a gigaton emissions reduction. Policy putting in place higher building efficiency standards could speed the growth of these industries to achieve this scale.

New Construction

New construction affords an opportunity to design for energy efficiency. By meeting the U.S. Green Building Council's LEED standards, buildings achieve an estimated 25 to 30% reduction in energy consumption annually.[23] Although LEED-certified buildings are currently a small fraction of total building stock, this fraction is growing; the number of LEED-certified buildings in the U.S. roughly doubled in 2004 and 2005 and grew by 45% from 165 to 240 buildings in 2006. Energy-efficiency improvements of 30% would not meet the 1-gigaton emissions reduction goal in the U.S. but globally could scale to save more than a gigaton.

If LEED standards were mandated across the U.S. residential and commercial construction sectors beginning in 2011, the average 30% efficiency gains obtained would offset approximately 150 megatons of CO_2e in the combined U.S. residential and commercial sector by 2020, or 15% of the 1-gigaton target. Globally, an across-the-board 30% efficiency gain in all new construction would reduce 2020 emissions by an estimated 640 megatons of CO_2e. More aggressive energy-efficiency standards (greater than 40% efficiency improvements) for new construction are needed to meet the gigaton goal.

Net-Zero Buildings

Buildings that integrate on-site renewable generation to achieve net-zero emissions have been pioneered in several U.S. communities, and new markets for net-zero buildings are opening across the country. The largest net-zero community to date is the Geos Neighborhood, planned for construction in 2008 outside Boulder, Colorado, with 250 homes powered by solar and geothermal energy.[24] Policy mandating net-zero emissions could be an important driver in this area. The 2007 California Energy Commission (CEC) annual report, for example, recommends net-zero residential construction by 2020 and net-zero commercial construction by 2030.[25] If the projected 2 million new homes to be built in the U.S. next year adhered to net-zero standards, the CO_2e footprint would reduced by an estimated 14 megatons. With an assumed 1.4% constant annual growth rate in construction, net-zero U.S. residential homes from 2011 onward could offset up to 158 megatons of CO_2e by 2020. Globally, a gigaton could be achieved through net-zero standards implemented in two of the major regions of development, e.g., North America and Central Asia.

The U.S. residential construction market has contracted between 2007 and 2009 and may take time to regain the 7% annual growth of the last decade. Current market size is approximately $360 billion, down from a peak in 2005 of approximately $596 billion.[26] The non-residential construction market has fared better with annualized growth of 4.5% from 2002 to 2007. The 2008 market is estimated at $585 billion and was projected to grow to $588 billion in 2009.[27] Expansion in the global industry, driven by India and China, has been projected to drive output to between $3 trillion and $4 trillion in 2009.[28]

Summary of Potential Cost Savings

Investment in efficiency offers significant cost savings over the long term. Annual U.S. expenditures on energy for buildings totaled more than $360 billion in 2008. Cost savings associated with a 25 to 30% average energy efficiency gain — as currently required for LEED certification and widely recognized as attainable through basic retrofitting with existing technology — are upwards of $85 billion per year. Actual cost savings are sensitive to fuel type and climate, among other variables.

One of the chief drivers of technology innovation — cost — has been lacking for many years in the energy-efficiency sector. Low energy costs have deterred major efforts in this area. This is changing in the face of the high energy costs experienced in recent years. The recognized need for low-carbon technologies is also spurring innovation.

Achieving Gigaton Scale

Meeting the gigaton challenge will require capital investment in the expansion and scaling of building sector energy-efficiency industries. All of the industries examined will need to scale much more rapidly than currently projected. The capital investment for scaling each of these individual efficiency technologies is considerably lower than that required to scale new energy generation.

Lighting

BACKGROUND

CFL and LED technology offer dramatic improvements in lighting efficiency of 70% and 88% on average, respectively, compared to standard incandescent fixtures.[29] Incandescents are widely recognized as inefficient in terms of energy use, and policies have been adopted in the European Union and the U.S. to phase out incandescent bulbs by 2012.[30] A complete phase-out of incandescents by 2020 could deliver approximately 400 megatons — 40% of the gigaton target — of CO_2e savings.

Incandescents dominate the world market today, totaling about 60% of lighting unit sales, but they are losing ground, down from 80% market share in 2005. Worldwide lighting unit sales have topped 18 billion annually over the past several years. The residential market is significantly larger than the commercial/industrial market in terms of unit sales (more than 15 billion). Revenues in two sectors are, however, roughly equal at more than $5 billion each.

Revenues and sales trends are moving in opposite directions. Unit sales are falling as more efficient bulbs with longer lifetimes take hold in the marketplace. These more expen-

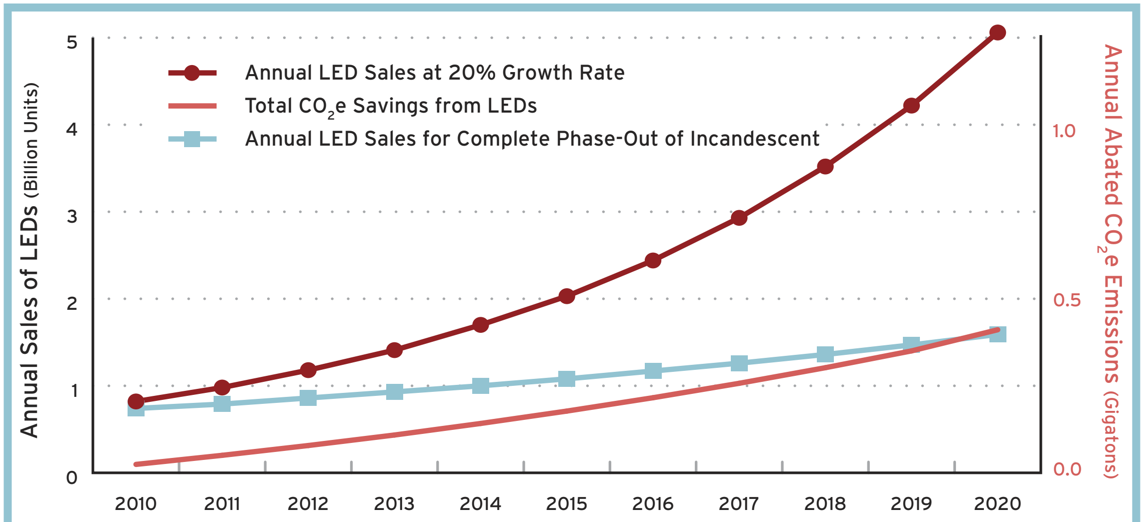

FIGURE 4. Phase-out by 2020 of 12 billion Incandescents Sold Worldwide in 2008. Global phase-out of incandescents could provide a 400-megaton reduction in CO_2e. Further reductions are possible through additional switch-overs to more efficient lighting technologies, e.g. from CFL to LED.

sive fixtures are still driving revenue upward. Notably, despite their majority market share, incandescents have less than 15% revenue share (approximately $1.6 billion).

CFLs currently have the second-largest market share (about 16% of unit sales and 20% of revenue), followed by halogen, and then linear fluorescents. LEDs are the fourth largest sector (with 5% market share and 17% revenue share) and by far the most rapidly growing. High-intensity-discharge lamps and linear fluorescents dominate with 25% and 21% of a $12-billion market, respectively. The total installed base of lighting units is estimated to be around 35 billion units.

SCALING THE INDUSTRY

LED sales grew from approximately 20 million to approximately 700 million between 2005 and 2009. The average 5-year growth rate is close to 200%. Growth between 2009 and 2010 is projected to be about 20%. At a constant annual growth rate of 20%, sales in 2020 would exceed 5 billion units. Cumulative replacements of incandescents at this growth rate would exceed the current number of bulbs in use, totaling more than 26 billion. LEDs would have to replace other light fixtures and meet new demand to sustain this growth rate. Phasing out inefficient incandescents over the next 10 years to achieve a 400-megaton reduction in CO_2e would require a constant annual growth rate of just 8%. At this rate, sales of LEDs would be more than 1.5 billion in 2020. Cumulative LED sales would total 12 billion and would have replaced incandescents.

Ramp-up of the LED industry requires investment in heavy machinery, including wafering and packaging machines. Figure 4 assumes that LEDs replace incandescents, offering 80% efficiency gains on a per-bulb basis. CFL is likely a transitional technology, given the advantages of LED: higher efficiency, improved optics, size, durability, longer lifetimes, and no mercury content.

The LED market has been growing impressively between 2004 and 2009, increasing market share from less than 1% in 2005 to about 5% in 2009, and increasing revenues from less than 1% to 17%. The 5-year constant annual growth rate (2004-2009) was more than 100%, slowing down in 2008 to close to 20%. Primary revenues in the sector still come from demand for automotive, cell phones, and outdoor and sign lighting.[31] LEDs have been recently adopted for commercial uses such as traffic signals, exit signs, and large outdoor displays. Higher efficiency and longer lifetimes make LEDs an attractive investment to commercial building users who face high energy loads. Because of the higher cost of LEDs (five to 10 times the cost of CFL technology), the residential market is projected to be several years off. As costs come down over the next 5 years, and LEDs become attractive for a wider range of uses, including residential, the market will accelerate.

CAPITAL INVESTMENT

The capital expenditure to scale the lighting industry to deliver 5 billion LEDs by 2020 is estimated to be on the order of $3 billion. This is a fraction of the capital required to reach the same level of CO_2e savings via a generation pathway, with generation costs on the order of hundreds of billions of dollars to cover the same power needs.

The capital investment trajectory in Figure 5 follows an exponential expansion pathway, accelerating with LED market expansion.

CHALLENGES TO ACCELERATED DEPLOYMENT

Cost is the major barrier to adoption of both CFLs and LEDs in residential settings where the payback periods are long as the up-front

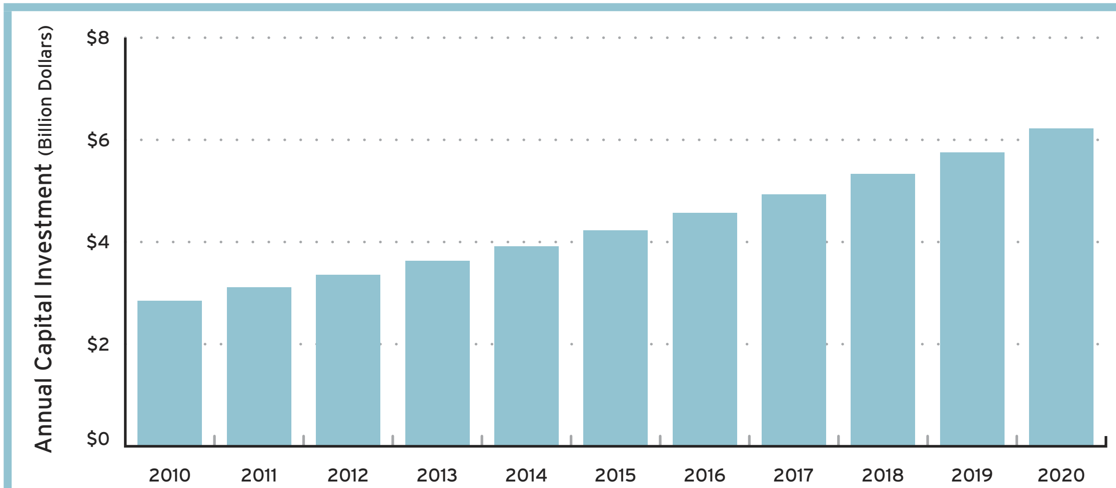

FIGURE 5. Annual Capital Investment in LED Lighting Production. The estimated cumulative investment over the 10-year period would total $47 billion.

cost of these two technologies is high. CFLs have higher up-front costs (2 to 10 times greater than incandescents), and LEDs are even more expensive currently. Over the lifetime of the bulb, the up-front investment is typically paid off, e.g., a $15 compact fluorescent bulb would save on average $30 in energy costs over its lifetime.[32]

Disposal is another issue. CFLs require care in disposal due to their mercury content. Light quality as measured by the color rendering index (CRI) is a concern with both CFLs and LEDs and an impediment to widespread consumer acceptance. LED technology has an advantage in that a filter can be applied to achieve more natural lighting color.

TECHNOLOGY INNOVATION

A major contributor to the cost of LEDs is the use of sapphire as a substrate. Materials advances could bring down the cost significantly. One such advance would be the use of low-cost metal-coated silicon wafers as an alternative substrate. One of the cost advantages of using silicon instead of sapphire is the ability of the industry to manufacture many devices simultaneously on large wafers of silicon; this it not feasible with sapphire. Other active areas of research focus on increasing the efficiency of LEDs and the overall light output (lumens per watt), which also translate into cost savings and improved light quality.

Windows

BACKGROUND

Advances in window and roofing technologies promote higher building envelope efficiency. Energy-efficiency upgrades are most effective when they are comprehensive (targeting windows, roofs, floors, and walls). Otherwise, air leaks remaining in one component can offset efficiency gains from another. Window technology has improved, offering greater thermal efficiencies than in the past and quadrupling R-values (the measure of a window's insulating properties, i.e., ability to prevent heat gain or loss) for standard window designs.

The analysis here assumes that energy-efficient windows exceed current performance standards by a factor of three. This translates into average energy savings of an estimated 8.5% on a per-building basis because of reduced heating and cooling loads. This could save an estimated 113 megatons of CO_2e emissions in the U.S. by 2020 with comprehensive retrofits and new technology adoption in the construction sector. Globally, new window technology in new construction could unlock up to 360 megatons of CO_2e savings.

SCALING THE TECHNOLOGY

To reach the gigaton goal, existing buildings would have to be retrofitted with new window technology. At an average efficiency gain of 8.5% on a per-building basis, an estimated 100 million residences and 4 million commercial buildings would need to install energy-efficient windows. Energy-efficient window sales would total an estimated 7 billion over the 10-year period. As shown in Figure 6, by 2018 all existing window demand would be met by energy-efficient windows.

A number of variables affect actual energy savings and the scale required to meet the gigaton target. Efficient windows allow for greater window area in building design without the associated energy losses. This could lead to energy savings from reduced lighting loads. Technology advances on the horizon would produce even more efficient windows

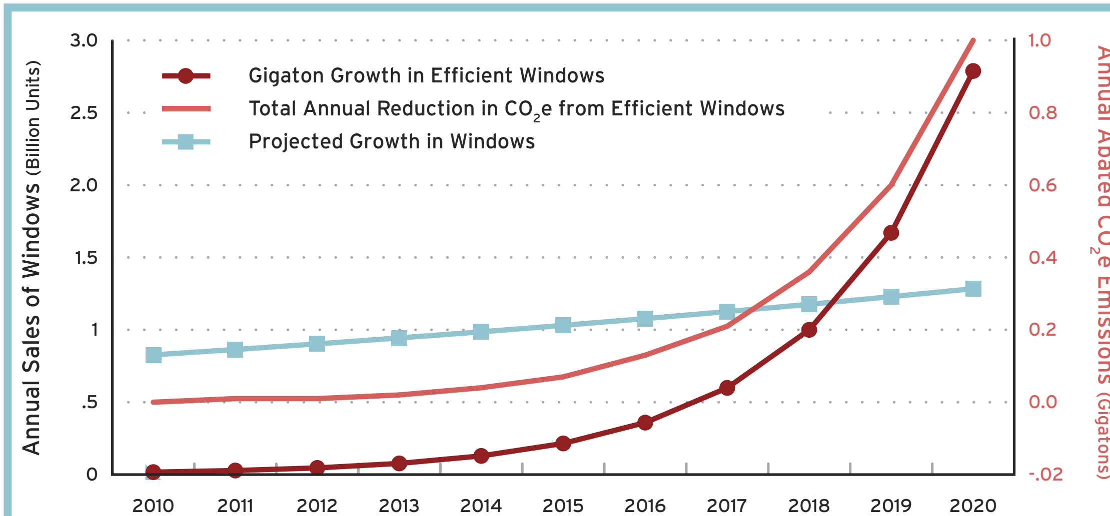

FIGURE 6. Growth in Energy-Efficient Window Sales. Assuming a 70% constant annual growth rate over the next 10 years, efficient window sales would reach 2.7 billion in 2020 and abate more than 1 gigaton of CO_2e that year. Sales for energy-efficient windows would exceed current projected demand for windows at that point, implying an uptake in the window replacement market. Over the 10-year period, more than 7 billion energy-efficient windows would be sold and installed.

than are currently available and allow even greater savings in new buildings, decreasing the number of window sales and retrofits required to reach the 1-gigaton target and allowing window technology to deliver more than 1 gigaton of CO_2e savings.

CAPITAL INVESTMENT

Replacement costs for windows vary based on frame type (vinyl, wood, or metal) and efficiency properties. High-R-value windows are currently more costly than standard windows by roughly a factor of three. In general, the industry is not highly capital intensive.

Capital outlay for production expansion in the energy-efficient window industry depends on the type of window being manufactured. Based on industry sources, capital expenditure per million units for new energy-efficient windows ranges from $20 to $25 million to scale to 1 million units of production. A million units is roughly 4% market share in the wood and metal-frame sector (slightly less in the vinyl sector, which is the largest segment of the current $15-billion market). Investment over the 10-year period to achieve the gigaton target is estimated to be close to $61 billion (see Figure 7). As with lighting, this is a fraction of the capital investment that would be required for new generation to achieve the same level of carbon reductions and energy output.

CHALLENGES TO ACCELERATED DEPLOYMENT

The challenges facing the efficient window industry are those facing any nascent industry: how to get market share. The industry has been growing rapidly. Reaching gigaton scale in the next 10 years is highly feasible but will require widespread adoption in new construction as well as some level of retrofit activity. With regard to new construction, the cost factor is important. The payback periods are short (less than 2 years) but developers — who don't pay the utility bills for the properties they build — may still opt in favor of lower sticker prices. Building codes are critical for ensuring the use of higher-efficiency windows.

TECHNOLOGY INNOVATION

Key areas for advances in windows include low emissivity (low-e) or spectrally selective coatings that prevent incoming light from heating up interior spaces, which reduces building air-conditioning load and thermal conductivity. Research efforts are also focused on reducing frame heat transfer. Current R-values for standard windows are 1 to 3. Energy-efficient windows have R-values as high as 5. The additional cost of energy-efficient windows is largely attributable to the increased manufacturing costs. For coated windows, ion-assisted processes can produce coatings with superior optical properties, longer lifetimes, and lower cost than current designs.

Insulation

BACKGROUND

Insulation is a critical, cost-effective component of building envelope efficiency. The thermal insulation market is dominated by mineral wool products (60% of market share) composed of siliceous materials: fiberglass, slagwool, and rockwool, supplied in batts, rolls, blankets, and tiles and other boards. Plastic (polystyrene and polyurethane) foam has the second-largest market share. Companies offering cellulose (paper) insulation and recycled cotton and wool insulation have a much smaller market share. Tightening of federal and state regulations on thermal and acoustic insulation could significantly drive demand in this industry.

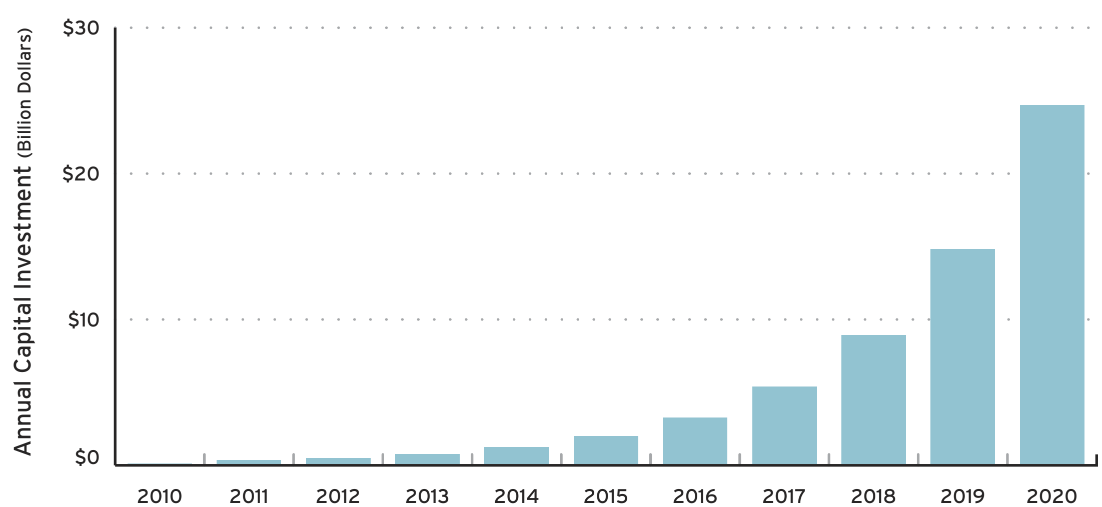

FIGURE 7. Annual Capital Investment in Energy-efficient Windows Production. The estimated cumulative investment over the 10-year period would total $61 billion.

SCALING THE TECHNOLOGY

On the gigaton pathway, 95 million residences and 42 thousand commercial spaces are insulated at DOE-recommended levels. Increasing insulation in these buildings, from current standards to DOE-recommended levels, would produce an estimated average efficiency gain of 30%. A gigaton scale-up of insulation in buildings would require significant annual growth in insulation upgrades to DOE-recommended levels. For instance, 1 gigaton in 2020 would be achieved by insulating 2.5 million homes and 1,500 commercial spaces in 2010, and continuing to grow the base of re-insulated buildings at a 28% constant annual growth rate over a 10-year period. Figure 8 shows insulation growth required to reach the gigaton goal.

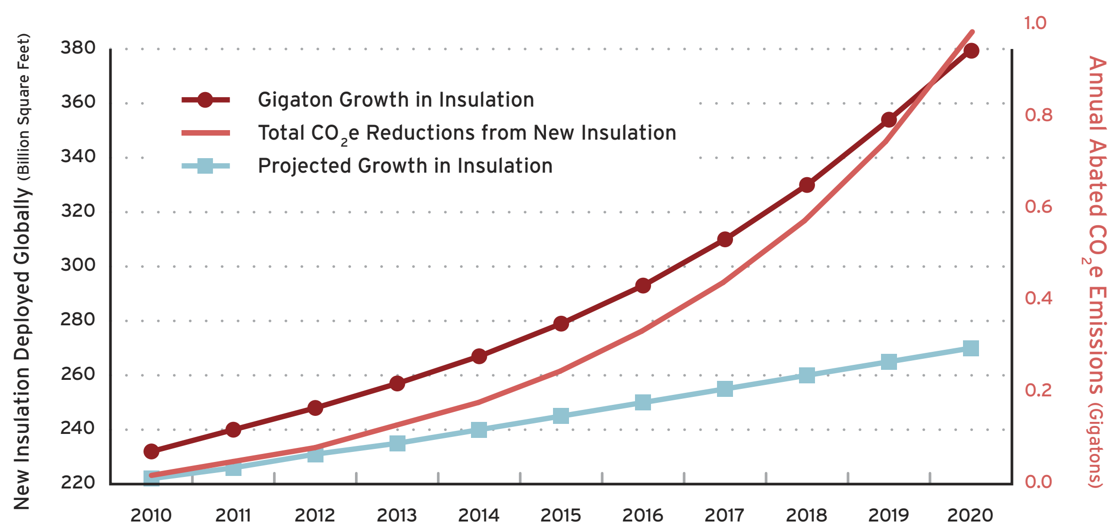

FIGURE 8. Growth in Insulation Sales. The insulation market would have to expand far beyond current projected demand to meet higher efficiency standards and achieve the gigaton target.

CAPITAL INVESTMENT

The cost of insulation per building depends on the type of insulation and the efficiency level required, as dictated by the climate. Annual capital investments to scale the industry are shown in Figure 9. Estimated cumulative investments over the 10-year period are close to $29.4 billion.

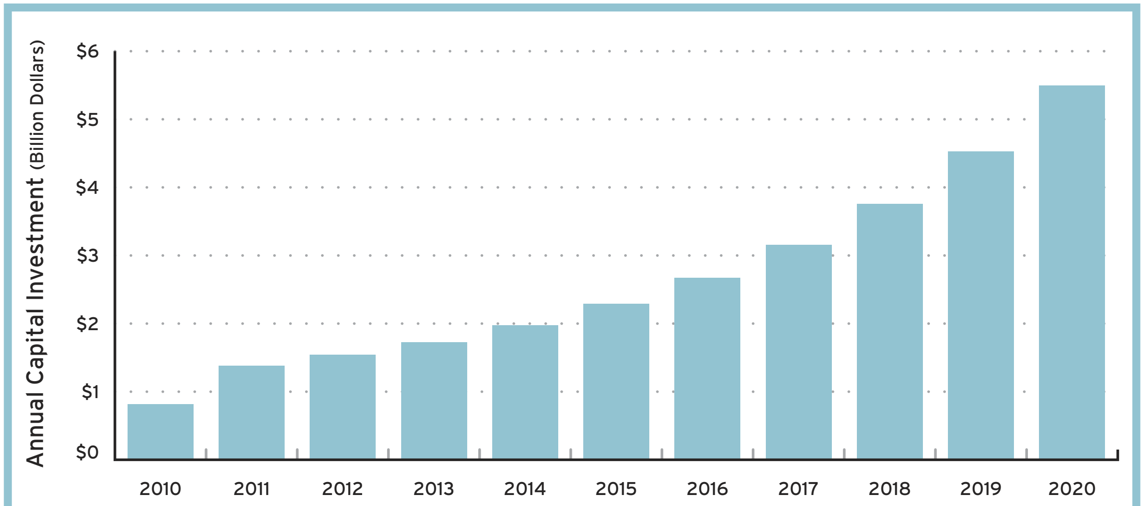

FIGURE 9. Annual Capital Investment in Insulation Production. The estimated cumulative investment to meet the gigaton goal for the 10-year period would be $29.4 billion.

CHALLENGES TO ACCELERATED DEPLOYMENT

The barriers to enhanced insulation in buildings are the same as those for energy-efficiency upgrades in general. Without building codes mandating higher levels of insulation, comprehensive upgrades are unlikely. Developers build to code and lack incentives to do otherwise. Consumer awareness of energy savings and demand for higher-performance buildings could drive some increase in demand.

TECHNOLOGY INNOVATION

New materials could play an important role in improving the efficiency, reducing the volume, and ultimately reducing the cost of insulation. Aerogels are currently used in non-building applications and have much higher R-values than conventional foams, reducing the insulation volume required. Current applications of aerogels are in the transport and refrigeration industries. Another insulation technology with current applications in appliances, transport, and equipment is vacuum panels. Air between the panel walls is evacuated, removing molecules that would transport heat, just as in thermos technology. Unlike thermos technology, vacuum-insulated panels require a core to support the walls. Common cores include Perlite, mineral powder, mineral fiber, fiberglass, and silica. Aerogels have also been used as cores. The panels have a membrane that seals them from moisture and other molecules. Thin aluminum with a plastic laminate is one effective membrane. Advances in less-permeable membranes are a key research area for this technology. There are concerns regarding panel lifetimes. Older vacuum-insulated technologies had lifetimes of 15 to 20 years. Lifetimes of greater than 50 years are projected for panels with silica or aerogel cores and newer less-permeable membrane technology. The higher cost of these advanced panels, driven by the manufacturing and processing costs for the core and membrane, currently limit their widespread adoption.

Structural insulated panels (SIPs) are an advanced building technology that is currently in use. The panels consist of an oriented strand board (OSB) veneer composed of engineered wood (wood chips as opposed to flat pieces of lumber, which can be made from small trees that can be grown and harvested renewably) and a core composed of petroleum-based polystyrene, polyurethane, or polyisocranate. The low levels of petroleum in these products result in a carbon payback period of less than 1 year. The advantages of SIPs are superior insulation, reduced leakage and degradation (a problem with conventional insulating foams), and a reduction in on-site waste as they are prefabricated. New materials for SIPs are an area for advancement. One example is the use of biocomposite, a resin manufactured by microbes that is ultimately biodegradable. Biocomposite is still a laboratory phenomenon.

Insulating concrete forms (ICFs) are another structural insulation technology. Five-inch concrete walls are paired with polystyrene foam insulation to provide a heavily insulated R-17 wall. Material advances (low-carbon alternatives to concrete, higher-efficiency and/or petroleum-free foam) and cost reductions for this technology are areas for advancement.

Finally, research efforts to improve the performance and application of conventional insulation materials are continuously under way. These efforts focus on ways to better measure building insulation needs and advanced methods to test insulation performance. New methods to increase the ease of insulation installation would certainly speed the retrofit market.

Public Policy

There are a number of recognized hurdles to new technology adoption and energy-efficient design/retrofit in the building sector. Public policy can speed the adoption of new building technologies that are cost effective but face other disincentives. Policy also has a role to play in promoting technologies that are not yet cost competitive but offer other benefits, including health benefits and lower greenhouse gas emissions.

Identified barriers to adoption of energy-efficient technology include:

1 – UP-FRONT COST

The city of Berkeley, eager to encourage its residents to install solar panels, addressed the high up-front cost of installation by providing a property tax lien. The city pays the up-front cost for the solar panels, and the building owners pay back the cost over time through higher property taxes. Under this system, the solar panel payments are attached to the building, so, if the building is sold, the original purchaser is no longer liable for the payments. Solar system payback periods of 3 to 5 years were a possible deterrent to installation of solar systems given the turnover in the residential market. Without such a system in place, a purchaser could be responsible for payments for solar panels in a house that s/he might not own in 3 years. Policies like Berkeley's could be applied to other efficient technologies.

2 – MISMATCHED INCENTIVES BETWEEN BUILDING OWNERS AND TENANTS

This is a classic agency problem, where the person controlling a decision does not actually face the consequences of the decision. A building owner has limited incentive to undertake energy-efficiency upgrades, either as a retrofit or in the construction phase, if the tenant, not the owner, will be responsible for the utility bills. At the same time, a tenant who wishes to be proactive about energy efficiency likely does not have the authority — and may not be able to get it — to make major changes to the building. In theory, contractual solutions could ameliorate the situation. Two examples include the: 1) long-term leases, which can be good for the building owner because they reduce turnover; if paired with owner-authorization for efficiency measures, the tenant could pay all, or a portion, of the energy-efficiency costs and recoup these costs over the longer lease period in the form of reduced energy bills, or 2) a sharing agreement, whereby both parties share the cost of energy-efficiency upgrades, and the tenant also makes an additional payment to the landowner that represents a portion of the energy bill savings. The attractiveness of energy-efficient and healthy buildings to tenants is a market force that could also help correct the current incentive issue.

3 – DISAGGREGATED BENEFITS FROM ENERGY SAVINGS

An efficiency gain of even 10% at the building level translates into huge society-wide benefits in terms of reduced energy costs, reduced infrastructure costs, reduced energy imports, and carbon savings. However, at the individual level — particularly the individual residential level — a 10% efficiency gain has a current annual value of $140 and an uncertain future value. The up-front cost, time, and effort to implement incremental energy-efficiency gains simply may not be priorities for individual residence owners and even some commercial building owners. Policies to aggregate benefits could be run through utilities or through municipalities and are discussed below.

4 – UTILITY REGULATION AND OPERATION DISINCENTIVES

Current regulation of utilities in most U.S. states does not favor energy efficiency. Utilities' revenues are tied to the amount of electricity sold. Programs to reduce energy use have a high up-front cost that utilities can't necessarily recoup whereas the cost of new generation can be passed on to consumers in the form of (approved) rate increases. The state of California has introduced new utility regulation that allows utilities to pass on efficiency costs to consumers. Incentives for consumers to reduce consumption might still be lacking in this arrangement but could be addressed through additional policy measures such as a tiered pricing system, in which efficient usage is defined based on what's achievable. Using more energy than is "efficient" places a user in a higher price tier. A user in a higher (inefficient) price tier has an incentive to decrease usage and can contact the utility for assistance, possibly in the form of a loan or a grant for energy-efficiency upgrades. A second policy that relies on the carrot rather than the stick could offer consumers an up-front payment for implementing energy-efficiency improvements. This payment would represent a portion of the avoided costs of generation expansion by the utility.

New Building Codes: A Fleet Model for Housing

The single most effective policy action that would address all four market failures above would be mandatory new energy-efficiency standards for all buildings. The new standards should be based on an assessment of current best practices and what is economical given a reasonable (3- to 5-year) payback period. Such a policy has the potential to reduce sectoral energy use by 30 to 40%. In the U.S., this would achieve 1 gigaton of CO_2e emissions reductions in 2020 due to reduced building energy use and would save an estimated $2.5 trillion in energy costs over the 10-year period.

As a practical matter, the policy would likely need to phase in the new building codes for retrofit but could make them mandatory for all new construction. A natural phase-in mechanism is to tie building upgrades to resale. This approach has been used in Germany. The concept behind such a policy is a "fleet" view of the building sector. The housing fleet in the U.S. currently comprises 113 million residences. Approximately 2 million new residences are added per annum, and 6 million residences resold. Based on these statistics, more than 75% of the housing fleet in 2020 (some 80 million residences) would meet the new efficiency standards (assuming that resold residences are not repeat resales).

New Construction Standards

Around the world, LEED-certified and net-zero energy buildings are being constructed. These buildings take advantage of the energy-efficiency technologies and measures described in this chapter but also focus on advanced building systems, such as reducing lighting load through expanded reliance on natural light, highly efficient heating/cooling systems, and sophisticated building control systems for HVAC, lighting, and electronics. Examples from Asia include the TaiGe Serviced Apartments in Shenzehn, China, the Pearl River Tower under construction in Guangzhou, China, the Festival Walk building in Hong Kong Kong, the Itoman City Hall in Japan, and the Low-Energy Office Building in Malaysia.[33] The first LEED platinum (the highest — most energy-efficient — level of LEED certification) building outside of the U.S., the CII-Godrej Green Business Center, was constructed in Godrej, India, in 2004. Such advanced building technologies could be standardized and distributed. Areas for further advance in new construction include building-integrated solar panels; building wind turbines and wind entrapment; and on-site water treatment, reuse, and recirculation.

Interactions with Other Gigaton Pathways

There is a synergy between the development of distributed renewable energy technology and mandates for a sustainable built environment. The design of net-zero buildings typically incorporates on-site renewable generation. This can include solar photovoltaic, solar thermal, or geothermal energy. For example, the Geos community homes mentioned above will rely on passive solar and a heat-recovery ventilation system. The possibility of larger-scale net-zero communities creates, in turn, the possibility of local renewable energy generation using solar thermal or wind technology.

A major energy-efficiency initiative in the U.S. could dampen if not eliminate demand for new electricity generation, at least in the short run. This could temporarily stall plans for some new renewable generation although renewables could still be in demand to replace retired existing fossil-fuel-based generation. In countries where energy demand is expanding much rapidly, e.g., parts of Asia, efficiency cannot replace the need for new generation but is even more urgent to enable these regions to meet total energy demand in the future.

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11. Actual energy savings are sensitive to climate region, house size, and existing insulation. Estimate is based on the average of four regional U.S. values (Northeast, Midwest, South, and West) and parameters for a "typical" U.S. residence as defined in the U.S. Department of Energy (DOE) (2007), *Buildings Energy Data Book.* Average U.S. house size is 2,047 sq. ft. Average square footage of wall space is 2,727 sq. foot. Average window area is 235 sq. ft. Existing windows are assumed to have an insulating value of R3 on average. Upgrade is to high-R-value windows (R15). Heating degree-days in the four regions range from 3,400 to 7,200.
12. Estimate based on U.S. lighting energy use in residential and commercial buildings; lighting loads in other countries (or regions) may be proportionately more/less of the total building energy use. Lighting represents 25% of the commercial energy use load in the U.S. versus 19% in China; it is 11% of the U.S. residential load and 9% of the Chinese residential load. Source: Zhou, N. (2007), *Energy Use in China: Sectoral Trends and Future Outlook,* Lawrence Berkeley National Laboratory, Berkeley CA, Energy Analysis Division. LBNL-61904; and Energy Information Association (EIA), (2006), *International Energy Outlook,* EIA, Washington, D.C. Lighting efficiency estimates (of 70% for compact fluorescent light (CFL) and 88% for light-emitting diode (LED) technology, respectively) are as reported by McKinsey (2007) for CFL and LED technology. Source: McKinsey. 2007. (See 4.)
13. Assumes that the targeted buildings are a representative cross section, i.e., that the 12% of buildings targeted actually account for 12% of emissions. The IPCC 2008 report on residential and commercial buildings estimates cost-effective energy savings of 75% in new construction are available through integrated design (without on-site generation). See 5.
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17. The 2 gigatons of CO_2e is based on an average of the A1 and B2 scenarios reported in the IPCC 2000 report and disaggregated in Price et al., see 16. The A1 scenario assumes the most rapid increase in energy-related CO_2e emissions (2.9%) of the four IPCC scenarios; B2 is the low-emissions scenario (1.8%). Overall global emissions were growing at an average rate of 1.7% annually from 1971 to 2000. The range of global abatement potential from new construction ranged from 1.7 gigatons CO_2e (B2) to 2.6 gigatons CO_2e (A1), assuming that growth in emissions comes primarily from new buildings and not from increases in energy use intensity in existing buildings.
18. Centrally Planned Asia includes China, Chinese Taipei, Hong Kong, and Vietnam. Source: Price, et al. 2007. See 16.
19. Estimate assumes that the percentage of energy lighting use in buildings globally is comparable to the percentage of lighting energy use in U.S. buildings.

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22. Estimate based on a projected 11.6 gigatons CO_2e global emissions from the building sector in 2020, the average of A1 and B2 scenarios from Price et al.(See 16.) Heating/cooling is estimated to be approximately 35% of energy use, based on U.S. numbers, with average insulation efficiency of 33% (based on average across U.S. regions). In practice, actual energy savings will be sensitive to the climate (measured in the model as heating degree-days and cooling degree-days).

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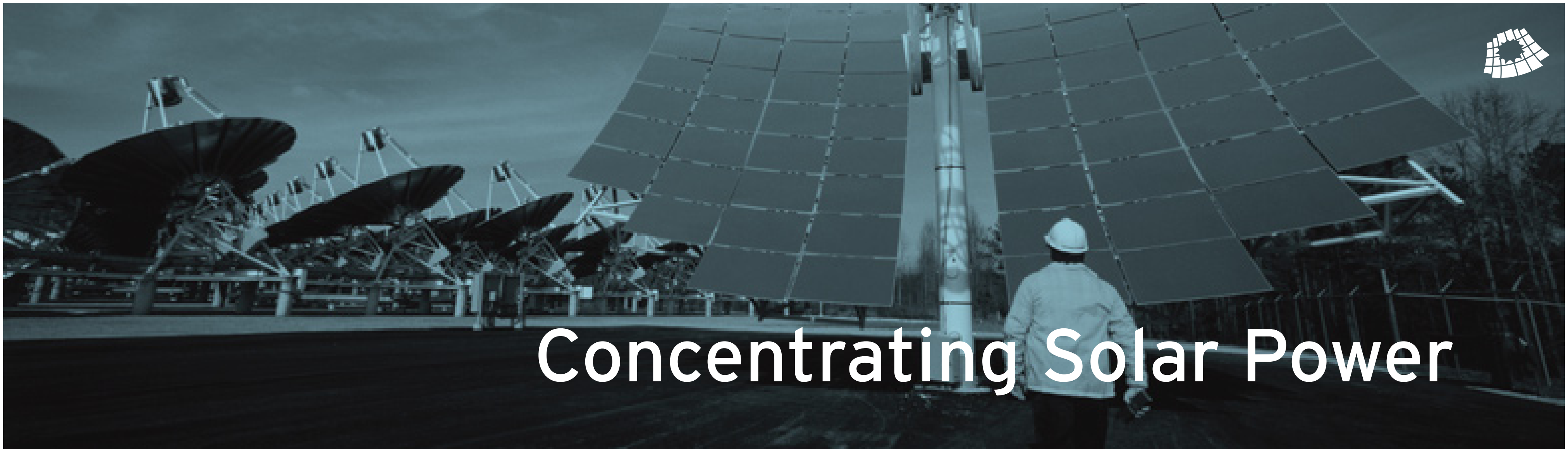

Concentrating Solar Power

MAIN POINTS

- Concentrating solar power (CSP) can achieve gigaton scale by 2020 for an investment of $2.24 trillion.
- Solar resources are abundant in the U.S. and globally to meet new energy demand; CSP is ideally situated to remote, high-insolation desert areas, so new transmission build-out is needed to bring CSP to high-population areas.
- Solar thermal systems with storage can provide consistent power and thus are attractive relative to intermittent power sources, e.g., solar photovoltaics and wind.
- Tested technology has been supplying cost-competitive solar thermal power in southern California for the past 20 years.

Overview

Concentrating solar power (CSP) is a renewable generation technology that uses mirrors or lenses to concentrate the sun's rays to heat a fluid, e.g., water, which produces steam to drive turbines. CSP differs from solar photovoltaic (PV) technology, which directly converts the sun's ultraviolet radiation to electricity using semiconductors. The CSP technologies discussed here are utility scale although some rooftop CSP applications are being developed. Solar PV rooftop applications are common; however, utility-scale solar PV is also being deployed.

Because no input fuel is required, CSP plants release little or no carbon dioxide equivalent (CO_2e) emissions. CSP is a proven technology with more than 350 megawatts (MW) of installed capacity operating commercially in the Mojave desert since the 1980s and several smaller new plants brought on line since 2006. The current worldwide installed capacity is more than 500 MW, relying mostly on the established line-focusing parabolic trough technology that provides peak demand generation. Several emerging technologies that promise higher conversion efficiencies and cost-competitive generation have been demonstrated on a smaller scale. These technologies, such as point-focusing power towers and line-focusing Fresnel reflectors, may extend the ability of CSP to provide shoulder or base-load power in addition to peak load.

There is a vast abundance of solar resources and qualified land for deployment of CSP. For example, in the southwestern U.S. alone, eligible land in proximity to transmission would readily allow for 200 gigawatts (GW) of potential CSP production. This would represent approximately ⅕ of projected U.S. installed generating capacity in 2020. The ability to store thermal energy gives CSP technology an advantage over renewable sources such as PV and wind that have not yet developed on-site storage. Although thermal storage has yet to be proven financially viable at commercial scale, plants with thermal heat storage facilities would be able to overcome solar power's intermittent nature, dispatch power on demand, shift generation to periods of peak demand, and achieve a higher capacity factor and thus reduce payback periods.

By the year 2020, an increase of approximately 492 GW of concentrating solar power capacity over today's installed base of 502 MW would reduce emissions by 1 gigaton of CO_2e per year. We estimate the total capital cost for such aggressive deployment to be approximately $2.2 trillion, nominal, or $4,546 per kilowatt (kW) of capacity. By 2020, we expect CSP plants to be cost competitive with today's natural gas plants at a levelized cost of electricity (LCOE) of approximately $67 per MWh (in 2009 dollars), a 51% reduction over 2009 LCOE.

The scale-up would produce an estimated 460,000 permanent jobs and 8.7 million temporary jobs in construction. CSP is one of the many gigaton technologies that would increase U.S. energy security and independence by reducing dependence on foreign oil.

An aggressive CSP deployment schedule will encounter obstacles. Foremost, investment in and support for research efforts are required to bring emerging technologies, particularly storage media, to a commercializable, cost-competitive stage. Further, we expect a gigaton ramp-up would result in supply chain bottlenecks, mainly in turbine and storage media supply. While there is a large amount of land worldwide that is suitable for CSP projects, siting and permitting could slow down deployment.

A supportive, stable policy environment will catalyze aggressive deployment of solar thermal generation. Technology-neutral policies, such as a price on carbon, as well as CSP-specific initiatives are required. A loan guarantee program would help overcome the high costs of financing emerging technologies. A streamlined approval process for plant siting and land-use permitting would expedite deployment. Lastly, significant investments in transmission infrastructure on the order of 10% to 20% of total plant capital cost are required; these can be triggered by revisions to rate-of-return regulation to attract private capital as well as federal oversight and a reorganized approval process.

Industry Background

The principles of concentrating direct sunlight into useful thermal energy are very basic, as a child with a magnifying glass on a sunny day can readily demonstrate. The basic engineering technologies for converting thermal energy into electricity have been commercially demonstrated for over 20 years, and CSP plants are used today to provide peak power.

Technology Overview

A CSP system employs mirrors or lenses (collectors) to concentrate sunlight on a receiver. Concentrated sunlight heats a heat-transfer fluid inside the receiver. The fluid is pumped to a central power block where it passes a heat exchanger and generates steam that drives a turbine or cycle engine to generate electricity. In general, the system beyond the heat exchanger is a conventional steam plant. There are four main CSP designs: parabolic trough, linear Fresnel reflector (LFR), tower, and dish systems. The technology most often used is parabolic trough mirrors; this is the most established and commercially proven technology, accounting for more than 90% of installed capacity.

TROUGH

Trough systems use long parabolic mirrors curved around a single axis to concentrate solar power on a receiver that runs down the length of each trough. The receiver contains a heat-transfer fluid, typically a synthetic oil, which is heated to approximately 390°C; this, in turn, generates steam, which drives a turbine in a traditional Rankine cycle. The parabolic mirrors rotate along a single axis, tracking the sun's movement.[1] Trough systems can be fitted with heat storage facilities, typically using molten salt as storage medium, that allow electricity generation to shift to cloudy or non-daylight hours. Such a system is employed by Andasol 1 in Spain.[2]

LINEAR FRESNEL REFLECTOR (LFR)

LFR systems are an alternative to trough systems. Rather than using parabolic-shaped reflectors, LFR systems employ long parallel rows of flat or slightly curved reflectors. Each reflector is independently tracked on a single axis to reflect sunlight onto a receiver suspended and fixed in space above the reflectors. As with parabolic trough systems, a heat-transfer fluid can be used to boil water in a steam generator although some LFR systems are being designed to support direct steam generation within the receiver, which could improve performance and cost.[3] Industry estimates that although LFR is less efficient than parabolic trough designs, it has an approximately 10% lower cost of electricity because solar field investment is less costly, operations and maintenance (O&M) material costs are lower because LFR has reduced breakage from wind loads compared to trough designs, and LFR offers easier access to mirrors for cleaning.[4]

Compact LFR (CLFR) systems are a variation on the LFR design. CLFR systems use multiple horizontal receivers over the field of reflectors. By aiming adjacent reflectors at different receivers, CLFR systems can space reflectors more closely, reducing the coverage area of the solar field.[5]

TOWER

"Power tower" systems use a field of hundreds to thousands of mirrors (heliostats) that individually track the sun along two axes and focus sunlight on a central receiver placed at the top of a tower. Because of the high concentration of solar energy, operating temperatures can range much higher than in trough or LFR systems, 450°C to 550°C and above, which enables higher operating efficiencies in the Rankine cycle. The higher operating temperatures also allow molten-salt heat-transfer and storage capabilities, so the plants can deliver electricity during cloudy periods or at night.[6]

DISH AND OTHER

Dish systems use a mosaic of mirror facets distributed over a dish surface to concentrate sunlight on a receiver placed at the dish's focal point. A working fluid such as hydrogen is heated in the receiver and used to drive either a turbine or a Stirling cycle engine (the latter is preferable due to its high efficiency). Because each dish rotates along two axes to track the sun, the size of the dish assembly is effectively limited, and a single dish typically generates only 10kW to 100 kW. For commercial-scale applications, a farm of several thousand dishes would need to be built.

A "solar chimney" is an experimental commercial-scale design that uses solar energy to heat air underneath an immense glass collector array and directs the airflow upward into a vertical chimney where it drives a turbine to generate electricity. An experimental plant built in Spain in the 1980s with a chimney 200m high and collection area of about 11 acres was capable of generating 50 kW of power.[7] Significantly larger plants of 100 MW are currently envisioned although these would require collection areas of 20 square kilometers (km^2) and chimneys 1 km high.[8]

CSP Industry

Commercial-scale CSP technology was first developed in the wake of the oil price peak of the 1970s. The largest plants constructed in this period were the nine Solar Electricity Generation Systems (SEGS) in the Mojave Desert in California, built from 1984 to 1991 by Luz International. Utilizing parabolic trough technology, the SEGS plants have a collective installed capacity of 354 MW and continue to operate today after having been acquired by several conglomerates in the wake of the Luz bankruptcy in 1991.

All other CSP projects during the post-1970s era remained relatively small pilot projects of 5 MW or less with the exception of the U.S. Department of Energy's 10-MW Solar One pilot plant in the Mojave Desert. First operational from 1982 to 1986 and designed to demonstrate solar power tower technology, it was upgraded in 1995 and operated until 1999 as the Solar Two project to demonstrate the ability of solar molten-salt technology to provide long-term, cost-effective thermal energy storage for electricity generation.

The collapse of oil prices and removal of government subsidies stalled further development of commercial CSP technology in the 1990s. For nearly two decades no new large-scale, grid-tied CSP plants were built anywhere in the world. However, with increasing focus on renewable energy in recent years, interest and investment in CSP have renewed, in part because of its technological maturity relative to other alternative energy technologies. In 2006, the 1-MW Saguaro Solar Generating Station came on line outside of Tucson AZ, followed quickly by the much larger 64-MW Nevada Solar One station outside of Boulder City NV in 2007. In 2008, the first European commercial CSP plant, the 50-MW Andasol 1 project, was completed in Granada, Spain. All three use a parabolic trough design similar in concept to that used in the pioneering SEGS facilities.

INDUSTRY GROWTH

The current worldwide installed capacity of CSP is 502 MW, of which 419 MW are in the U.S.[9,10,11] The vast majority of this global capacity (467 MW) is generated by line-focusing parabolic trough systems. Currently, there are only two power tower stations in commercial operation, both located in Spain near the city of Seville. Named PS10 and PS20, these power towers came on line in 2007 and 2009 and have capacities of 10 and 20 MW, respectively. Widespread power tower deployment might be delayed until proven to be financially viable.[12,13]

In the U.S., a further 8,500 MW of CSP capacity is scheduled for installation by 2014.[14,15] Approximately 40% of this capacity is expected to utilize parabolic trough technology, and the remainder is expected to use LFR, power tower, and dish technologies.[16] Among the companies developing CSP projects are: Brightsource, a power tower developer, that has signed power purchase agreements with both Southern California Edison and Pacific Gas & Electric Company (PG&E) for a total capacity of more 2,100 MW and Ausra which has announced a similar power purchase agreement with PGE&E for a 177-MW LFR plant at Carrizo CA. Other hybrid fossil fuel-trough installations are planned in California at the City of Palmdale (50 MW) and Victorville (the 50-MW 2 Hybrid Power Project).[17,18]

Outside of the U.S., Spain is the leader in the CSP market with 1,037 MW of capacity currently under construction and an additional 6,000 MW of projects in the pipeline.[19] Spain's attraction to CSP technology has been spurred by government incentives, including the Spanish Royal Degree, which calls for 500 MW of CSP by 2010. Of the planned CSP projects in Spain, 96% will utilize parabolic trough technology, with the technology choice linked to government incentives and subsidies (which cap the feed-in tariff at 50 MW, creating little incentive for higher output technologies.)[20]

Other regions with plans for CSP development include the Middle East, North Africa, and Australia. In the Middle East, 325 MW of CSP capacity are being planned in countries such as Israel, Egypt, Algeria, Abu Dhabi, and Morocco.[21] At the same time, the Mediterranean Solar Plan aims to install 10 to 12 GW of solar thermal power in North Africa and the Middle East to provide electricity to 35 million people in Europe by 2020.[22,23]

Advantages of CSP

CSP technology has several advantages as a renewable electricity generation source. First, 354 MW of trough plants have been in commercial operation for more than 20 years, proving the reliability of solar thermal generation. Second, like other renewable electricity generation technologies, solar thermal is immune to fuel-cost fluctuations because the fuel input is sunshine; this has both economic and energy security advantages for consumers. CSP has access to abundant resources, with a vast area of land that could host CSP plants.[24] In the southwestern U.S. alone, eligible land in proximity to transmission would allow for 200 GW of potential power production, equal to ⅕ of existing U.S. electricity generation capacity.[25,26]

The thermal energy generated by a CSP solar field does not need to be immediately used for power generation but can be stored for later use. Thermal energy can be stored much more efficiently than electrical energy, typically in the form of molten salt held in highly insulated storage tanks. Other alternative storage media, including concrete, water, synthetic oils, and phase-change materials, are being considered. Storage gives CSP technology several considerable advantages:

- Reliable operations during cloudy or nighttime conditions
- Near instantaneous dispatchable power to meet expected and unexpected peak demand
- The ability to shift electrical production from the natural peak of insolation to higher-priced peak demand, thereby increasing profitability and investment returns
- The ability of the solar field to be oversized relative to turbine capacity, thereby decreasing turbine costs, increasing the capacity factor, and reducing the payback period[27]

Lastly, CSP plants can be easily hybridized with fossil-fuel heat sources (e.g., natural-gas-fired boilers), which increases plant reliability because the fossil-fuel back-up can bridge periods when sunlight is insufficient. Furthermore, the fossil-fuel heat sources can be used to boost operating temperatures to maximize plant efficiency and output.

Achieving Gigaton Scale

To abate 1 gigaton of CO_2e emissions globally, approximately 492 GW of CSP capacity, or roughly 4,900 plants of 100 MW capacity, would need to be added by 2020.[28] This would represent approximately 9% of global, or slightly more than 45% of U.S., projected electricity generation capacity in 2020.[29] If transmission constraints are set aside, land resources are more than ample to meet the gigaton goal.[30] Promising areas for CSP plants include the U.S., Spain, North Africa, the Middle East, India, Chile, Mexico, and Australia.

Scaling the Industry

In many respects, natural gas plants operate similarly to CSP and have similar construction periods, so they can be used as a reference for CSP plant potential.[31] As a point of comparison, over 10 years starting in 1997, natural gas generation capacity expanded by 217 GW in the U.S. alone.[32,33] This 113% expansion was spurred mainly by cheap natural gas prices, which suggests that a price on carbon or a similar policy to achieve grid parity could spur the CSP industry to reach gigaton scale.

To meet the gigaton goal, the projected ramp-up curve adds a maximum 110 GW of global CSP capacity per year, which is not unprecedented growth if we look at natural gas for comparison. In 2002, approximately 60 GW of natural gas-combustion turbines were added in the U.S. alone, which represents a year-over-year installed capacity expansion of approximately 25%.[34,35] Richter et al. (2009) simulated an aggressive CSP deployment schedule that assumes adequate political will and commitment to CSP and associated transmission build-out. The authors estimate annual deployment will peak at 70 to 80 GW per year around 2030. This deployment schedule would yield 2.1 gigatons of CO_2e savings by 2050. Even with a set of moderate assumptions, the authors estimate the world could have a solar power capacity of more than 830 GW by 2050 based on annual deployments of 41 GW.[36] Figure 1 shows the gigaton growth projection for CSP compared to the current projection.

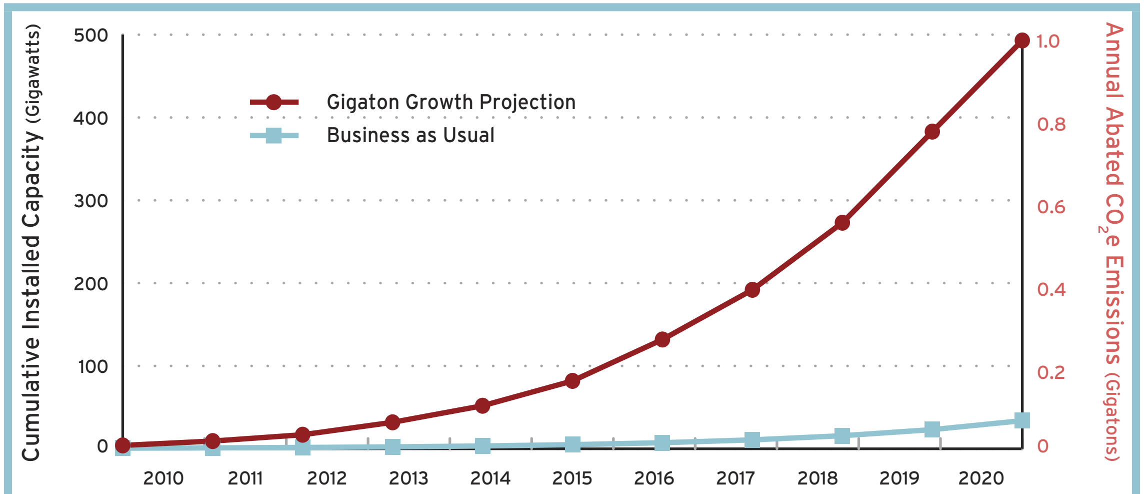

FIGURE 1. Growth in Concentrating Solar Power Generation Capacity. Source: DLR, Emerging Energy Research, L.E.K. Analysis.

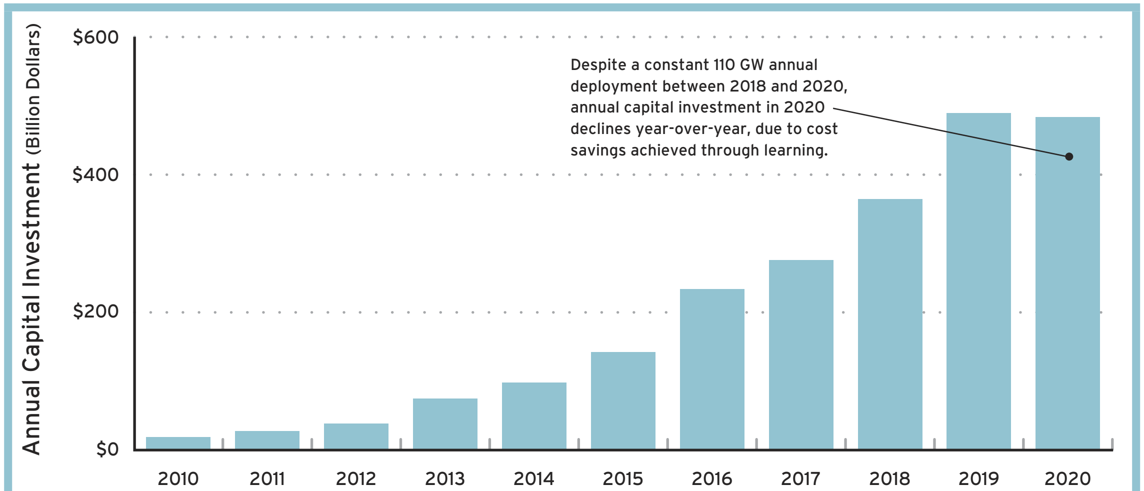

FIGURE 2. Annual Capital Investment in Concentrating Solar Power Generation Capacity. Source: L.E.K. Analysis.

In the absence of a gigaton goal, global solar thermal power capacity is still expected to grow very quickly over the next decade. Emerging Energy Research estimates that CSP capacity will grow at approximately 18% per year to 25 GW by 2020. DLR conservatively estimates that the solar thermal industry could expand to 5 GW installed capacity by 2015, compared to approximately 60 GW projected under the gigaton build-out.

Although CSP does not emit carbon during operation, the construction phase can be carbon-intensive. The life-cycle carbon footprint of solar thermal plants is estimated to be 10 to 90 grams CO_2e per kilowatt hour (kWh) produced.[37,38] This compares to approximately 1,000 grams CO_2e per kWh for coal and 490 grams per kWh for natural gas plants.[39,40,41,42] If we take into account the life-cycle emissions of both CSP and the average grid generation plant (assuming 606 grams CO_2e per kWh), the installed CSP capacity would have to be approximately 470 to 540 GW to abate 1 gigaton of CO_2e emissions annually.

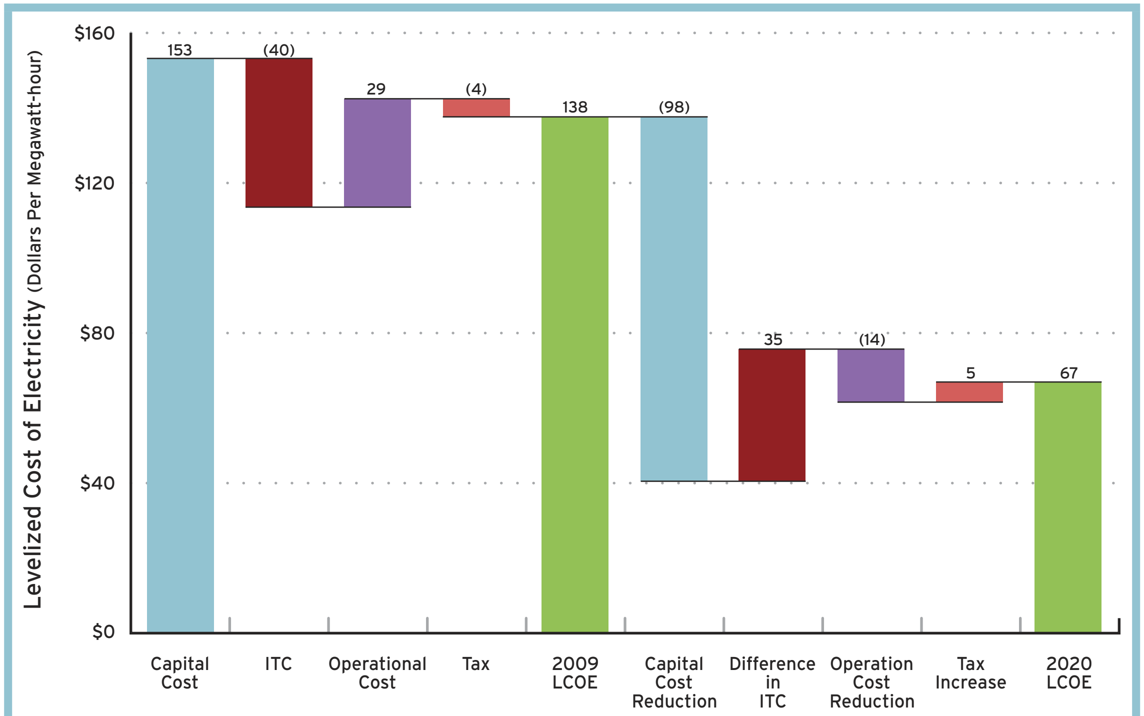

FIGURE 3. Levelized Cost of Electricity (LCOE) for a 100-MW CSP Plant (2009 to 2020).

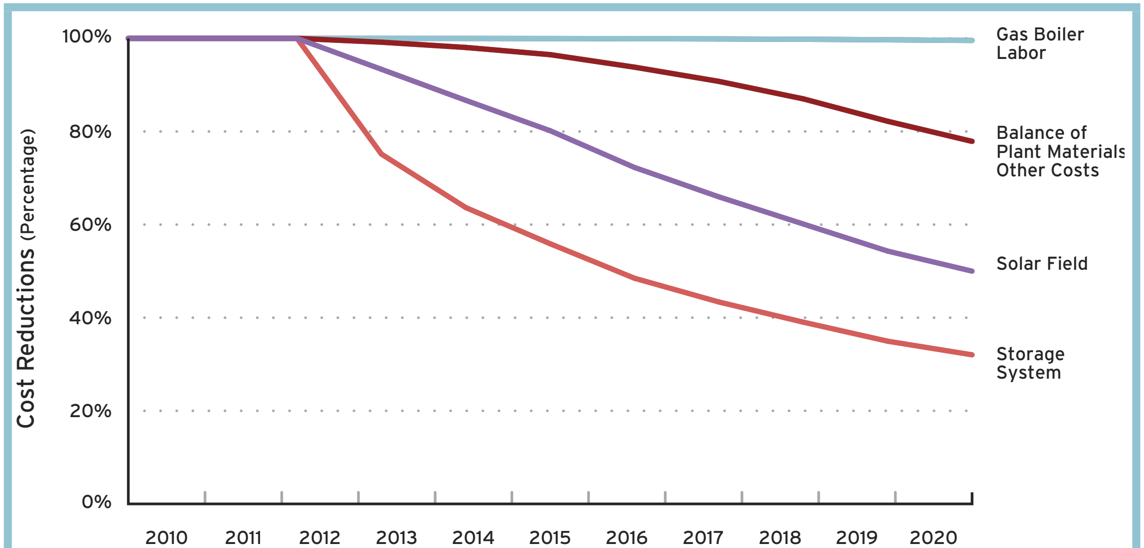

FIGURE 4. Learning Curve-Based Cumulative Cost Reductions.

Capital Investment

To meet the gigaton goal, a cumulative capital investment of approximately $2.2 trillion (nominal), or an average $4,546 per kW, is required. This figure excludes incentives or expenses related to financing. Figure 2 shows annual capital investment in CSP from 2010 to 2020 for the gigaton pathway.

To estimate the level of investment required, we have made assumptions about future cost reductions for specific CSP plant components. For example, additional cost reductions are likely in solar field installations, but relatively few cost savings are expected in turbine and boiler construction and design. In total, the capital costs of a CSP plant are expected to decrease by more than 60% in real terms over the next 10 years. As a result, the LCOE of $67 per megawatt hour (MWh) (real 2009 dollars) in 2020 is 51% lower than the LCOE in 2009 ($138 per KWh).[43] Our LCOE estimates are generally in line with, although slightly higher than, industry estimates, because we include several cost components that are not explicitly accounted for in other studies.[44,45,46,47] Figure 3 shows the LCOE for a 100-MW CSP plant, and Figure 4 shows cumulative projected cost reductions based on increased knowledge about CSP installations over time.

Jobs in the CSP Industry

Construction and operation of solar thermal plants will have significant economic benefits. A large number of component inputs require specialized production, much of which is likely to be local if there is aggressive regional deployment of CSP.[48] Additionally, construction labor is likely to be sourced locally. A 100-MW CSP plant is estimated to create 455 construction jobs per year. Another estimated

3,500 jobs are created indirectly within the supply chain to support construction.

Black & Veatch estimate that 94 operations and maintenance (O&M) jobs are created directly at the plant and indirectly within the supply chain for every 100-MW plant, compared to 56 and 13 for a combined-cycle or simple-cycle natural gas plant, respectively.[49] This is the result of more labor-intensive operations within the CSP plant.

For CSP to reach gigaton scale, close to half a million (approximately 460,000) permanent jobs in operations would be created by 2020. In construction, a maximum of 8.7 million construction workers per year would be required, which is likely a high estimate, as it is a linear extrapolation of current labor requirements. Investment would be needed to provide education and training to expand the solar thermal workforce on that scale.

Figure 5 shows jobs that would be created in the CSP sector during the gigaton scale-up.

Challenges to Accelerated Deployment

Introducing 492 GW of new generation capacity in a 10-year period will require scaling of component industries for solar thermal plants, transmission build-out, and resolution of issues regarding land use and water supply.

SUPPLY CHAIN

Although a significant portion of a CSP plant consists of commodity inputs, components such as mirrors, receivers, and turbines or other generation technology must be sourced from specialized manufacturers. For example, parabolic trough technology requires thin linear parabolic reflectors with a steel frame, specially coated steel absorbers containing a heat-transfer fluid, and steam-driven turbines. Power towers employ components similar to those used in parabolic trough plants, namely small glass reflectors attached to a metal backing with a special coating, a steel tower structure, and a ground-based generator. All of these industries will have to scale many-fold to provide inputs as the technology is deployed.

The cost of CSP is sensitive to the commodity prices of steel, aluminum, glass, and concrete. Price increases in these commodity markets driven by rising global demand and economic expansion in the developing world (China in particular) could result in higher CSP construction costs. One anticipated supply chain constriction is for molten salt.[50] The single source of molten salt is in Chile, and competing agricultural uses (for fertilizer) have already led to restrictions in its availability. Alternative storage solutions are under development in response to this pressure.

Tight turbine supply may hamper an accelerated roll-out of CSP. Leading producers of steam turbines include market leaders Siemens and GE, accounting for just under half of total production, as well as Alstom, LMZ, Mitsubishi, Toshiba, Hitachi, and Skoda, among others.[51] Manufacturing capacity for turbines has not kept pace with demand, resulting in stalled availability and leading GE to announce a $50-million investment to increase production capacity at its steam-turbine facility.[52] Prior to the economic downturn of 2009, wait periods for steam turbine delivery exceeded 3 years because of bottlenecks at large forging plants. In 2009, they are expected to approach 30 months but are unlikely to fall below 2 years.[53]

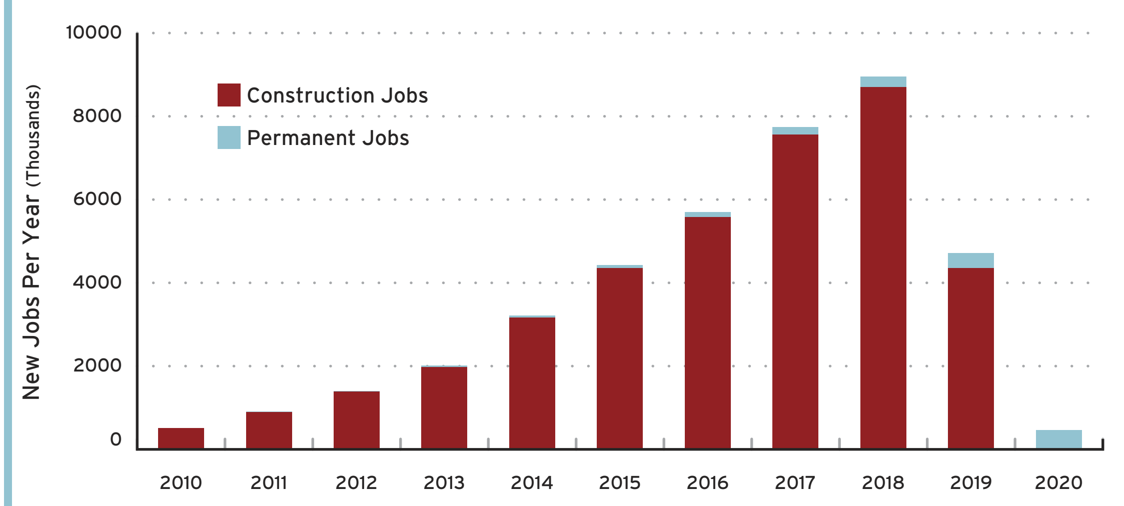

FIGURE 5: Jobs Created in the Concentrating Solar Power Industry. Source: Stoddard, L., et al., L.E.K. Analysis.

LAND QUALIFICATION, ACCESS, AND ECOSYSTEMS

Land-use considerations are an important issue because CSP plants require large areas of contiguous land. For example, Ausra's relatively efficient design requires 1 square mile of space for a 177-MW CSP.[54] Expanding to 492 GW could require in excess of 3,000 square miles, which is slightly more than 2% of the land mass of Nevada.

Ecosystem concerns arise when proposed sites are in sensitive desert areas. The deployment of large-scale solar affects local ecosystems through shading or complete coverage of land tracts. The need to complete environmental reviews and take habitat concerns into account will slow down deployment in some areas. The lack of unified permitting policies can place substantial multi-year delays on CSP deployment. This is an area where policy support can accelerate permitting and deployment time significantly.

WATER

Depending on the technology used and the local geography, access to water could be a constraint on deployment of CSP. The degree of water constraint depends on a plant's use of water as a working fluid, heat-transfer fluid, and/or cleaning fluid for the solar collectors. Technical advances would allow dry cooling of the steam cycle, reducing water needs by 90% compared to water usage in wet-cooled plants.[55,56] Innovations in soil-resistant mirror coatings would also dramatically reduce water requirements.

TRANSMISSION

The areas of the world with strong solar thermal resources, including the southwestern U.S., Gobi desert, Northern Africa, and Tibetan plateau, are not necessarily close to cities and other major load centers.[57] High insolation requirements make the technology unsuitable for high-demand regions with insufficient sunlight for CSP, such as the UK, Germany, and Japan.[58] Thus, for CSP reach the gigaton goal, a global transmission build-out would be required to link solar generating regions to load centers. The required new high-voltage transmission lines could use direct current, as this method can transport electricity with lower line losses over long distances (>500km) than alternating current.[59]

Estimates for the costs of transmission infrastructure construction are notoriously unreliable as they are highly dependent on topography, line length, and other project-specific features. Various cost estimates suggest that transmission requirements could add 10% to 20% to the capital investment required for CSP plant deployment.

Technology Innovation

Further technological innovation is required to bring down CSP technology costs and improve operating efficiencies. Key areas for research and development (R&D) include:

- *Increased thermal storage capacity* — Thermal storage allows a plant to increase both the availability and value of its energy.
- *New collector space frame designs* — Components in the solar field account for 25% of the cost of a CSP plant. More efficient designs would minimize materials use and decrease plant installation costs.
- *New reflective surfaces* — New surface treatments could increase optical efficiency of collectors and further reduce solar field costs by reducing the collection area required.
- *Modular collector designs* — Small, modular collectors can be easily installed and rapidly deployed, which would further decrease solar field construction costs.[60,61]

Game Changers

Several advances could dramatically change CSP expansion prospects, by lowering costs. (See Figure 6.)

SIGNIFICANTLY LOWER COSTS FOR LARGE-SCALE THERMAL ENERGY STORAGE

Molten-salt storage systems cost between $30 and $50/kWh-thermal. If storage costs decreased to $15 to $20/kWh-thermal or less, CSP with large-scale thermal storage could become a baseload technology. One proposed low-cost storage medium is concrete. First-generation prototypes have successfully been operating for 2 years and generating more than 300 kWh annually.[62] Effective low-cost thermal storage would increase the capacity factor of CSP plants, enabling them to generate and sell more power and recover costs more quickly.

Currently, thermal storage research is focused on both solid thermal energy storage media and phase-change materials. Direct storage of steam is used at PS10, but this method is limited to providing buffer storage for peak power generation. Solid-state storage media include high-temperature concrete, alumina, and rock. Phase-change materials, such as sodium, potassium nitrates, and chlorides, offer cost savings because of the high amount of energy that can be stored in very low volume.[63]

A cautionary note on storage: although a variety of storage mechanisms are available, they have yet to be proven economically viable. Spain's Andasol 1 is the first grid-tied plant to use molten salt for thermal storage, with the ability to run its 50-MW turbine for 7.5 hours on storage alone. However, the plant is heavily supported by Spain's feed-in tariffs that pay 2.5 to 3 times the average electricity price and limit qualifying facilities to 50-MW turbines.[64,65] It remains to be seen whether molten salt or other storage media can be economically deployed without subsidies.

HIGH-OPERATING-TEMPERATURE SYSTEMS

Current CSP plants are designed to operate near 500°C. Raising the operating temperature range would have several material benefits. Most importantly, higher operating temperatures would allow use of dry heat exchangers for thermal exhaust, thereby dramatically decreasing the need for water for cooling. Furthermore, CSP plants would be able to operate with greater turbine efficiency, which would decrease land use per unit of output and support higher density around transmission interconnects.

However, higher-temperature environments can put considerable stress on components, and certain storage salts can become corrosive at high temperatures. Research is directed at overcoming these drawbacks.

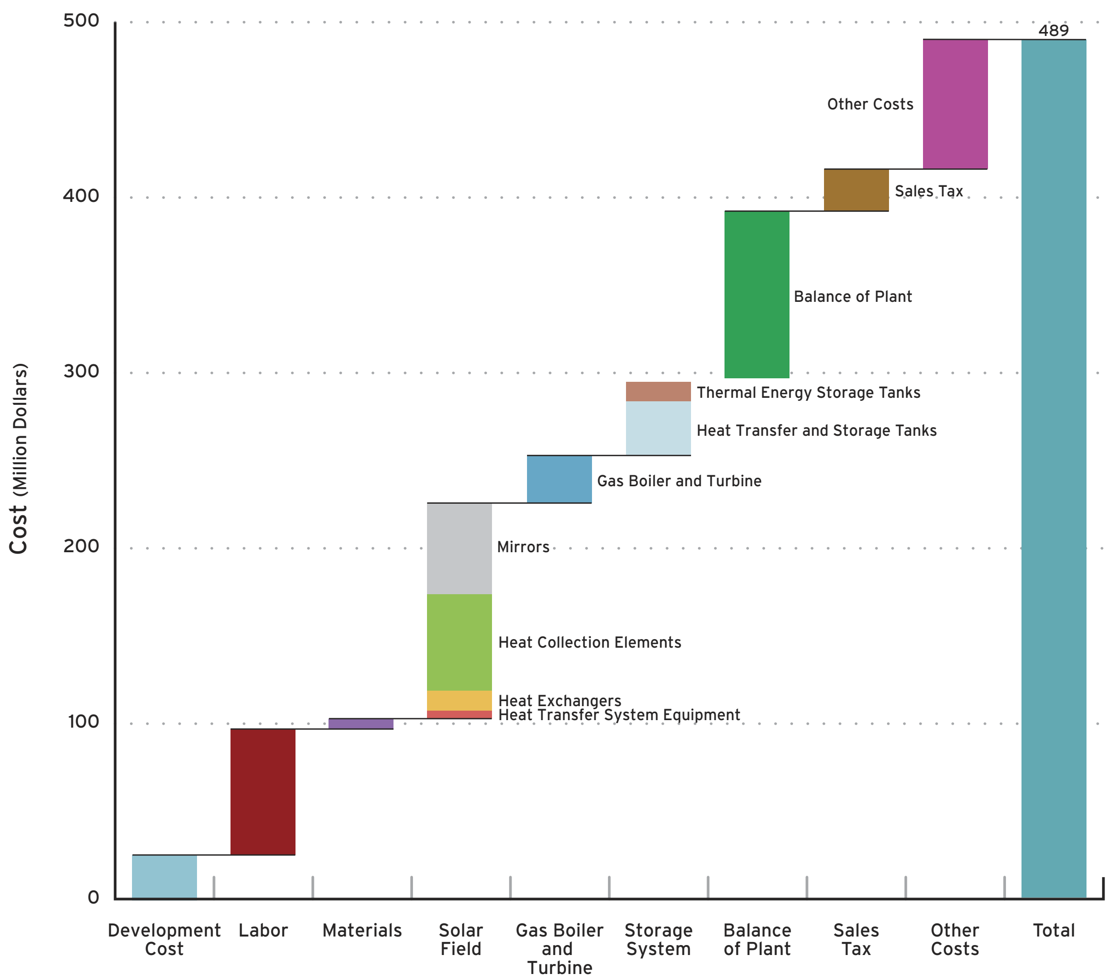

FIGURE 6. CSP Plant Cost by Category for 100-MW Capacity Plant.

Public Policy

The lesson from the 1980s is that stable energy policy can make or break the industry, as evidenced by the Luz bankruptcy, which was precipitated by cancellation of tax credits. Lead times for CSP development and construction are long — in excess of 2 years[66] – such that, for example, only a distant-horizon investment tax credit (ITC) expiration would allow sufficient time for projects to take full advantage of tax credits. Stable public policy that supports the technology-neutral development of renewable energy — including a direct carbon tax, loan guarantees for large projects, and feed-in tariffs — is needed to support the 1-gigaton growth trajectory.
In addition, policy areas that are critical to achieving gigaton scale specifically with solar thermal energy include solar enterprise zones, ITCs and loan guarantees, and transmission regulation.

SOLAR ENTERPRISE ZONES

A preemptive inventory by governments of available and suitable lands for CSP siting would be a major step in preparing the way for substantial solar thermal expansion. The Renewable Energy Transmission Initiative (RETI) is undertaking such an effort in California, with plans to assess available land based on cost effectiveness and environmental benignity. RETI will then identity renewable energy zones and begin transmission development. RETI is an excellent model for national and international expansion. Government funding could be used to accelerate the effort.

Shading from mirrors where land is sloped can make siting thermal power plants difficult. Public support for CSP would ideally lead to government pre-approval of large areas of desert where the shading and grading impacts of CSP and utility-scale plants would be minimal. Environmental impact assessment may be required for other aspects of the installation, including water usage. Pre-approval could significantly shorten the pre-construction stage and expedite deployment of solar thermal generation.

INVESTMENT TAX CREDITS AND LOAN GUARANTEES

Similar to wind power, solar thermal's long project lead times increase the need for and efficacy of a long-term stable policy environment. Developers will not initiate projects if financing is uncertain. A long-term extension of tax credits in the U.S. and other countries beyond 2016 that matches the long-term horizon for developing CSP could stimulate investment significantly. For example, a National Renewable Energy Laboratory (NREL) analysis simulated the effects of an ITC expiration extension to 11 years. The study found that this extension would lead to a 22-fold increase in CSP deployment over the business as usual projection.[67] Conversely, Spain's recent reversal of its feed-in tariffs has left several developers stranded.[68]

Large capital costs are associated with building a solar thermal project. Financing availability and risk premiums are major obstacles for projects. Loan guarantees are, therefore, a powerful tool that government could use to expand the CSP sector while demanding accountability from developers. Currently $10 billion in loan guarantees is available in the U.S. for early commercial use of new or significantly improved technologies in energy-related projects, and the American Recovery and Reinvestment Act of 2009 appropriated a further $6 billion in loan guarantees for renewable energy technologies including solar thermal.[69]

TRANSMISSION REGULATION

Current rate-of-return regulations on transmission plants in the U.S. create a barrier to private investment and, consequently, the adoption of solar thermal power. Policy action to revise these regulations would be an important step in supporting large-scale CSP deployment. Congress authorized financial incentives to increase private investment in transmission infrastructure in 2006. However, these incentives have, thus far, not been able to generate sufficient private investment.[70] The magnitude of the investment required to implement gigaton scale suggests that further aligning the private sector with investments in transmission capacity may be an important catalyst for growth.

Transmission build-out suffers not only from uncertainty about costs but also a history of cost overruns resulting from delays and rerouting.[71] Regulatory obstacles such as siting, permitting, and environmental concerns can significantly delay transmission construction. Federal oversight and an efficient approval process could significantly aid the rollout of all types of centralized renewable electricity generation, not just solar thermal.

Interactions with Other Gigaton Pathways

The electricity generation profile of a solar thermal plant overlaps with the load profile of a municipal utility, i.e., CSP is suited to meet daytime peak demand particularly on summer days.[72] Thermal storage or gas-fueled backup enhances the match with utility demand profiles. Thus, CSP can complement clean baseload technologies, such as nuclear and geothermal.

Paired with long-term effective storage, solar thermal could eventually supply baseload power generation. This suggests a possible synergy with the plug-in hybrid vehicle (PHEV) pathway. The proliferation of PHEVs could ultimately provide grid storage for excess power production during the day when solar power plants are at maximum generation. This load could then be transferred to the grid at later points in the day and through the evening.

CSP faces competition from concentrating solar PV and particularly thin-film solar, both of which have similar intra-day and yearly generation profiles. The centralized nature of CSP makes it attractive in terms of wide-scale deployment because on a cost basis it competes more directly with fossil-fuel alternatives. However, the non-distributed nature of most solar thermal necessitates transmission build-out, increasing total deployment cost.

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Construction Materials

MAIN POINTS

- Construction materials can achieve gigaton scale by 2020 for an investment of $445 billion. Creating 328 thousand direct new jobs, and enhancing energy security by reducing energy use.*
- Multiple gigaton-scale pathways exist in the construction materials sector; the biggest single opportunity for CO_2e reduction is low-carbon cement.
- No single country's building sector can achieve gigaton scale alone, with the possible exception of China if that country shifted to low-carbon cement production.
- Jobs and investment numbers based on transformation of the cement industry.
- Green building materials are the fastest-growing sector in the building materials category.

Overview

The global construction sector presents a tremendous opportunity for carbon emissions reduction, sustainable growth, and innovation. The combined construction and manufacturing sectors accounted for an estimated 17% of total global emissions in 2005, or approximately 9 gigatons of carbon dioxide equivalent (CO_2e) emissions.[1] Construction intensity is predicted to increase more than 5% globally during the next several years, largely from activity in China and India.[2]

The manufacture of building materials and components accounts for between 40% and 50% of the total global flow of raw materials.[3] Given emissions proportional to raw materials processed, this implies 4 to 4.5 gigatons of CO_2e directly from the construction industry in 2005, increasing at roughly 2.5% per year.

The construction materials sector is baroque, in need of modernization. Concrete is a perfect example. This most commonly used material got its last update in the late 1800s. The industry — which has been the subject of media attention and alone emits more than 2 gigatons of CO_2e per annum — is under pressure to change. Other areas of the trade have equal (if not as large) potential for improvement.

Gigaton Pathways in the Construction Materials Sector

There are a number of pathways to substantial CO_2e reductions in the construction materials sector. Below are five that have the potential to reach gigaton scale. The first three focus on commonly used construction materials, and the last two target construction industry practices:

1. Concrete
2. Wood products
3. Ceramics and glass
4. Whole-building design
5. Salvage

A strategy that targets one of two ubiquitous building materials (concrete or wood) could achieve the gigaton goal. Eliminating 1 gigaton of CO_2e through the concrete sector would require that 50% of portland cement production used in concrete — roughly 2,000 megatons of production — be low carbon by 2020. The wood strategy entails substitution of wood for higher-embodied-carbon materials in structural applications and, at the same time, replacing wood with lower-carbon materials in other applications. Engineered wood is also part of the solution here. The ceramics and glass strategy includes changes in raw materials as well as furnace size, fuel, and other production process elements. A whole-building design approach would target carbon reductions in a range of common building materials, including flooring, siding, roofing, and concrete. The salvage approach focuses on resource recovery and avoidance of new emissions through reuse of previously used materials.

Product innovation (development of low-carbon materials) and conservation-minded design are essential in the new age of building materials. New materials under development include biocomposites, such as polymers grown by microorganisms, and products fashioned out of waste streams (recycled materials). Conservation-minded designs use products with recycled content such as cellulose (recycled newsprint) or cotton (recycled blue jean) insulation as well as salvage materials.

PATHWAY 1 – CONCRETE

Concrete is composed of cement mixed with water and aggregate (gravel, crushed stone, and sand). The most commonly used cement is portland cement, produced from limestone in an energy-intensive process that uses high-temperature kilns. The energy use by the kilns is the root cause of the high CO_2e emissions associated with concrete use. The cement industry is responsible for an estimated 5% of global carbon emissions, or 2.1 gigatons CO_2e, with worldwide cement production (and thus emissions) projected to almost double by 2020.[4] Low-carbon cement mixes currently under development could cut CO_2e emissions associated with cement production approximately in half and avoid more than 1 gigaton annually by 2020. This strategy requires high adoption levels to achieve the 1 gigaton target. Production capacity in the cement industry is projected to increase at 5% compound annual growth rate (CAGR) during the next 10 years. If this expansion occurs through investment in low-carbon cement production, more than 1 gigaton of CO_2e emissions could be avoided in 2020.

PATHWAY 2 – WOOD PRODUCTS

The embodied energy in wood is low relative to the embodied energy in other common building materials such as concrete and steel. In applications where wood can be substituted for concrete and steel, e.g., for residential house framing, carbon savings can be realized. However, in other applications where wood is traditionally used, e.g. flooring and siding, carbon savings may be achieved by switching away from wood. Examples of materials with even lower embodied carbon than wood include bio-based products, such as bamboo, and recycled materials. A key consideration when comparing wood and its substitutes is the energy (and carbon) associated with transport of materials. Transport of low-carbon materials can rapidly erode the benefits associated with their use. For example, imported bamboo used in construction in Denver, Colorado has higher embodied carbon than on-site concrete production because of the energy required to move bamboo from its Asian point of origin.[5] Embodied energy in bamboo is only 15 megajoules (MJ)/ton; in comparison, the embodied energy in cement is 1,452 MJ/ton. However, the transport of bamboo requires an estimated 4,928 MJ/ton. Transport using cleaner fuels, e.g., new biofuels, or local growth and production of materials could alter this equation.

The Consortium for Research on Renewable Industrial Materials (CORRIM) found a net savings of 26% (11 metric tons CO_2e) per home when switching from steel to wood-frame construction at a representative test site in Minneapolis. CORRIM also reported a savings of 31% (7 tons CO_2e) when switching from concrete to wood in Atlanta.[6] The different climates dictate different uses of materials, including insulation levels, which lowers the overall carbon intensity of the Atlanta home relative to the Minneapolis home. Concrete and steel houses account for 18% and 8% respectively of the residential construction market, with market share increasing. An estimated 6 megatons of CO_2e could be avoided in the construction phase of homes in the U.S. by switching from these higher-embodied-carbon materials to wood.[7] This achieves less than 1% of the gigaton goal, but, if extended globally, the impact of this shift could be much larger.

A chief concern about possible increased reliance on wood is the impact on forestland and ecosystems and, in general, whether further scaling of the industry could be achieved sustainably. Currently, nearly 1.4 billion tons of roundwood are produced globally per year. The total embodied carbon in wood products depends on harvesting, processing, and, ultimately, transport. The embodied energy from wood use in the construction industry ranges from 7.4 to 16 MJ/kilogram (kg) depending on the level of processing.[8] Total embodied carbon in the 1.4 billion tons of roundwood used annually is estimated to be close to 800 gigatons. This is not an annual figure because energy inputs for wood production occur over a 50- to 100-year period. The implied annual embodied carbon is therefore between 8 and 16 gigatons CO_2e. Substituting low-carbon materials for wood remains an area of great potential. Lower-carbon alternatives to hardwood flooring include engineered wood, bamboo, cork, recycled rubber, and linoleum. Biocomposites that are still under development may prove to be another important area.

PATHWAY 3 – CERAMICS AND GLASS INDUSTRIES

The Intergovernmental Panel on Climate Change (IPCC) reports that there are no currently reliable statistics on international production of ceramics and glass. Based on reported consumption of bricks, tile, and other ceramic products in China, the European Union (EU), the U.S., Pakistan, India, and Bangladesh, worldwide consumption exceeds 2 gigatons a year of product, resulting in estimated emissions of more than 400 megatons of CO_2e.[9] Annual per-capita consumption of ceramic products (in tons) in China is estimated to be three times the consumption in the EU and 10 times the consumption in the U.S. (1.2, 0.4, and 0.1 tons/per capita, respectively). The combined annual production of container and flat glass is estimated to produce emissions of 40 to 50 megatons CO_2e. With construction rates continuing to rise, both industries are projected to expand.

Emissions are largely attributable to the energy required to run large furnaces or kilns in the processing phase. In this sense, the production of glass and ceramics is comparable to the production of cement. Glass is produced by melting raw materials, generally silica, soda ash, and limestone. Ceramics are fired in high-temperature kilns. There is a high degree of variability in energy use across the industry, which includes both large industrial operations and cottage and artisan industries. Changes in materials composition — e.g., the increased use of cullet (recycled glass) and, for ceramics, substitution of clay and shale for fly ash — reduces the carbon footprint of these industries. Technologies that blend minerals with other batch components to reduce the melting point of the batch are an energy-saving approach currently under development.[10] Other approaches include increasing furnace size, using regenerative heating, switching to natural gas from oil, or further optimizing production by improving process control and reducing rejection rates. Installation of larger oxy-fuel furnaces could facilitate carbon capture and sequestration.

PATHWAY 4 – WHOLE-BUILDING DESIGN

A fourth gigaton-scale strategy targets whole-building design. The carbon emissions associated with construction of the average U.S. home vary based on location and building materials employed. The CORRIM model estimates CO_2e emissions ranging from 23 tons to 47 tons for homes constructed using different frames at two test sites: Atlanta (warm climate) and Minneapolis (cold climate). At an average value of 39 tons per home, the projected 2 million U.S. homes to be built between 2010 and 2020 would account for 78 megatons of CO_2e annually. Worldwide, with even higher construction rates in developing countries, total carbon emissions from residential construction could come close to 1 gigaton.

Based on estimates of construction-related annual carbon emissions currently exceeding 2 gigatons and increasing, a reduction of 50% in the amount of energy consumed in the construction of residential and commercial buildings could avoid 1 gigaton of carbon emissions in 2020. The whole-building strategy would introduce a portfolio of lower-carbon materials that, collectively, could achieve the 1-gigaton CO_2e reduction level. Typical components for residential construction include wood or steel studs with sheathing, insulation, gypsum board, siding for exterior walls, windows composed of frames and specified glass type, polyethylene vapor barrier, wood roof trusses, and shingles. Innovations to reduce the carbon footprint of building construction include low-carbon replacements for gypsum board, roof shingles composed of recycled materials, and cellulose insulation in place of mineral wool or polystyrene, all of which are available today.

In commercial construction, the heavy use of steel and cement pose a significant challenge. However, the use of lower-energy components, particularly glass, that don't play a structural role could still deliver significant savings in this sector.

PATHWAY 5 – SALVAGE

Resource and energy recovery from previously used building materials could avoid significant carbon emissions. A recent study by the U.K. Department for Environment, Food, and Rural Affairs (DEFRA) examined CO_2e offsets from enhanced recycling and energy harvesting programs for common waste streams. The study estimates that energy harvesting from wood products could reduce emissions by between 11 and 80 megatons of CO_2e annually in the U.K. Recycling of non-ferrous metals would offset 10 megatons of CO_2e and ferrous metals 44 megatons of CO_2e in the U.K.[11] Scaled globally, these programs have the potential to offset 1 gigaton of CO_2e annually.

Carbon offsets from resource and energy recovery are sensitive to the energy used to transport recycled goods. To achieve maximum savings, local processing is required. Reuse of ferrous and non-ferrous materials can offer significant offsets. Because wood products contain relatively low embodied energy, energy recovery is favored over resource recovery; i.e., burning wood to recover its embodied energy is preferable to substitution of new harvesting although both energy recovery and resource recovery offer carbon savings.

Building materials reuse centers already operate in a number of U.S. cities, including Minneapolis, Chicago, and New York. A non-profit, Reuse People of America, opened a building materials center in Los Angeles in June 2008. The center aims to recycle 1,500 tons of building materials waste during its first 2 years; that amount represents less than 1% of the estimated 160 million tons of building materials making their way into landfills in the U.S. The estimated carbon savings from recycling the entire waste stream are between 130 and 210 megatons of CO_2e. The Bioregional project in the U.K., among others, is developing similar organizations based on the U.S. model.[12]

Industry Background

The building materials industry can be subdivided into several product categories, some of which correspond to the gigaton pathways previously identified: concrete and wood products (includes flooring and millwork). Other product categories correspond to the ceramic and glass and whole-design pathways: siding and roofing, windows, and thermal insulation. Figure 1 describes the building materials industry product categories and key trends. Green building materials is the fastest-growing market in the construction materials sector. A noted problem facing the industry is the need for certification or standards for "green products."[13] Certification should be based on a complete life-cycle analysis (LCA) of embodied carbon in products. The Athena Institute has developed an LCA model that takes into consideration product manufacturing (including energy used in reprocessing recycled materials), on-site construction, maintenance and replacement, and demolition. The on-site construction estimates consider the carbon impact of transporting materials to the construction site. To create a workable system, a standard "at gate" rating could be issued based on embodied carbon in a product when its manufacture is complete, to which transportation carbon could then added based on the final destination. The U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) is studying the embodied carbon in products as an additional consideration for its existing building guidelines.

PRODUCT CATEGORY	DESCRIPTION	EXISTING "GREEN" OPTIONS
Wood Products	Hard and soft lumber, plywood, board (particle, fiber, block, and oriented strand), veneer	Sustainable forestry certified woods; salvage woods
Siding	Wood, plastic, metal, stucco, fiber cement, and stone	Product selection based on recycled content and recycleability, including aluminum, plastic, stone, and wood
Windows	Double-paned, glazed, steel-framed, wood-framed, polyvinyl chloride (PVC)-framed	High-R-value windows
Flooring	Solid wood, finished/prefinished wood, engineered wood, parquet	Sustainable forestry certified woods; bamboo, cork, coco palm
Thermal Insulation	Mineral wool, including fiberglass, cellulose, plastic foam, structural insulated panels (SIPS)	Cellulose (85% post-consumer natural fiber, typically newspaper) and fiberglass with greater recycled content (>35%)
Millwork	Ready-made wood products, including molding, doors, and cabinets, among other products	Sustainable forestry certified woods; bamboo, cork, coco palm

FIGURE 1. Green Building Materials Product Categories and Trends. Source: SBI (2007) *Green Building Materials in the U.S*

Concrete

Clinker, which is produced by an energy-intensive process of heating limestone to high temperatures, is the main feedstock for cement used in concrete production. The energy used to produce clinker accounts for more than half the embodied carbon in cement production. Blending agents that replace clinker in cement production, including pozzolona (volcanic ash) and fly ash from coal-burning plants, can reduce carbon emissions associated with the process by half. However, pozzolona and fly ash availability will ultimately constrain this technology from scaling fully. Hemp-lime masonry is being researched as another alternative to portland cement.

The cement industry is reasonably consolidated with several dominant global players: Lafarge, Holcim, Heidelberg, Cemex. The high capital cost of new facilities is a barrier to entry by new enterprises. The industry is also vertically integrated, with large producers of cement mixes (portland and masonry cement) also active in the ready-mix concrete and concrete products businesses. Ready-mix concrete is the biggest end use of cement, accounting for approximately 75%. The second largest end use is concrete products, which includes tiles, bricks, blocks, and pipes. The current global market size is estimated to be over $250 billion.[14] The current market in the U.S. for cement products is estimated at $12 billion, with projected growth of 3% over the next 5 years.[15] The U.S. market experienced a slowdown between 2007 and 2009, in keeping with an overall downward construction industry trend during this period.

Notably, U.S. cement production is a very small percentage (approximately 4%) of global production; in contrast, China accounts for more than half of global production. Global cement production is currently estimated at 2,644 megatons and predicted to reach 4,000 megatons by 2020. An estimated 118 cement plants operate in the U.S.[16] India is second to China in cement production; Japan, Korea, Spain, Russia, Thailand, Brazil, Italy, Turkey, Indonesia, Mexico, Germany, Iran, Egypt, Vietnam, Saudi Arabia, and France all produce between 20 to 70 megatons a year.[17]

Wood Products (Including Flooring and Millwork)

Substituting sustainably harvested wood for steel or concrete framing in residential homes could reduce carbon emissions during construction by 21 to 37% per home. The chief concern with increased wood use is global deforestation. The two current certification standards for sustainably harvested wood products are by the Forest Stewardship Council (FSC) and the Sustainable Forestry Initiative (FSI). The latter organization is sponsored by the timber industry. A report by the FSC estimates the annual U.S. certified, or green, wood market at $5 billion out of a total $45 billion.

Deforestation from increased use of wood can be minimized through the use of salvage wood. There are a number of current salvage operations. Engineered woods and plastics can be substituted for wood in some applications and could reduce overall wood use in residential construction or offset expanded use of wood for framing if the industry shifts away from steel and concrete.

In the U.S., the lumber and plywood manufacturing industries encompass roughly 5,000 companies. The lumber industry is composed of timber management companies and logging companies. In the U.S., there are approximately 300 of the former and 12,000 of the latter. The timber industry is a $30-billion industry.[18] The sale of lumber and other structural materials accounts for 74% of revenue in the $74-billion market for building materials dealers. This 2008 figure was down 1.3% from 2007, reflecting a downturn in home spending.[19]

Wood is a popular choice for flooring. The overall U.S. flooring market was $2 billion in 2006. The market for green flooring, including wood substitutes such as bamboo, cork, cocopalm, and certified wood, was an estimated $300 million and growing at 19% per year. The criticism of these alternatives to wood flooring is the high energy cost for transporting them from their location of manufacture to building sites worldwide, which possibly outweighs the benefits from relying on materials with "at gate" lower embodied energy. The flooring sector has reportedly low penetration of green products to date.[20]

The millwork category comprises ready-made wood products, including molding, doors, and cabinets. Trends include using exotic woods and larger-profile molding and millwork. The market is estimated to grow slowly in 2009 (1.7%) to $9.8 billion in the U.S.[21]

Siding and Roofing

In the siding market, products with recycled content or the potential for easy recycling are being marketed as green. These include aluminum, wood, some plastics, and stone. Engineered siding typically involves less on-site waste during construction, as it is pre-fit, and can include recycled content. One example of engineered siding is a wood-cement hybrid, where wood fibers are mixed with cement to produce a durable product. From the carbon-emissions-reduction perspective, the longevity of the product is important, i.e., that it either will not need replacement during the lifetime of the building or can be reused. Engineered siding also makes used of fingerjointed materials, which bond together small pieces of scrap wood (that might otherwise be wasted) to form larger pieces. Finally, siding can be built with materials from other waste streams, such as sawdust or paper. Lower-carbon materials that are aesthetically acceptable and durable could transform the siding market.

The U.S. siding market was estimated at $5.5 billion in 2008 and is projected to grow by 3.5% annually during the next 5 years.[22] The industry is highly fragmented, with many sellers serving smaller regional markets. Firms compete principally on price. Entry into the wholesale market is not significantly hampered by licensing requirements, government regulation, or resource constraints. Large competitors in this area include Owens Corning Sales, LLC; American Builders & Contractors Supply, Co., Inc.; Guardian Industries Corp.; and Gulfside Supply, Inc. Two trends affecting the profit margins in this industry are rising energy costs (affecting processing and transportation costs) and increasing prices for raw materials.

Standard roofing materials include asphalt shingles, metal guttering and downspouts, solar reflective film, and weatherstripping products. Green variants include shingles made of recycled rubber, tile, or other recycled materials. The U.S. roofing market is estimated at $6.1 billion, growing at roughly 10%.

Windows

Recent advances in windows do not necessarily entail less energy-intensive manufacture but focus on improved building energy efficiency, i.e., higher insulating value (R-value). Processes that reduce the energy required to produce flat glass, such as mineral additions to lower the melting point of the batch, have the potential to reduce embodied carbon in windows.

The U.S. windows market was estimated to be worth $10.6 billion in 2008.[23] There was a slow downturn in windows sales in the U.S. in 2008-2009, in keeping with the overall slowdown in the construction market. The market for U.S.-manufactured glass is projected to grow at around 2% in 2009, with some recovery in the construction market but continued pressure from imported products.

Thermal Insulation

The insulation market is dominated by two main types of insulation: mineral wool, which includes fiber glass, and plastic foam. In the U.S., these two types of products account for approximately 90% of sales. Cellulose, primarily composed of recycled paper, is considered a green alternative to fiberglass and polyurethane products. Other insulation products marketed as green include wool and recycled cloth (blue jeans).[24] Low-carbon, easy-application insulation technologies could scale to offset carbon in both the retrofit and new construction industries. Spray insulation or loose insulation is typically easier to install in retrofits. Aerogels, whose predominant use is currently in the packaging industry, are known for their high thermal efficiency (up to 40 times the insulating power of fiberglass) and can significantly reduce the volume of insulation required. Aerogels can provide the same level of insulation as standard materials, e.g. mineral wool and cellulose, while occupying approximately ⅓ the volume. Applications of aerogels for building envelope insulation are not currently cost competitive. Aerogel applications in the refrigeration sector could enhance refrigeration efficiency, with refrigeration accounting for close to 40 gigatons of CO_2e emissions in the U.S. residential and commercial sectors.

Although much of the activity in the green building sector focuses on reuse and recyclability of materials, product innovation is also under way. Biocomposites are an example of a new medium under development with a number of potential applications for thermal insulation. Structural insulated panels (SIPs) are typically composed of timber and mineral wool components. Alternative materials such as biocomposites for use in SIPs promise low carbon content and biodegradability at the end of the building life cycle.[25]

Green Building Materials Market

The U.S. building materials market includes more than 50,000 companies with annual sales totaling $250 billion.[26] Growth in the green building materials category has been strong between 2007 and 2009 despite an overall slump in the U.S. construction market. The 2006 industry constant annual growth rate was an estimated 23%, with wholesale revenues estimated at $2.2 billion, predicted to increase to approximately $5 billion by 2011.[27] Green building materials still represent a small portion (about 1.2%) of the total.

Although growth in the conventional materials sector was down in 2006, sales were up in the green building lines at two large materials suppliers, Honeywell International, Inc. and Carlisle Co. Honeywell saw sales of its energy-efficient “expanding” foam insulation rise by 20%, and Carlisle’s Ecostar roof shingles made of recycled rubber jumped 35%.[28]

Achieving Gigaton Scale

Meeting the 1-gigaton target requires scaling of one or more aspects of the building materials industry and has implications for industry structure as well as land use and public policy. The construction industry is expected to grow globally by more than 5% per year during the gigaton time frame (2010 to 2020), which creates the opportunity to direct planned investment into the manufacture and distribution of green building materials.

Concrete

No single country’s building sector can achieve the gigaton goal alone, with the possible exception of China if that country shifted to low-carbon cement production.

SCALING THE TECHNOLOGY

Figure 2 shows low-carbon cement plant capacity required to reduce emissions by 1 gigaton CO_2e. Most of the new cement capacity going forward will have to be low-carbon cement to achieve the gigaton goal by 2020 in the concrete sector.

CAPITAL INVESTMENT

The estimated capital investment required over the next 10 years to achieve 1 gigaton of CO_2e in the different sectors of the building materials industry varies from $ 8 billion (salvage) to a high of $600 billion (con-

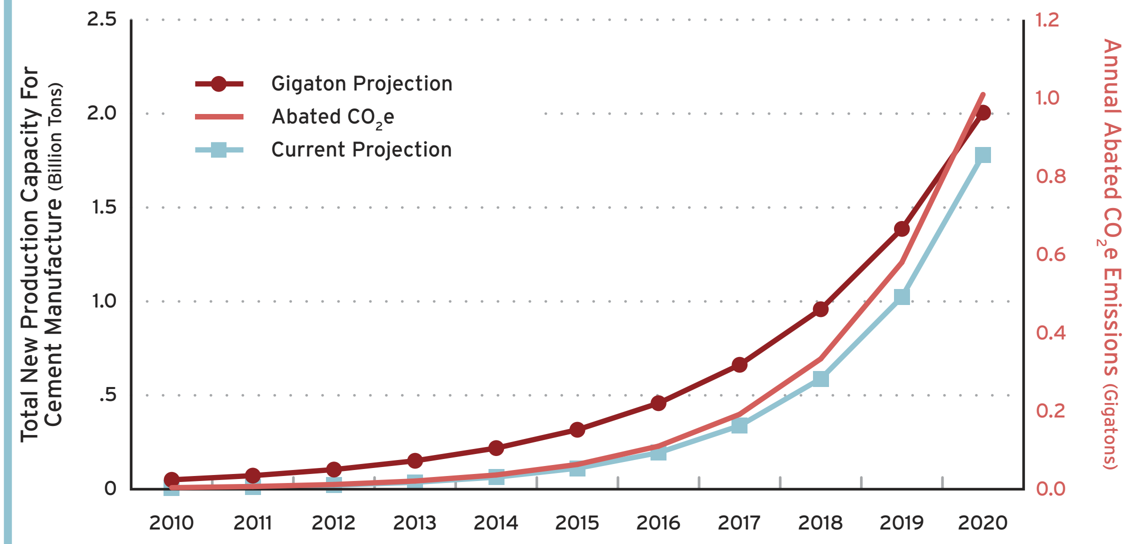

FIGURE 2. Growth in Low-carbon Cement Production Capacity.

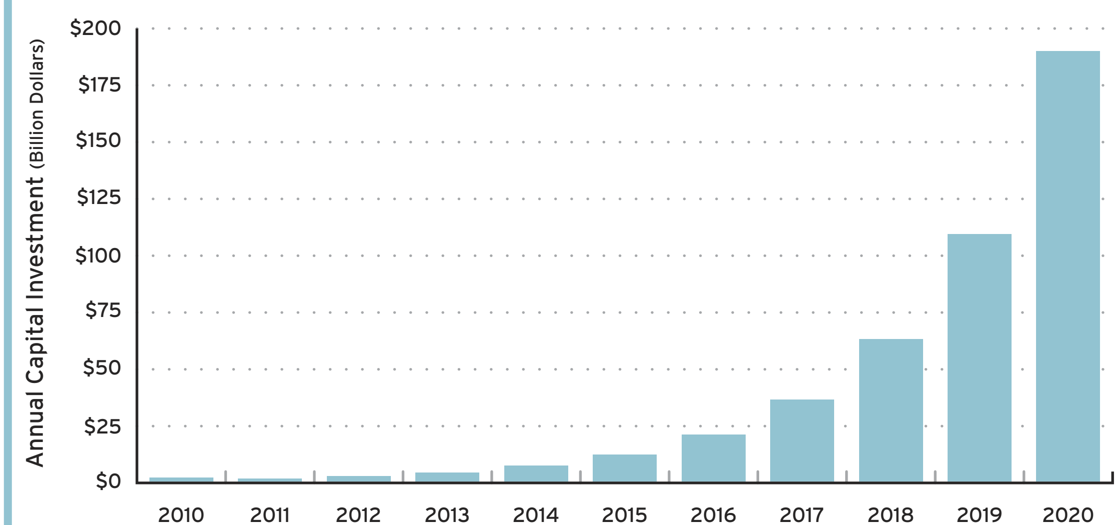

FIGURE 3. Annual Capital Investment in Low-carbon Cement Production. This is the annual investment needed to reach the gigaton goal.

crete), as detailed below. Capital investment required to start up cement production is estimated at between $250 and $300 million for a million-ton facility. Total output by the industry is currently more than 2,600 million tons of cement annually, expected to approximately double by 2020.[29] This implies a $500- to $600-billion capital investment still to come over the next 10 years. Because the U.S. market is only approximately 4% of the global market, much of this investment will take place abroad. Figure 3 shows the annual capital investment in new low-carbon cement plants.

JOBS IN THE CEMENT INDUSTRY

Employment in the cement industry is already projected to grow in accord with industry expansion. The decision to invest in low-carbon cement production instead of traditional portland cement to meet what is projected to be a doubling of demand for cement over the next 10 years would not foreseeably change the total number of manufacturing jobs added. It could have some impact on where job growth takes place. For instance, a U.S. investment in low-carbon cement technology could increase production and add manufacturing jobs within the country. In addition, the conversion of existing facilities could create new jobs.

Figure 4 shows the estimated direct permanent employment numbers for the expansion of the cement industry in the next 10 years

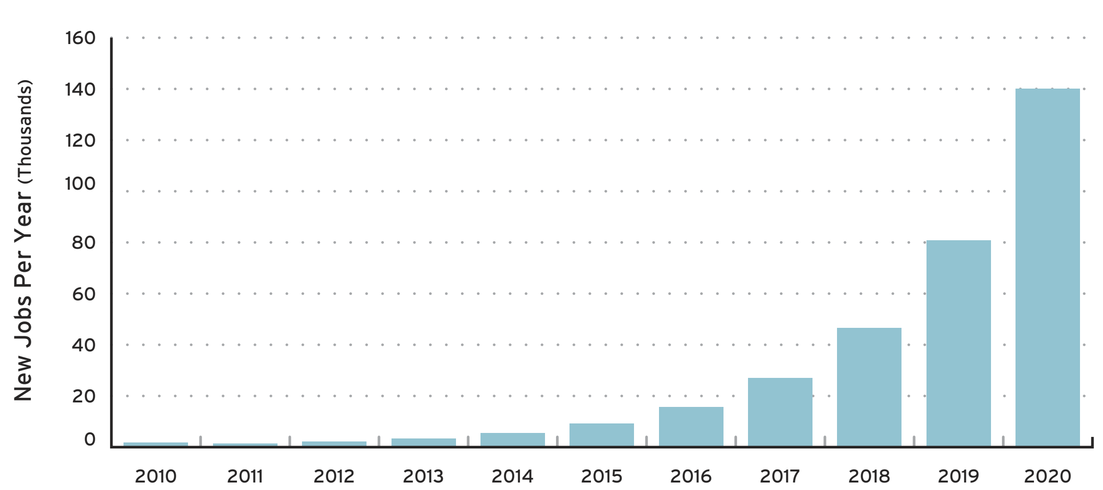

FIGURE 4. Jobs Created in the Low-carbon Cement Industry. These are the jobs created for the gigaton expansion pathway.

Wood Products Industry

The U.S. market for sawn lumber is estimated at 28 billion square feet annually. To support expansion of this market at the projected 3.6% growth rate, the industry will have to invest approximately $88 million per year.[30] Higher penetration levels for green materials and wood substitutes may ultimately decrease this number although a countervailing force is the substitution of wood frames for higher-carbon steel and concrete frames.

In the green building materials market, projections suggest that demand for green wood for structural purposes will grow at 21% per year for the next 5 years. Demand for green flooring and green millwork will grow at 18% and 24%, respectively. The implied industry investment to keep up with these growth rates is $14.1 billion (structural wood), $0.64 billion (flooring), and $4.6 billion (millwork). The combined investment over the next 10 years from 2010 to 2020 is estimated at $342 billion.

Ceramics and Glass Industry

The U.S. glass industry is growing slowly under pressure from imports. Growth is projected at a modest 0.4% over the next 5 years, with imports growing at 3.3%. The glass industry is a capital-intensive industry. Annual investment to support a 3.4% growth rate for construction-related glass is estimated to be $1 billion. (For the entire industry, including container glass and blown glass, the investment level would be closer to $2.35 billion.)

The ceramics industry is also capital intensive, requiring the construction of large furnaces for processing. Ceramic tile is 21.3% of sales in the $21.7-billion flooring market. Capital investment to support annual growth of 2% (constant annual growth rate from 2003 to 2007) is estimated at $190 million. Over the next 10 years, combined investment in ceramics and glass would total more than $14 billion. Additional investment would be required to implement efficiency measures, e.g., increased furnace size or improved process control, to achieve carbon savings in these industries.

Whole-Building Design

Growth in the green building materials sector is projected to exceed average growth across all materials sectors. Total investment in this area — in the insulation, siding, wood products, flooring, roofing, windows, and millwork sectors — to support double-digit growth over the next 10 years will exceed $370 billion. Millwork has the highest projected growth rate (also currently the lowest market penetration) and the second-highest associated cost, at $165 billion over the 10-year period from 2010 to 2020. The structural wood category also requires large capital investment over the 10-year period, upwards of $168 billion. To support growth rates of 13% and 20% respectively, the siding and insulation markets will each require more than $1 billion annually. To support growth of 18% per year, the green flooring sector will require investment on the order of half a billion dollars annually.

Salvage Market

Salvage operations have relatively low overhead. A 1,000-ton facility costs around $50 thousand. This represents a tiny fraction of the U.S. building materials waste stream. Scaling to handle most of the 160 million tons dumped annually in the gigaton time frame would imply a 10-year expenditure of close to $8 billion. On top of this investment, there are labor costs, possible transportation costs, and additional processing costs for certain materials.

Land-Use Implications

Land-use impacts from the building sector include the indirect impacts attributable to increased demand for inputs to processed building materials and the direct impact of urban expansion. The indirect impacts include increases in mining activity (lime, for example, is a primary input to the manufacture of concrete) as well as increased rates of deforestation. Cultivation of wood substitutes, such as bamboo, can also have significant land-use impacts. When relying on non-recycled content, the cellulose insulation industry increases demand for plant fibers, including cotton. The direct impacts of the building industry are from urban expansion and associated the destruction of habitat or farmland. Cities and communities designed to have (or increase) dense populations rather than expanding their land area can prevent continued habitat/farmland encroachment.

Industry Restructuring

The construction industry responds to two pressures: regulation and cost. Regulation that requires either the use of more sustainable building materials or that offers incentives for early adopters would accelerate industry restructuring. Without strong consumer demand for green materials, there is limited incentive to adopt these materials unless they are either mandated under code or cheaper than existing alternatives. New materials or technologies that are cost competitive at gate still face barriers to adoption if their use adds to total construction time for a project. General contractors with green building know-how are integral to efforts to speed the adoption of these new materials. Training programs and workshops by new materials companies help increase awareness and impart necessary skills for working with green building products.

Developers, designers, subcontractors, and suppliers make up the construction supply chain. There are a number of key interdependencies, and the form of the contractual arrangement for a construction project can prove important to innovation. Under typical building contracts, architects draw up the plans but hand over control of a project's execution to contractors, who may ultimately eschew higher-cost design elements, thereby stymieing innovation. Contractors usually attain contracts through bid or price quotes, so cost containment is a key issue. Restructuring of the industry to provide incentives to contractors to procure and incorporate green building materials could boost adoption rates of these materials. Construction materials may be sourced by large materials companies that hold long-standing relations with contractors. This can be both a help and a hindrance. If a materials supplier develops a cost-effective green alternative, there is a direct channel for introduction. However, rigid procurement relations also inhibit competition from new materials companies. More open bidding would address this and also address the information barrier.

Public Policy

Currently, building materials used in construction must comply with industry standards, and the approval process can be a bottleneck for introduction of new materials. Accelerated approval processes for green building materials and new building codes that extend beyond design for energy efficiency and actually mandate low-energy/low-carbon design and the use of green materials would dramatically boost adoption.

In addition, consistent certification of products is needed, based on an accepted LCA as well as on additional metrics that quantify the emissions burden related to transporting products. As the materials sector evolves, there is a pressing need for an easy-to-apply LCA tool and a standard rating system for comparing products to assess their true carbon impact.

There may be resistance to adoption of new building materials both by incumbents and by those bearing the higher cost. Tax breaks or other incentives to reduce the cost associated with green building materials may be necessary initially.

Interactions with Other Gigaton Pathways

Given the long transit distances for some building materials, the use of lower-carbon fuels in place of petroleum could significantly reduce the embodied carbon in a number of prevalent or popular building materials. Biofuels offer significant carbon savings over petroleum. The green building materials market could support transport operations running on clean fuels, delivering materials worldwide.

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Geothermal

MAIN POINTS

- Geothermal can achieve gigaton scale by 2020 – contingent on development of Enhanced Geothermal Systems (EGS) – for an investment of $919 billion.
- EGS development will require an estimated $1 billion in R&D to be market ready.
- Major areas for technology support include transmission, drilling, reservoir stimulation, downhole pumps, energy conversion, and exploration.
- Geothermal will ramp slowly; each project requires roughly 5-7 years.
- Existing hydrothermal (naturally occurring geothermal) resources are projected to be able to contribute 90 GW of installed capacity if fully developed, or 40% of the gigaton target of 238 GW.

Overview

Geothermal energy is a renewable resource with significant potential to reduce carbon emissions. Geothermal systems tap thermal energy trapped under the earth's surface and convert this energy to usable electricity. Geothermal energy is an umbrella term that refers to several types of resources; currently only naturally-occuring hydrothermal resources are being exploited commercially. Enhanced geothermal systems (EGS), in which heat is extracted from the earth by injecting fluid into an artificially created, hydraulically fractured reservoir that attempts to replicate natural hydrothermal conditions, are not yet commercially viable but could be within the next 10 years.

Unlike intermittent alternative energy sources such as wind and solar, geothermal can provide baseload power; it is available 24 hours a day, 365 days a year with capacity factors often exceeding 90%.[1] Moreover, geothermal produces little or no carbon dioxide equivalent (CO_2e) emissions. A large-scale expansion of geothermal energy production could have a huge impact in lowering world greenhouse gas emissions and helping to wean the global economy from fossil fuels. An increase of approximately 238 gigawatts (GW) of geothermal electricity capacity over today's installed base of 10 GW would reduce CO_2e emissions by 1 gigaton per year.

Despite geothermal's great potential, scaling the industry up in such a short time frame presents a number of challenges. The primary challenge is to bring EGS technology to market, because existing hydrothermal resources are estimated to be capable of supplying only approximately 40% (90 GW) of the additional capacity needed globally, i.e., not enough to achieve gigaton-scale emissions reductions. Although in principle EGS can be commercialized given enough funding and support, the Gigaton Throwdown 10-year time frame for achieving the technological advances and scale-up of geothermal energy is more rapid than has previously been considered.[2]

The scale-up investment would be at least $800 million to $1 billion for EGS technology development alone, and research and development and deployment (RD&D) money would need to be accessed rapidly.[3] Strong policy measures would also be needed to push technology development forward and encourage capacity increases. Notably, $350 million in U.S. federal funding was recently approved as part of the American Recovery and Reinvestment Act. In addition to RD&D funding, large amounts of capital will be required for new power plants. The estimated capital investment to build new geothermal power plants is $919 billion, with an average cost of about $3,900/kilowatt (kW) installed. Scaling up to meet the gigaton goal would produce more than a million jobs with 35,000 created in the next 3 years. Challenges to accelerated deployment include workforce expansion, drilling, transmission, and large component infrastructure expansion.

Industry Background

Electricity is produced from geothermal energy by extracting hot water or steam from wells drilled into a geothermal reservoir and either running the steam directly through a turbine connected to a generator or using the hot water to vaporize a secondary fluid that is run through a turbine connected to a generator. Geothermal power plants generally have a smaller environmental footprint than other renewable energy sources because much of the infrastructure is hidden underground. The first geothermal power plant was built more than 100 years ago in Italy, so experience with geothermal power plant design and operation is considerable.

Commercial development of conventional geothermal (hydrothermal) systems requires that three natural phenomena be found together. First, a rock formation at high temperatures must be located near the earth's surface, usually within 1 to 4 kilometers (km), so that it can be easily reached by drilling. Second, the rock formation must be naturally fractured and have sufficient permeability for fluid to circulate and flow to a drilled production well. Finally, the formation must contain naturally occurring fluids that are circulated through and heated by the rock and produced by the well in sufficient quantities to economically generate electricity. These conditions are mainly found at tectonic plate boundaries and thus are geographically constrained to certain regions. In the U.S., hydrothermal electrical generation projects are generally located in western states.

Enhanced geothermal systems (EGS), a technology still being developed, could greatly increase the availability of geothermal energy. EGS are designed for accessible hot rock deposits that lack sufficient natural permeability and/or fluids to support economic production rates of hot water or steam. EGS technology seeks to replicate a naturally occurring geothermal system by using hydraulic pressure to create a fracture network that increases the permeability of the rock formation and then circulating fluid through this permeable system. Once the fluid has been heated by the rock, it is used to generate electricity in a power conversion cycle and then reinjected into the formation, creating a closed, sustainable loop.[4] EGS would significantly increase the global potential for exploiting geothermal resources.

Other geothermal technologies (geothermal direct use, geothermal heat pumps, and cogeneration) all have great potential for global greenhouse gas emission abatement but are not covered in this analysis.

Geothermal Industry

Geothermal energy generation increased during the oil crises of the late 1970s, decreased as the price of fossil fuels dropped, and is on the rise again in response to incentives such as renewable portfolio standards (RPSs, e.g., in California and Nevada), feed-in tariffs (e.g., in Germany), and production tax credits along with increased emphasis on sustainable energy sources worldwide.

In 2007, worldwide geothermal electrical capacity was close to 10,000 megawatts (MW) in 24 countries.[5] The U.S. leads the world in geothermal generation with almost 2,700 MW installed, yet in 2007 geothermal provided only 0.35% of the total U.S. energy consumption.[6] In other countries, geothermal supplies a significant portion of total energy used. For instance, in Iceland, geothermal energy provided 67.1% of the country's primary energy needs in 2007.[7]

EGS has been under development since the 1970s starting at the Los Alamos National Laboratory in New Mexico and continuing today in several projects around the world.[8] However, EGS is not currently commercially viable. The major challenge to EGS commercial viability is being able to provide sufficient production flow rates from wells without reducing the life of the reservoir through cooling of the rock formation or thermal breakthrough (short-circuiting) of fluid flow through the reservoir.[9]

Industry Growth

In March 2009, the Geothermal Energy Association estimated that 5,487 MW of geothermal electricity capacity were under development in the U.S. in 12 states, up from 3,960 MW in August of 2008.[10] A 2007 report showed that worldwide about 200 to 250 MW of geothermal electricity capacity had been added annually since 2005.[11] Figure 1 shows the distribution of the new capacity added by country.

Estimates of global hydrothermal energy still to be tapped range from 46 GW to 6,000 GW.[12,13] The large range is due to the inherent uncertainty in estimating an underground resource. Similar to oil and gas reserves, geothermal is hard to assess accurately, and in many countries little or no data are available on geothermal potential. For calculations in this study, an estimate of 100 GW of global geothermal potential was used.[14] Relative to the 10 GW currently being exploited, this figure indicates a great hydrothermal potential that could still be harnessed. In addition to potential hydrothermal resources, the potential to extract heat using EGS is even greater. It has been estimated at 11.2 x 10^7 exajoules, or more than a thousand times greater than the hydrothermal electricity resource potential.[15] A recent assessment by the United States Geological Survey (USGS) estimated more than 500 GW of power production potential from EGS in the western U.S. alone.[16]

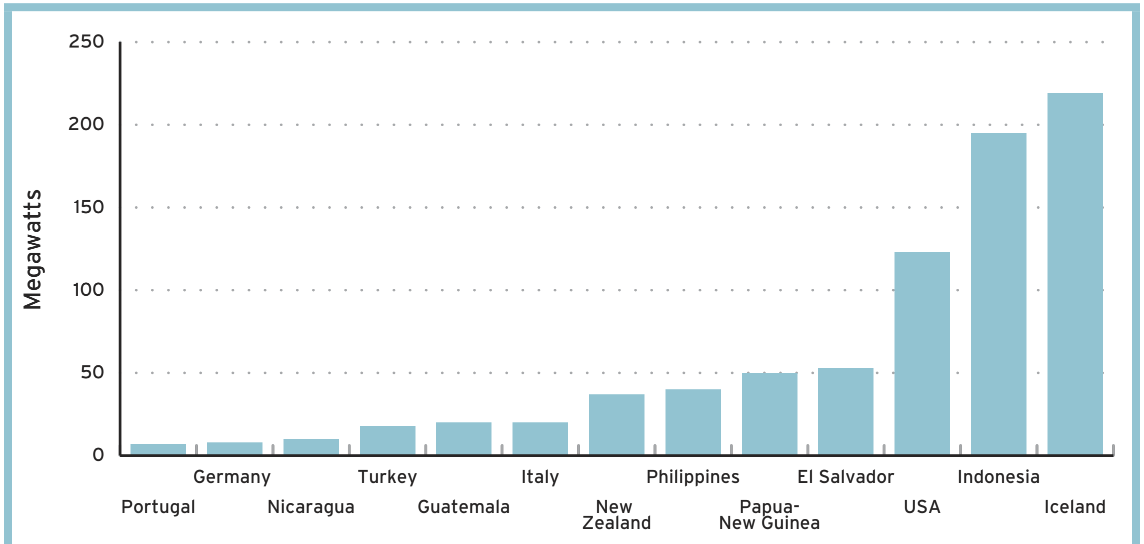

FIGURE 1. New Geothermal Capacity Added Worldwide 2005-2007.[17]

Value Chain

The average development timeline for a new hydrothermal project is about 5 to 7 years.[18] Consequently, even with a very strong push for more geothermal electrical power plants starting today, it is unlikely that the annual new capacity on line would increase dramatically for at least 5 years. The development process begins with about 2 years of exploration and pre-feasibility studies including geophysical and geochemical surveys and collection of geological and temperature gradient data. If the survey results are favorable, the feasibility phase begins with drilling of an exploration well to confirm the resource. More confirmation wells are drilled, the resource reserves are estimated, and preliminary design of the power plant and well field are completed. The feasibility phase usually takes about 2 years, and, if this phase is successful, the project moves into the detailed design and construction phase, which typically takes about 2 to 3 years and entails final drilling, testing of wells, completed design, and then construction of the power plant.[19]

During the first two phases of development, financing for the project is hard to obtain as the risk and cost of finding the resource can be significant.[20] Drilling costs, for example, usually represent about 20% to 50% of the total cost of a high-temperature hydrothermal power plant, and for EGS plants that percentage can be even higher.[21] Consequently, much effort is being focused on lowering initial costs and improving exploration techniques.

Achieving Gigaton Scale

Because of its consistent availability, geothermal has strong potential to replace baseload capacity that is currently provided by fossil fuels like coal and natural gas.

Scaling the Industry

The global geothermal industry must add approximately 238 GW of new capacity to reduce CO_2e emissions by 1 gigaton annually. We assume that the remaining hydrothermal potential, 90 GW, would be harnessed to meet this goal, and an additional 148 GW would come from the plentiful EGS resource base.[22] The hydrothermal capacity would mostly be developed in tectonic plate boundary areas, e.g., the western U.S., eastern Asia, the African Rift Valley, and the North Atlantic Ridge. EGS will not have the same geographic limitations and will be spread throughout the world. In Figure 2 the gigaton-reduction trajectories are compared with conservative projections based on historical data that assume a 5% annual growth rate from 2007 capacity. The graph also shows the CO_2e abatement that would be achieved by the total new installed capacity of geothermal energy. The gigaton trajectory represents a 25-fold increase over 2007 geothermal capacity by 2020 with the largest annual increase being 100 GW in 2020.

Capital Investment

The significant, rapid increase in geothermal capacity needed to reduce emissions by 1 gigaton in 2020 will require substantial capital investment in technology development, power plant construction, drilling capacity, large-component manufacturing capacity, and workforce and transmission line expansion.

RESEARCH, DEVELOPMENT, AND DEPLOYMENT

A 2006 Massachusetts Institute of Technology (MIT) report estimated that, for the U.S. to reach 100 GW of geothermal energy before 2050, an RD&D investment of $800 million to $1 billion would be needed over the next 15 years.[23] The Gigaton Throwdown requires 148 GW of EGS capacity in 2020, 30 years earlier than the MIT report assumes, so this investment would have to be made in a much shorter time frame than was contemplated in the MIT assessment.

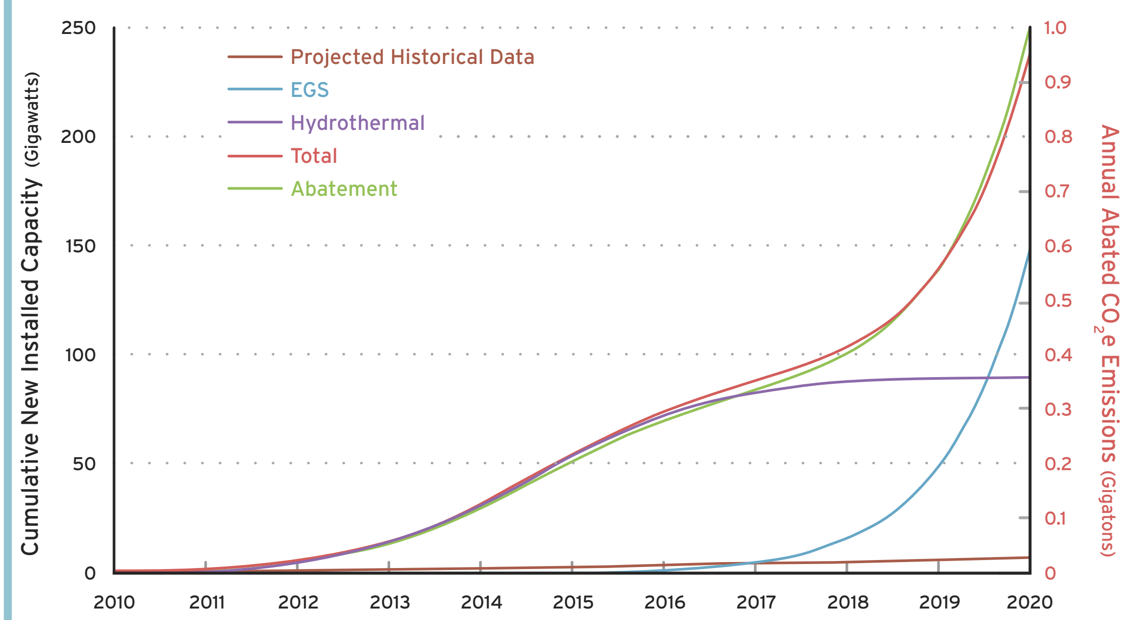

FIGURE 2. Growth in Geothermal Generation Capacity. A combination of hydrothermal and commercialized enhanced geothermal systems (EGS) could increase capacity by approximately 240 gigawatts (GW) over today's installed base of 10 GW to reduce carbon emissions by 1 gigaton (Gt) per year by 2020.

CAPITAL INVESTMENT IN NEW PLANTS

Capital investment in new power plants and accompanying well fields will be the largest element of the financing needed to avoid 1 gigaton of carbon equivalent (CO_2e) emissions by 2020. The capital costs of a geothermal power plant depend heavily on the quality and depth of the geothermal resource being tapped. In addition, EGS technology is not yet commercially viable, so future production costs for EGS are estimates. However, some assumptions allow us to approximate the total capital investment needed.

Three types of power conversion cycles are used to generate electricity from geothermal resources: dry steam, flash (liquid + vapor), and binary systems (heat from geofluid is transferred to a working fluid that goes through a closed loop cycle, similar to what happens in a conventional coal or nuclear plant). The choice of technology depends on the temperature and quality of the geofluid. Geothermal power plants coming on line today use either flash or binary technology. Binary plants are more expensive but more efficient for lower-temperature resources. It can be assumed that the hydrothermal capacity coming on line in the next decade will continue to be a mix of flash and binary plants, and drilling costs for these plants will be similar to those for plants coming on line today. Thus the current average cost per kW can be used to approximate the capital investment needed.

A report published by the Western Governors Association in 2006 estimated geothermal capital costs at $3,000 to $4,000/kW depending on the accessibility and quality of the resource.[24] We used those estimates to assess the capital expenditures for new hydrothermal plants that would have to come on line in the gigaton-scale CO_2e scenario. As more and more hydrothermal potential is harnessed and it becomes harder to find viable resources, developers will exploit resources that are more difficult to access, so costs will go up. In this study, we assume that at first $3,000/kW-resources are harnessed and then, as production and development increase, more capital-intensive resources will be tapped, so costs will increase to $3,500/kW. Finally, as hydrothermal capacity maxes out, capital costs will rise to $4,000/kW. Based on these assumptions, we calculate that 90-GW expansion of geothermal capacity will require an investment of about $320 billion in new power plants.

The majority of EGS power plants will most likely be binary plants. Drilling and reservoir stimulation costs for EGS power plants are expected to be higher than for natural geothermal systems because reservoirs have to be created by fracturing rock, and much of the heat being mined is likely to be deeper than natural hydrothermal resources.

The cost of EGS resources will follow a trajectory opposite to the increasing cost of hydrothermal development. Because EGS technology is not currently commercialized, costs are high; because technology advances, costs will come down. As the 148 GW needed to accomplish 1 gigaton CO_2e will not come close to maxing out the resource, costs will continue to go down throughout the period of interest in this report. Using results of analysis of EGS capital costs in 2008, this study assumes that these costs will be between $4,000 and $12,000/kW.[25] For demonstration plants, costs will be at the high end, about $12,000 per kW. Once a few demonstration plants are on line, costs are assumed to decrease to $8,000/kW as a result of technology development and deployment experience. As technology continues to mature and a significant EGS capacity comes on line, estimated costs decrease to $4,000/kW and are comparable to hydrothermal capital investment costs from then on as a result of lessons learned from development and installation of prior systems. Based on the above assumptions, total capital investment needed for new EGS power plants is approximately $599 billion.

Thus, the total capital investment cost for both categories of new geothermal power plants, hydrothermal and EGS, is about $919 billion. Figure 3 shows the total annual capital investment needed by year.

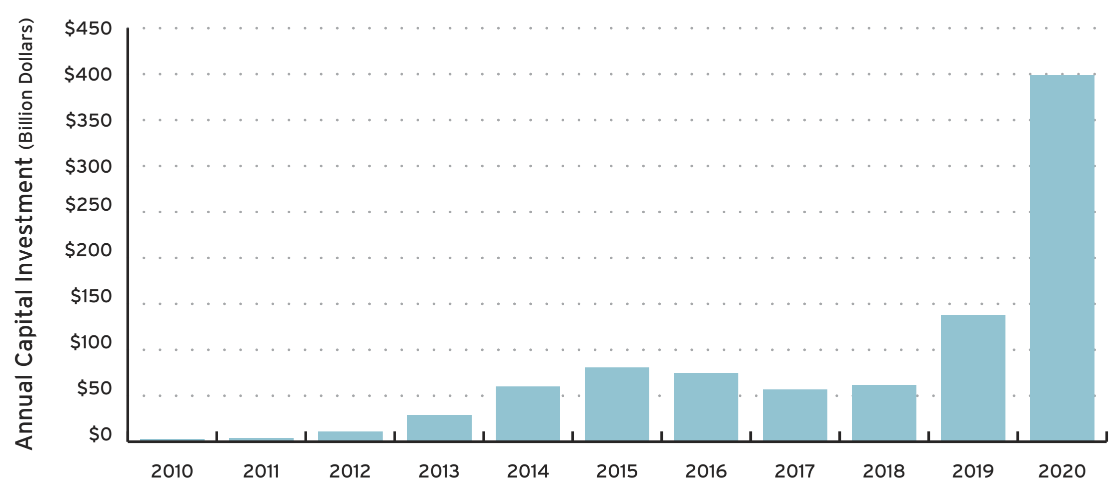

FIGURE 3. Annual Capital Investment in Geothermal Generation Capacity. Cumulative investment to get to the gigaton target by 2020: $919 billion.

Jobs in the Geothermal Industry

During the late 1980s and 1990s, geothermal saw very little development activity, and geothermal personnel moved to other sectors. A 2001 publication by the California Energy Commission reported that for each MW of geothermal energy developed, four construction jobs and 1.7 operation and maintenance jobs are created.[26] Using these numbers, we calculate that an expansion of 238 GW of geothermal capacity would create about 1.4 million jobs, of which about 405,000 would be permanent (see Figure 4). Investment would be needed to provide education and training to expand the geothermal workforce on that scale.

Challenges to Accelerated Deployment

Achieving a 238-GW expansion in geothermal electricity production within a decade will prove very difficult if not impossible. Geothermal energy faces the same challenges related to rapid expansion of capacity, large capital investment, and increases in workforce and transmission and component manufacturing infrastructure that many other renewable technologies face. In addition, critical developments in EGS technology are required to meet the gigaton goal. (See Technology Innovation section).

Drilling Capacity

Drilling capacity is needed to access or engineer a geothermal reservoir. Geothermal energy competes with the oil and gas industry for drilling rigs, personnel, and expertise. Although oil and gas wells are not identical to geothermal wells, many attributes are similar. Increased geothermal development activity will force a major shift of drilling capacity to geothermal and an expansion in the numbers of rigs equipped for geothermal well drilling.

Large-Component Manufacturing Capacity

Turbine and cooling tower manufacturing infrastructure for the geothermal industry is limited and needs to be expanded significantly if geothermal electrical capacity is to be dramatically increased to meet the gigaton goal. Currently the lead time for a geothermal turbine is on the order of years, and very few manufacturers produce the main cooling tower parts.

Transmission Lines

Natural geothermal resources are confined to specific geographic regions; transmission lines have to be erected to connect geothermal generation to the electricity grid if the resources are to be used outside their local regions. Thus, expansion of geothermal energy will entail a large investment in transmission line capacity.

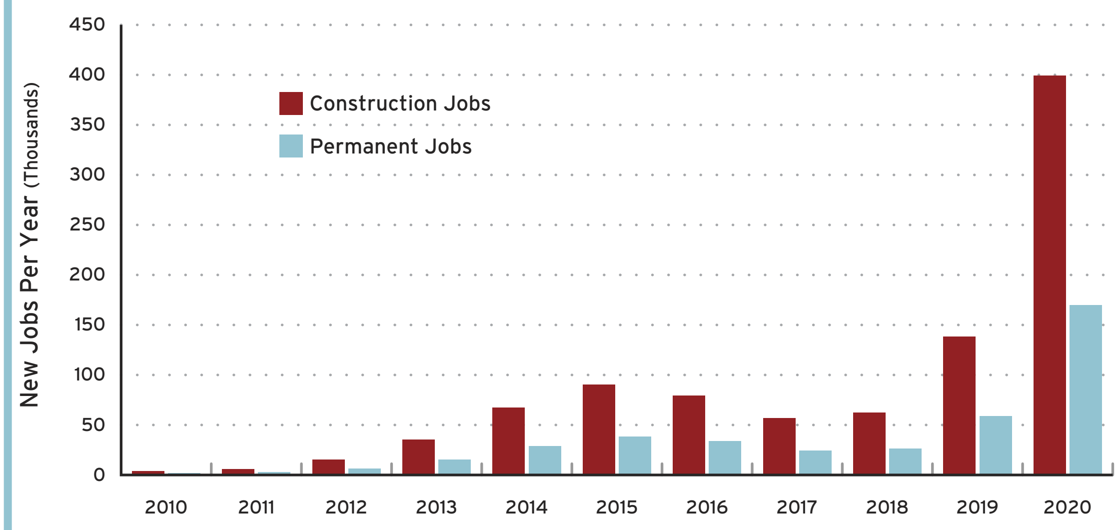

FIGURE 4. Jobs Created in the Geothermal Industry. Total jobs created on the gigaton trajectory: 1.4 million.

Technology Innovation

The main opportunities for innovation in the geothermal sector are in EGS although many opportunities also remain to lower cost and risk in hydrothermal resource exploration and drilling. Past EGS projects have made significant advances, but challenges remain before EGS systems can be economical in today's energy market. (See Figure 5 below.)

The main challenge to commercially developing EGS is to achieve sufficient connectivity within a heat reservoir to sustain high production flow rates while preventing the reservoir from cooling. Current demonstration sites have achieved sustained production-well flow rates of ~25 kilograms per second (kg/s), but flow rates of 40 to 80 kg/s will be needed to make EGS commercially viable on a large scale.[27] This will require improved techniques that can open multiple fractures within a single well. Technologies such as high-temperature packers, which can isolate zones in the wellbore for stimulation, or other advanced isolation techniques must be developed. High-temperature downhole pumps in production wells would also help increase production flow rates. If EGS technology is to scale up, these critical issues must be addressed.

Innovation in EGS technology will not only benefit EGS developers but will also be valuable to conventional geothermal projects. Many of the methods and tools used in EGS are or can be used in hydrothermal projects. For instance, stimulation of a reservoir has been shown to increase productivity in hydrothermal projects, and advances in sensor and drilling equipment will be useful in conventional geothermal projects as well.

A noteworthy innovation being worked on in the hydrothermal sector is to extract geofluids from hydrothermal systems at supercritical conditions. A supercritical fluid is critical temperature and pressure (e.g., for water, the critical temperature, T_C, = 374°C, and the critical pressure, P_C, = 221 bar) and exhibits properties of both liquids and gases. For hydrothermal systems, these combined properties are attractive; a supercritical water reservoir would produce fluids with steam-like energy content at water-like densities, so that much higher power output could be extracted on a per-well basis. Supercritical geothermal resources are restricted to unique geographic regions, such as those found in Iceland. The supercritical environment is very challenging because of high temperatures, high pressures, and unknown geochemistry. However, the potential benefits of overcoming these challenges are great, including not only significantly increased power output per well, but also production of higher-value, high-pressure, high-temperature steam and the possibility of extended lifetimes for geothermal reservoirs.[28]

Currently the market for downhole tools specific to the geothermal industry is small compared to the market for the oil and gas industry, so there is little incentive for innovation to serve geothermal needs. For instance, packers and downhole pumps used in the oil and gas industry are generally not designed to withstand the high temperatures or corrosive elements encountered in geothermal wells. As

TECHNOLOGY	STATE OF THE ART	BARRIERS	INNOVATION OPPORTUNITIES	APPLICATION
Drilling	Rotary Table Rigs Tricone Roller and PDC[a] bits Telescoping Casing Program Wireline Downhole Tools	High Costs Temperature Limitations (designed for oil and gas, not geothermal)	Continuous Drilling Systems Monobore Casing Casing While Drilling High-Temperature Tools	Hydrothermal and EGS
Reservoir Stimulation	Demonstration Projects 25 kg/s Production Flow Rates 1 km³ Reservoir Volume	Immature Technology 40–80 kg/s Production Flow Rates Needed	High-Temperature Packers Novel Well Interval Isolation Techniques "First-to-Commercial" Experience	EGS Marginal Hydrothermal Fields
Downhole Pumps	Line-Shaft Pumps to 600 m Electric Submersibles to 175° C	Temperature Limitations Depth Limitations	High-Temperature Electric Submersible Pumps	EGS Hydrothermal Reservoirs 175 – 225° C (too hot to pump, too cool for flash plants)
Energy Conversion Systems / Power Plants	Binary Plants (Isopentane and Isobutane): 100–200+° C Flash and Steam Plants: 200+° C Cooling Towers (where water available) Air-Cooled Condensers (ACCs)	Efficiency Limits (esp. at low temperatures) Decreased Power Output at High Ambient Temperatures (ACC)	Supercritical Rankine Cycles Novel Binary Fluids (ex. refrigerants) Advanced Cooling Systems	Medium-Low Temperature Hydrothermal EGS
Exploration and Resource Confirmation	Surface Manifestations Ground Heat-Flow Measurements Exploration Wells Determination of Stress Field (EGS)	Exploration Wells Expensive to Drill Year(s) to Prove a Resource	GIS[b] Mapping of Geothermal Indicators / Resource Assessment Novel Techniques to Determine Temperature / Stress Field / Fluid at Depth Airborne Reconnaissance	Hydrothermal and EGS

FIGURE 5. Geothermal Technology State of the Art, Barriers, and Opportunities.
[a] Polycrystalline diamond compact [b] Geographic Information Systems

the size of the geothermal industry grows, innovation in technology specific to geothermal applications will grow as well.

Public Policy

The fastest way to put geothermal energy on a level playing field with fossil fuels would be to incorporate the price of carbon into the price of energy. Several U.S. states have adopted renewable portfolio standards that require utilities to obtain a certain percentage of energy production from renewable sources. These standards have been a strong incentive for geothermal energy production because geothermal provides utilities with a baseload renewable energy source.

GOVERNMENT FUNDED RD&D

EGS technology is still in the development stage and requires significant RD&D investment before it will be attractive to the commercial market. Large amounts of capital will have to be invested in the technology in the near term if it is to grow to a significant scale within a few years. Because the technology is not yet proven commercially and the capital investment needed is very large, it is likely that private investors will be reluctant to fund this work, so much of the investment would have to come from the government sector.

LOAN GUARANTEES/TAX POLICIES

Large up-front capital costs are associated with building a geothermal project. Finding this capital can be challenging, especially as equity providers often do not have a solid understanding of the geothermal industry. Loan guarantees are a powerful tool that government could use to expand the geothermal sector while demanding accountability from developers. Currently $10 billion in loan guarantees is available in the U.S. for early commercial use of new or significantly improved technologies in energy-related projects, and The American Recovery and Reinvestment Act of 2009 appropriated a further $6 billion in loan guarantees for renewable energy technologies including geothermal energy.[29,30]

In recent years, tax incentives have been successfully used in the U.S. to encourage geothermal development. Production tax credits (PTCs) increase the revenue and thus the economic feasibility of projects. Currently, PTCs are available for geothermal energy projects that come on line before the end of 2013. U.S. geothermal developers can also choose to take advantage of a 10% investment tax credit (ITC) instead of the PTC.[31] Of the two options, the PTC is usually the preferred credit for geothermal energy projects because of geothermal's high capacity factor.[32] It is critical that tax policies be designed for the technologies they support and with long-term objectives in mind; geothermal tax credits should have at least a 5- to 7-year horizon to fully support nascent projects.

LAND ISSUES

In the U.S., an estimated 46% of the hydrothermal electricity potential lies beneath federally owned land.[33] Consequently, federal geothermal leasing regulations and processes are crucial to the development of U.S. geothermal capacity. Until recently, leasing processes were a critical bottleneck to increased geothermal electricity production; a 20-year waiting period for a federal geothermal lease was not uncommon. The Energy Policy Act of 2005 included provisions to correct this problem, stipulating that all first-time-offered geothermal lease sales must be conducted through a nomination and open auction process similar to the process for federal oil and gas leases. Since the enactment of the new regulations, the Bureau of Land Management (BLM), which administers federal geothermal leases, has held several geothermal lease auctions resulting in the sale of numerous leases. In addition, the BLM and U.S. Forest Service in late 2008 completed a Programmatic Environmental Impact Statement (PEIS) that is intended to facilitate future geothermal leasing.[34] The PEIS opened 118 million acres of public lands and 79 million acres of National Forest lands to potential geothermal leasing by amending land use plans.[35]

RISK MITIGATION

Geothermal energy differs from other renewable sources because the resource being harnessed is hidden beneath the ground. Unlike wind and solar, where the resource can be measured relatively easily, geothermal reservoirs have to be confirmed by drilling expensive wells. All policy support that reduces the up-front risk and thus improves the project's business case will thus be effective in incentivizing capacity development. Less-expensive exploration techniques, including resistivity and magnetic-telluric surveys, thermal gradient wells, and fluid analysis, can be used to try to estimate the exact location of the resource before a well is drilled and thus reduce the risk of drilling a non-productive well. Public policy must support this type of risk mitigation by focusing on measures that support further development of exploration techniques and lowering of drilling costs.

Publicly funded resource assessments can also be instrumental in facilitating geothermal energy development. The USGS recently updated its geothermal resource assessment for the U.S. from the last assessment, which was published in 1979. In contrast, USGS performs annual resource assessments for oil and gas. In Iceland, the government has continually funded geothermal resource assessments for decades, and this support has played a central role in Icelandic geothermal development.[36]

Interactions with Other Gigaton Pathways

Geothermal provides low-carbon baseload power. As such, it can complement renewables such as solar that provide peak power during the daytime. Co-development of such resources is an area for future work.

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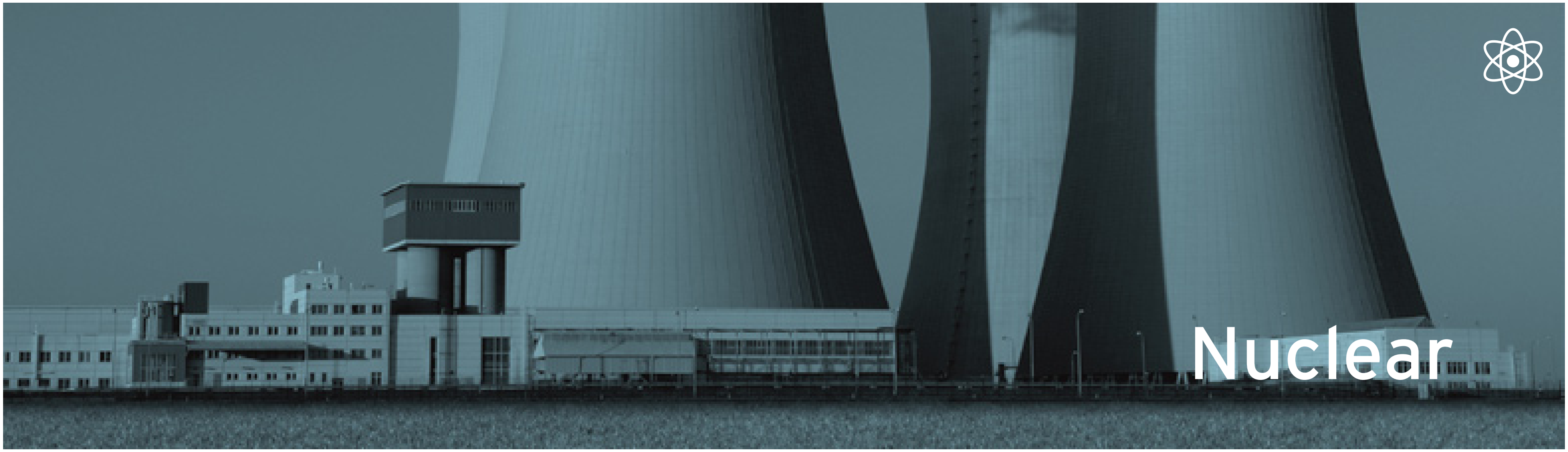
GIGATON THROWDOWN



Nuclear

MAIN POINTS

- Nuclear can increase by gigaton scale by 2020 for an investment of $1.27 trilllion.
- Nuclear power already displaces more than 1 gigaton of Co2e annually.
- Major technical challenges to scaling nuclear include rapid expansion of the supply chain, including the build-out of large steel forges and expansion of the workforce.
- Concerns surrounding weapons proliferation, waste disposal, security and safety make nuclear power uniquely challenging.
- High costs and lengthy permitting periods have stalled nuclear growth in the U.S. and other western countries; much of the expansion in nuclear is poised to happen in Asia.

Overview

Nuclear power currently generates 372 gigawatts (GW) of power worldwide, providing 20% of U.S. and 15% of global electricity, with minimal carbon dioxide equivalent (CO_2e) emissions. Global expansion of nuclear power would add significant low-carbon, baseload generation and help growing economies avoid increasing reliance on high-carbon fuel sources, such as coal. Approximately 250 new GW-scale nuclear plants would be required by 2020 — a 67% increase in the current nuclear base — to reduce CO_2e emissions by 1 gigaton annually. Sustaining this pace of construction would be unprecedented for the nuclear industry, requiring delivery of a finished nuclear plant every month.

The nuclear industry has stagnated in western countries for several decades, but recent concerns about climate change and fossil fuel prices, coupled with subsidies for nuclear energy, have led to construction starts on 44 nuclear plants worldwide, chiefly in Asia, and a spike in proposed nuclear plants in the U.S. (See Figure 1.) Nonetheless, the industry continues to face serious challenges to rapid, large-scale growth: costs, component manufacture scale-up, and waste disposal.

Capital costs, including component manufacturing and plant construction, account for more than half of the cost of nuclear electricity. These costs have skyrocketed during the past several years. With overnight capital costs estimated from $3,000 to $6,700 per kilowatt (kW) for new reactors, expanding global nuclear power to avoid 1 gigaton of CO_2e emissions by 2020 would require between $709 billion and $1,690 billion in capital investment (see Figure 2). Unlike other emerging low-carbon energy technologies, nuclear power may not realize long-term cost reductions unless experience with standardized designs drives down costs substantially, and the manufacturing supply chain — with its ultra-large forges, trained workers (a gigaton scale-up in nuclear power would create an estimated 268 thousand direct jobs), and uranium enrichment facilities — can expand in advance of new reactor construction. These constraints, in addition to the costs of waste disposal and the security risks associated with an expanded global nuclear sector, could forestall a rapid nuclear expansion or raise reactor costs substantially.

The cost record for recent Asian and European plants is too limited so far to justify conclusions about future costs. There are potential indications of cost reductions for recent Asian plants, but overruns in Europe and rising cost estimates for planned U.S. plants are reminiscent of the cost escalations during the last nuclear revival more than 30 years ago.[1]

If expansion barriers are surmounted, nuclear power still is likely to be more expensive than average U.S. wholesale electricity rates. If low-cost estimates for nuclear power hold true, policies that put a reasonable price on carbon emissions could make nuclear power competitive in the U.S. If costs for new nuclear plants are closer to the high estimates, no carbon price foreseeable by 2020 would likely be sufficient to make nuclear energy competitive purely on a cost basis. In countries with higher electricity costs, nuclear power might be competitive without a price on carbon emissions. New nuclear power plants are likely to be built more rapidly outside the U.S., in countries with a combination of lower costs, fewer regulatory requirements, and less historical experience with construction cost overruns and plant cancellations. In countries with cost-effective distributed renewable energy options, the case for nuclear is weaker.

These cost and supply-chain barriers to rapid scaling of global nuclear power are daunting for the near term. But France redirected its power infrastructure from overwhelming reliance upon oil to 78% nuclear generation in about 25 years. If cost is not a primary consideration, the French example suggests that, given strong national or international resolve and perhaps twice as much time as the 2010–2020 time frame considered for the Gigaton Throwdown, large-scale nuclear power could be realized.

Industry Background

Nuclear reactors generate electricity by harnessing heat created by controlled splitting of uranium atoms (fission). Fission reactors typically consist of rods of mined and enriched uranium held in a vessel containing pressurized, boiling, or "heavy" (deuterium) water. Fission reactions within the fuel rods create heat that is transferred to steam turbines and converted to electricity. Technical and economic constraints of fission reactors mean that nuclear plants cannot be stopped and started frequently. For this reason, and because of relatively low fuel costs, nuclear power is best suited for baseload generation.

Nuclear Industry

The U.S. nuclear energy industry's average capacity factor was 91.5% in 2007, and the global average was approximately 80%, both higher than for most other generation technologies.[2,3,4] Reactor capacity factors are high because reactors are shut down infrequently for refueling and maintenance. In addition, a move to higher fuel enrichment levels has have reduced the frequency of refueling and thus increased capacity factors.[5] Nuclear plant capacity factor increases effectively added 16.3 GW to U.S. generation capacity between 1982 and 2004.[6] Nuclear plants' operating lifetimes are also turning out to be longer than originally planned, with a new wave of 20-year license extensions in process that will extend plant lifetimes to 60 years; another round of extensions to 80 years is under discussion.

The nuclear industry consists of vendors, such as Westinghouse, Hitachi, and General Electric; engineering, procurement, and construction firms contracted by utilities or others to build reactors; component suppliers, including those with ultra-large forging facilities; utilities, investors, and plant operators; and the uranium fuel-cycle industry, which mines, enriches, and delivers fuel.

Nuclear Reactor Technologies

Current nuclear reactors use pressurized light water, boiling light water, heavy water, or graphite-moderated technologies. These "Generation II" technologies are refinements on the designs of the original reactors built after World War II. Gen II reactors employ active, redundant safety systems. Compared to Gen II reactors, "Gen III" reactors or "evolutionary" reactors marketed in the 1990s were stronger structurally and had additional safety systems, including active pumping in case of an accident. Gen III plants also generally had standardized, simpler designs intended to lower cost and expedite permitting; higher safety factors; higher availability; and longer expected lifetimes. To date, four Gen III reactors have been built in Japan, and two are under construction in Taiwan.[7,8]

New reactor proposals worldwide are dominated by "Gen III+" designs, which are marketed as having larger economies of scale in power production, greater standardization, and increased ability to adjust output to follow demand changes. Two Gen III+ designs (AP1000 and ESBWR) also use passive safety systems (e.g., gravity-flow coolant water rather than active pumping or mechanical action after an accident). This reduces the amount of equipment and the size of the reactor building, resulting in potentially substantial economic savings.

Few Gen III+ reactors have been built to date though many are planned or proposed, and a handful are under construction in France, Finland, Japan, South Korea, and China. In the U.S., the Nuclear Regulatory Commission (NRC) has certified one manufacturer's Gen III+ design and is reviewing two others. Manufacturers and laboratories are also researching "Gen IV" reactors, but these designs are not expected to begin operating prior to 2030.

Industry Growth

As of October 2008, 16 licensing applications had been submitted for Gen III+ plants in the U.S., and another four applications were anticipated.[9] Most reactors under construction are in Asia, and this trend is likely to continue because of lower costs, shorter permitting times, and more rapidly increasing energy demand there.

Numbers of proposed and planned reactors have increased since the beginning of 2007, as shown in Figure 1. Globally, pressurized water technology dominates among the 37 reactors currently under construction though a mix of technologies is represented. Although more than 200 gigawatt-equivalent (GWe) of new reactors has been proposed globally, fewer than 30 GWe are currently under construction. Industry expansion depends on how quickly — if at all — construction begins on each of these proposed reactors.

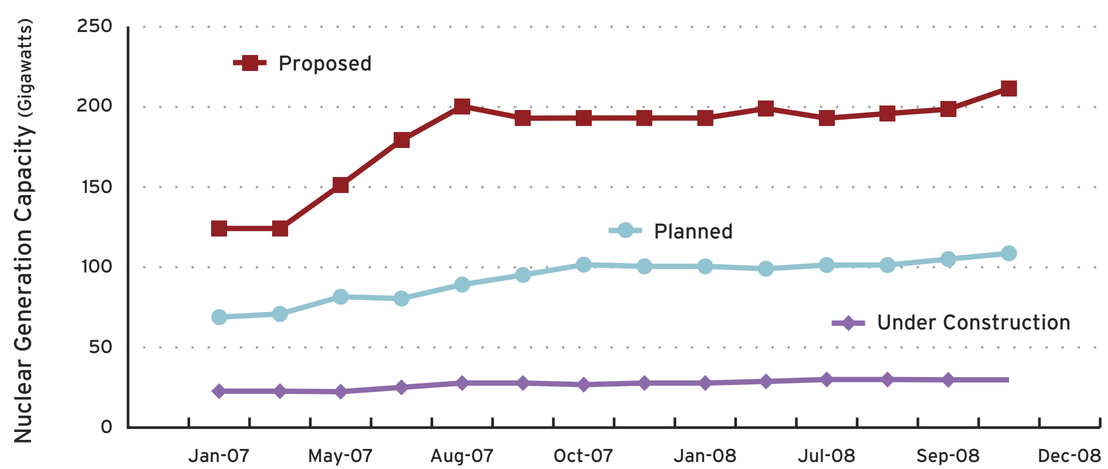


FIGURE 1. Proposed and Planned Nuclear Reactor Construction Worldwide. Reactor proposals have increased dramatically since 2007, but few have started construction. "Proposed" represents specific reactors or site proposals; "planned" means funding or major commitment is in place; "under construction" means building has begun. Source: World Nuclear Association, 2007-2008[10]

Achieving Gigaton Scale

Meeting the gigaton goal would require the addition of 248 GW of nuclear generation capacity worldwide; capital investment of $709 billion to $1,690 billion (not including waste storage or disposal facilities); major scaling of component manufacturing and the workforce; solutions for security, safety, and waste disposal issues; and public policy to address cost, liability, and licensing issues among others.[11]

Scaling the Industry

To abate 1 gigaton of CO_2e emissions annually by 2020, the nuclear industry must add approximately 248 GW of generation capacity worldwide, as shown in Figure 2. These new reactors would consist primarily of Gen III+ designs while newer designs are researched and tested.

The Cost of Nuclear Electricity

To calculate the cost of new Gen III+ nuclear plants, we use a variety of economic assumptions, listed in Figure 3. All assumptions represent the range of likely values from low to high.

We assume a negligible CO_2e per kW-hour (kWh) for nuclear power including emissions during construction, and CO_2e per kWh for reference electricity. All values are in 2007$US unless otherwise specified.

All cost estimates include tax deductions on debt interest and asset depreciation de-

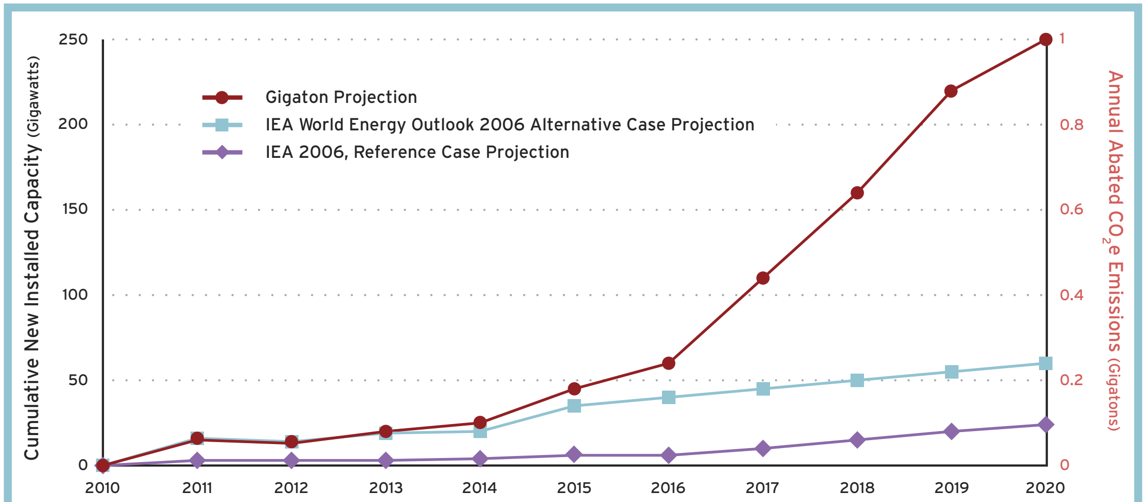


FIGURE 2. Growth in Nuclear Generation Capacity. Additional nuclear generation capacity and CO_2 emissions conserved annually under 1-gigaton and International Energy Agency scenarios. The gigaton trajectory represents a significant departure from many other projections, including the international agency's reference and alternative cases. In the IEA reference case, the nuclear industry expands by 3% above 2020 levels while it expands by 10% in the alternative case. The gigaton trajectory constitutes a 67% increase in nuclear capacity worldwide above 2010 levels.

	ESTIMATE (CURRENCY IN 2007 DOLLARS US)		
Cost Factor / Assumption	Low	Expected	High
Overnight Capital Cost	$3,000/kW	$4,850/kW	$6,700/kW
Annual Capital Cost Escalation	0.0%	0.5%	1.0%
Plant Lifetime	60 years	50 years	40 years
Construction Duration	5 years	5.5 years	6 years
Debt/Equity Financing Ratio	50%	50%	50%
Debt Financing Interest Rate	6.5%	7.5%	8.5%
Equity Financing Rate of Return	12%	13.5%	15%
Fixed Operations & Maintenance	$100/kW-yr	$110/kW-yr	$120/kW-yr
Variable Operations & Maintenance	$0.005/kWh	$0.005/kWh	$0.005/kWh
Grid Integration	$20/kW-yr	$20/kW-yr	$20/kW-yr
Lifetime Capacity Factor, 2010	90%	83%	75%
Lifetime Capacity Factor, 2020	90%	88%	85%
Front-end Fuel Costs	$0.012/kWh	$0.0145/kWh	$0.017/kWh
Waste Disposal	$0.001/kWh	$0.0015/kWh	$0.002/kWh
Life-cycle CO_2e Emissions	1.5 g[a]CO_2e/kWh	1.5 gCO_2e/kWh	1.5 gCO_2e/kWh

FIGURE 3. Cost Assumptions With Low, High, And Expected Estimates for Gen III+ Nuclear Plants.
[a] grams

ductions according to the current 15-year straight-line depreciation schedule currently used in the U.S. Calculations do not include other public subsidies.

Levelized Cost of Electricity (LCOE)

The cost of electricity from new nuclear plants is estimated to be from 6.2 to 15.5 cents per kWh for plants coming on line in 2010, versus an average cost of electricity in the U.S. of 5.4 cents per kWh during the same period.[12] The LCOE varies from country to country, but nuclear power will probably cost more than competing fossil generation sources globally. Figure 4 illustrates the cost of electricity for nuclear power in the low and high cases, showing a slight cost increase through 2020.

The high and low LCOE estimates vary significantly because each case represents the convergence of all worst- or best-case assumptions. The cost of nuclear electricity is most sensitive to changes in overnight capital cost and debt financing.

Cost of Conserved Carbon: An Implied Carbon Price

Each kWh of electricity generated from nuclear power costs more than average wholesale electricity rates but avoids electricity produced by carbon-emitting sources. The cost of conserved carbon measures the extra cost of electricity from nuclear power per metric ton (ton) of CO_2e emissions avoided. It also approximates the carbon price necessary to make nuclear power economically competitive with high-carbon electricity sources. The carbon price to make nuclear plants coming on line in 2010 competitive with U.S. average electricity rates varies dramatically between the low- and high-cost estimates, from $12

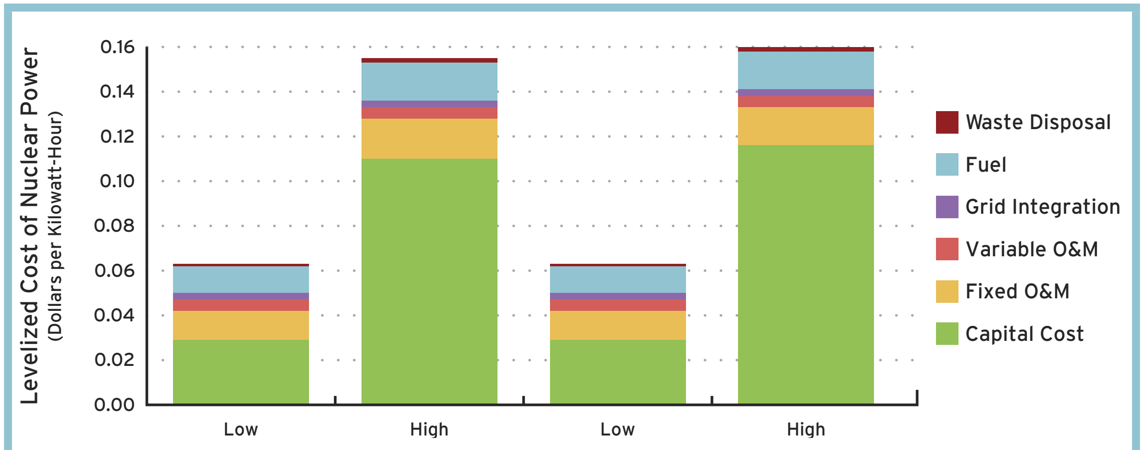


FIGURE 4. Cost of Electricity Produced by New Gen III+ Nuclear Plants.

to $181 per ton CO_2e emitted, as shown in Figure 5.

The low and high cases differ more than tenfold because the degree to which the nuclear LCOE exceeds retail rates — not the absolute LCOE itself — determines the carbon price. Although the low-cost LCOE is only 0.8 cents above retail rates, the high-cost case exceeds retail by roughly 10 cents. This disparity relative to retail rates creates the wide range of possible carbon prices.[13]

Capital Investment

To reduce CO_2e emissions by 1 gigaton in 2020 would require significant capital investment in new nuclear plant construction, workforce expansion, and supply chains for both plant manufacturing and uranium fuel. The level of capital investment and therefore the overall cost of electricity from nuclear generation depend on a variety of factors, from materials costs to construction time.

CAPITAL INVESTMENT IN NEW PLANTS

The capital cost of licensing and constructing new nuclear plants is overwhelmingly the largest element of nuclear capital investment and nearly impossible to quantify precisely. Capital cost estimates from industry sources, media, and academic literature range from $1,500 per kW to $10,000 per kW.[14,15] A portion of this divergence may be ascribed to the differences in what particular estimates include: some may include interest, yearly inflation, or transmission upgrades. But industry members also report significant difficulty in determining cost projections; a top official at the World Nuclear Association, which advocates for nuclear power, publicly stated in mid-2008 that it is "impossible to produce definitive estimates for new nuclear plants costs at this time."[16]

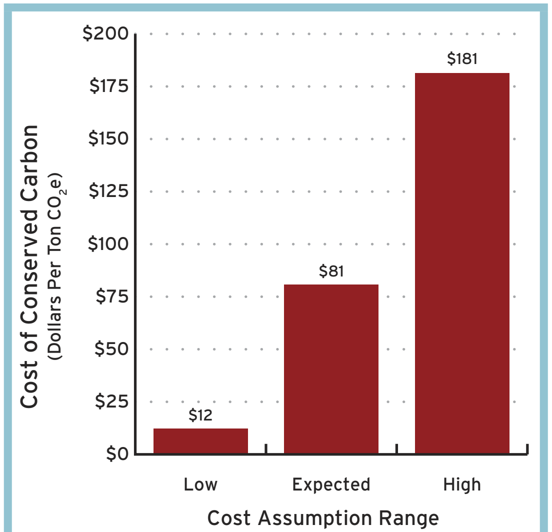


FIGURE 5. Cost Of Conserved Carbon In 2010, For Low, Expected, And High Cost Assumptions.

Based on estimates by an expert group convened by the Keystone Center for Science and Public Policy, we use $3,000 per kW as the low estimate of overnight capital costs. The new plant construction estimate incorporates the cost of raw materials, component manufacturing, engineering and construction labor, procurement contractor fees, and government licensing. As overnight costs are converted to capital costs, interest accrued during plant construction comes into play and, because of relatively long nuclear construction times, accounts for a significant portion of capital costs.

Nuclear plant capital cost estimates have increased substantially since the Keystone study. Applications to the U.S. Department of Energy Loan Guarantee Program in December 2008 indicate that utilities and other investors expect overnight costs closer to $6,659. Plants outside the U.S. may be cheaper for a variety of reasons, but we use this value to establish a high-end estimate of $6,700 per kW for overnight capital costs.

The Berkeley Cost of Conserved Carbon (C3) model estimates total capital investment of $709 billion to $1,690 billion through 2020 to scale nuclear power to meet the gigaton goal. This figure is substantially larger than the investments estimated under the International Energy Agency (IEA) reference and alternative scenarios. Figure 6 shows the annual capital investment in new plants, and Figure 7 shows total nuclear capital investment during the gigaton time frame for three cases.

Reactor Component Manufacturing: Ultra-Large Steel Forges

The nuclear reactor core holds fuel rods and is designed to contain radioactive materials and coolants at high pressures and temperatures. Unlike some earlier reactor designs, Gen III and III+ reactors call for reactor vessels and structural rings to be forged in fewer pieces to increase safety and reduce inspection and maintenance costs. These designs, and thus most new plants built between now and 2020, require forges large enough to press pieces exceeding 600 metric tons (tons) in weight.

Currently, Japan Steel Works in Osaka, Japan is the only facility with presses large enough to forge 600 tons or more of hot steel ingot into a single reactor vessel component. Japan Steel Works can manufacture five pressure vessels annually, has invested $400 million to increase its capacity to 8.5 vessels per year by 2010, and is reportedly booked through the end of 2010.[17,18,19] Several investors are reported to be securing funding for additional ultra-large forge facilities, but supply continues to be very limited, and industry experts report waiting periods as long as 2 to 3 years for large steel parts.[20] Nuclear plants being planned in the U.S. are already making reserve payments to Japan Steel Works averaging about $5 million per vessel and valve set, with lead times of 6 to 8 years.[21] Final costs for a pressure vessel can be $100 million or higher.

New nuclear reactors compete with other industries worldwide for the use of ultra-large steel forging facilities. Reaching the gigaton goal by 2020 would require forging of components for approximately 190 reactor vessels by 2017, and forging must take place several years in advance of the date reactors come on line. To meet the gigaton goal, the industry would have to expand nine-fold over today's 5.5 vessels per year during the next 7 years, to a global capacity of roughly 50 vessels per year. This rapid supply chain growth could accommodate construction demand if the industry makes adequate investment in expanded facilities, but near-term shortages of reactor vessels are likely to delay construction and drive up prices during the next several years.

A nine-fold expansion of forging capacity would require a large influx of capital by investors confident that demand for ultra-large forging will persist long enough to produce a

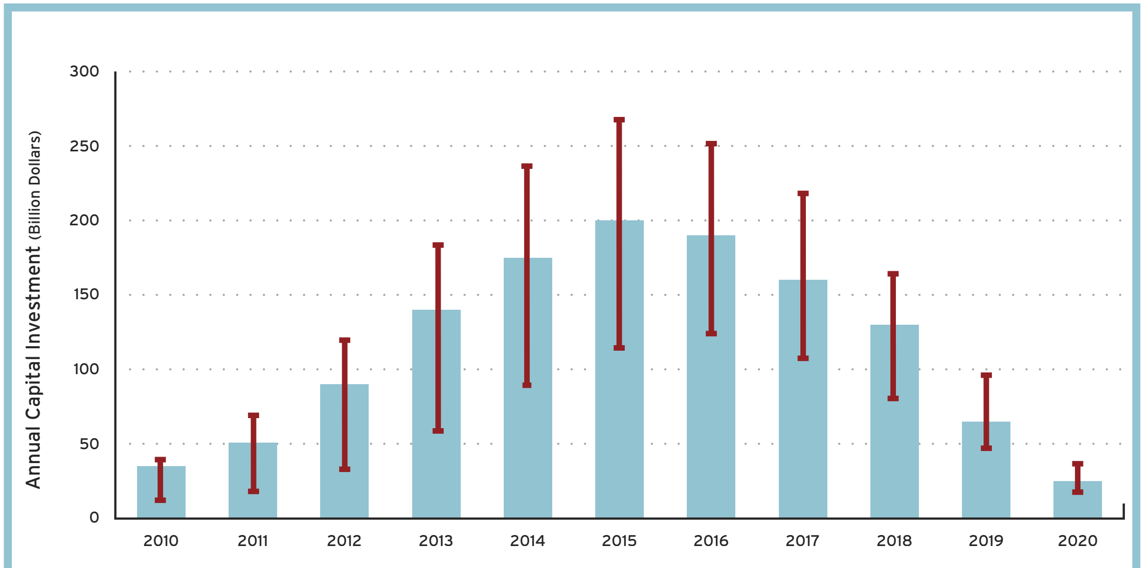


FIGURE 6. Annual Capital Investment in Nuclear Generation Capacity. Error bars represent low- and high-range assumption estimates. Does not include investments for any plants coming online after 2020. The gigaton goal requires that capital investment ramp up through the first half of the decade and peak at $115-$268 billion in 2015.

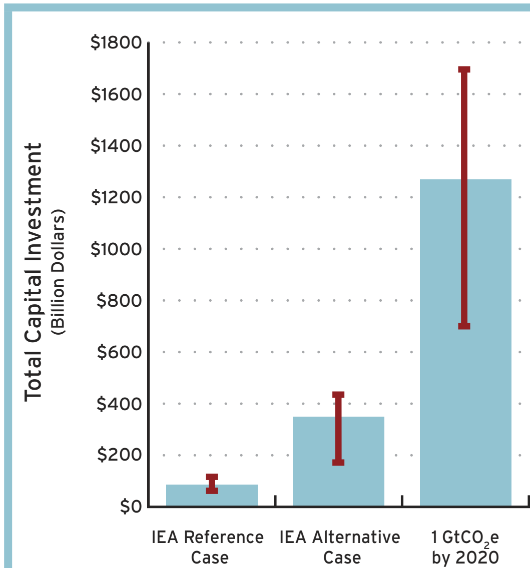


FIGURE 7. Total Nuclear Capital Investment 2010-2020. Values calculated as a straight undiscounted sum of 2007$US investments in each year 2010-2020.

reasonable rate of return. Reactor manufacturers may attempt to work around the 600-ton forge constraint by using smaller existing forge facilities and welding together smaller reactor pieces. However, these additional welds would require more frequent regular inspections once installed and corresponding increases in cost and reduction in capacity factor.[22]

The industry is responding to the growing forge demand. China First Heavy Industries Ltd. is reportedly investing $2.3 billion in forging facilities large enough for reactor vessels. Doosan Heavy Industries & Construction Co. of South Korea, Japan Casting & Forgings Corp., and Britain's Sheffield Forgemasters International Ltd. have all indicated interest in investing in ultra-large forging capacity.[23] In August 2008, Shaw Group and Westinghouse proposed a plant in Louisiana, and, in October 2008, Areva and Northrop Grumman Shipbuilding announced a new facility in Virginia, both to make large modular components for reactors. Nonetheless, ultra-large forging continues to be a major chokepoint that, along with other supply chain and workforce shortages, could limit rapid expansion of the nuclear industry and raise costs for projects.

Uranium Mining and Processing

Uranium used in today's nuclear reactors is mined, chemically separated, and then enriched to concentrations necessary for fission reactors. Fuel entering typical light water reactors is not sufficiently enriched for use in nuclear weapons, but spent fuel from these reactors contains sufficient recoverable fissile materials to make weapons. All uranium fuel today is extracted through terrestrial mining; more than half is mined in Canada, Australia, and Kazakhstan.[24] Recent increases in uranium prices are driving the industry toward non-traditional terrestrial mining techniques. Vast quantities of dissolved uranium are present in ocean waters worldwide, but uranium extraction from seawater is not yet cost competitive.

Uranium prices have doubled since 2000, primarily because demand is outpacing global production capacity. According to a U.S. Energy Information Administration report, global uranium consumption is expected to increase by nearly 40% between 2010 and 2030.[25] About 1⁄10 of U.S. nuclear fuel comes from blended-down uranium from dismantled Russian nuclear warheads. The "Megatons to Megawatts" program ends in 2013, but a new agreement will permit Russian enrichment firms to supply 20% of the U.S. fuel market, increasing over time. Most of the remaining supply comes from enrichment firms that are majority-owned by the British, Dutch, and French governments. Virtually all uranium fueling U.S. reactors therefore comes from sources that have government support. A rapid expansion of the industry would require dramatic increases in global uranium mining and processing capacity. Tight supplies of enriched uranium may lead to high prices, lower long-term profits for investors in nuclear plants, and reduced expansion of nuclear generation. However, global resources and reserves of raw uranium ore are sufficient to support near-term growth of nuclear power. In addition, re-enrichment of uranium recovered from spent fuel could be used to supplement supplies, albeit at higher cost with added security and proliferation risk from reprocessing and enrichment.

Jobs in the Nuclear Industry

As mentioned earlier, scaling nuclear power to abate a gigaton of CO_2e emissions would require expansion of a vast, international supply chain for specialty alloys, unique modular components, highly skilled labor and, in many cases, uniquely experienced, nuclear-certified firms. No attempt is made here to capture the full effects of a global nuclear renaissance on employment throughout that value chain. However, if reliable western-centric sources exist to meet average annual labor requirements for Gen III+ plants, to which minor, informed additions can be made for ongoing operations of new reactors, annual labor can be estimated. Figure 8 summarizes annual labor requirements for the gigaton nuclear trajectory.

Challenges to Accelerated Deployment

Massive industry growth will strain the manufacturing supply chain and, as discussed above, require enormous investment in steel forge capacity and uranium mining expansion. Increasing demand threatens to increase nuclear plant costs. In addition to these challenges, public perception, political opposition, security, weapons proliferation, and waste disposal risks affect nuclear power more than other generation technologies and could present significant barriers to industry expansion regardless of the economics.

CONSTRUCTION AND ENGINEERING WORKFORCE

Building a nuclear power plant takes a variety of firms, choreographed by an engineering, procurement, and construction (EPC) services contractor. Nuclear-certified workers and firms (the "N-stamp" certified sector)

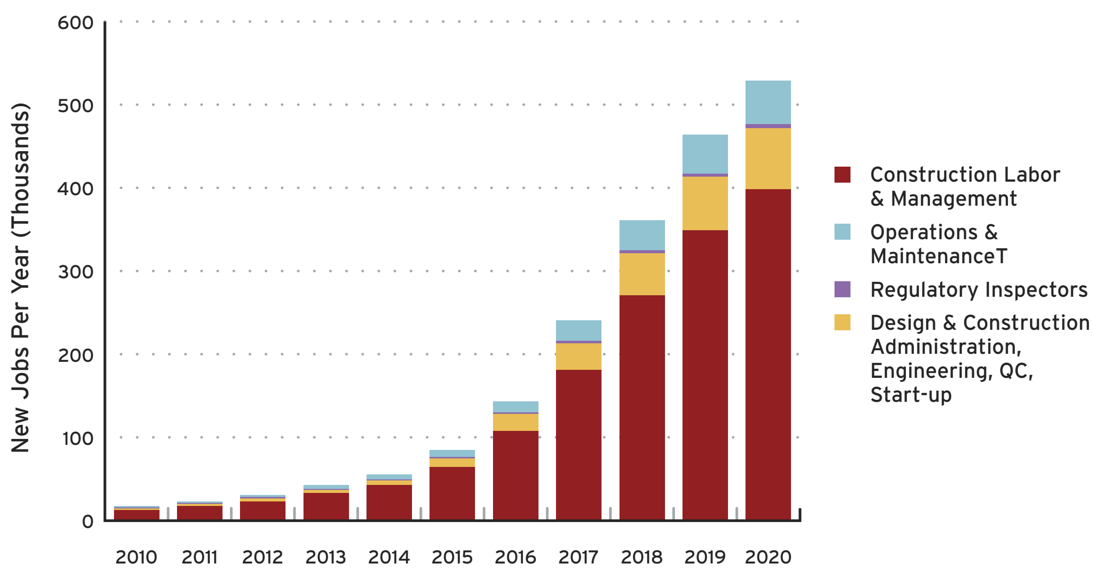


FIGURE 8. Jobs Created in the Nuclear Industry. Annual jobs created for gigaton expansion.

have declined in number significantly during recent decades. The EPC industry would have to expand to support a dramatic ramp-up of plant construction. The labor force of nuclear engineers, engineers in other disciplines with nuclear-specific expertise, and other staff that operate and maintain reactors would likewise have to expand. There have been some recent increases; the number of undergraduate nuclear engineering degrees granted in the U.S. has increased by 160% since 2000, and comparable master's degrees have increased 70%.[26]

PUBLIC PERCEPTION AND POLITICAL OPPOSITION

Public perceptions that nuclear power is unsafe, environmentally damaging, or connected to capital-intensive, centralized governance have historically generated political opposition to nuclear power. This opposition intensified after the Three Mile Island and Chernobyl reactor accidents. It continues today although a few environmentalists have endorsed nuclear power for its potential for reducing CO_2e emissions, and U.S. surveys suggest the public is open to considering nuclear power as part of the solution to climate change.

PROLIFERATION AND SECURITY RISKS

Materials in the nuclear fuel supply and waste chains can be used in nuclear and radiological weapons. Spent fuel rods contain enough plutonium to build nuclear bombs, and materials at every stage of the fuel cycle present radiological hazards and thus must be safeguarded against theft, sabotage, and accident. As a result, expanding nuclear power presents unique, pressing challenges for securing fuel against theft, weapons proliferation, and radiological releases. In particular, risk arises from state authorities or insiders diverting nuclear materials to weapons, or from outsiders stealing materials for use in weapons or detonating them on site. For example, detonating a conventional explosive next to spent fuel or the fuel separation products could render a considerable quantity of nuclear infrastructure or other infrastructure unusable for decades. Such an event could severely damage public and investor confidence in the nuclear industry and eliminate new and existing nuclear facilities from the future low-carbon generation mix.

Nuclear fuel, transportation, and waste storage facilities also must be kept secure from theft, sabotage, or accidental release of radioactivity. Any large-scale expansion of nuclear fuel or power facilities would strain an undermanned International Atomic Energy Agency and further reduce the frequency of inspection and the likelihood of discovering illicit diversions of nuclear materials to weapons purposes.

Public Policy

In the U.S., power producers have said that they will not invest in new plants without greater regulatory certainty and increased public sharing of the costs and risks of nuclear power. The U.S. Congress responded with regulatory reforms and subsidies starting in the late 1990s and culminating in the Energy Policy Act of 2005 (EPACT 2005). Other countries support nuclear power to varying degrees. Supportive public policies might stimulate an expansion in the nuclear industry, but the substantial U.S. subsidy of at least 37% of the cost of nuclear electricity has not resulted in new plant construction. It is not known whether public policy support can stimulate the industry or is an efficient use of government funds to reduce carbon emissions.

STREAMLINED LICENSING

The licensing process for nuclear reactors can cause significant delay in bringing a plant on line and adds uncertainty to nuclear power plant investments. Because plant designs have not historically been standardized, each plant has been licensed separately, and operation was not licensed until construction was finished. However, the NRC now has a program that certifies standardized designs and offers a combined construction and operating license (COL), approving a plant's design and operation in the same process. Once a COL is available for a standardized plant design, other sites referencing this COL can expect more rapid licensing, in an estimated 36 months. The cost of each COL is relatively small, and utilities can be encouraged to apply for and bank a larger number of licenses than they might use. Although no COLs have been finalized for specific sites, the new process may reduce licensing delays during construction and thus risk to investors.

LIABILITY LIMITS

Though the probability of a major accident at a U.S. reactor is very low, it poses a prohibitively expensive risk for investors. The U.S. Price-Anderson Act requires that nuclear plant owners purchase liability insurance, caps owners' liability at approximately $9.3 billion, and prohibits civil suits against plant licensees to recover damages. EPACT 2005 extended Price-Anderson by 20 years. Although this act does not necessarily require outlay of public funds, it represents the possibility of large public subsidies in the event of an accident. The NRC and U.S. Department of Energy (DOE) have concluded that Price-Anderson diminishes insurance premiums for nuclear plant owners and thus qualifies as a subsidy. Estimates of the value of this subsidy vary from 2 to 3 cents per kWh and $100 billion in total for the industry to 1⁄10 of a cent per kWh or $600,000 per reactor per year, the difference depending heavily on the odds of a catastrophic accident with damages likely to exceed a pool of private funds among reactor owners.[27,28]

LOAN GUARANTEES

Investments in new plants can be a large fraction of a utility's total capitalization, making equity financing difficult. DOE, for example, is currently administering a program to guarantee up to $18.5 billion in loans for nuclear power facilities.[29] DOE announced in October 2008 that $122 billion in guarantee applications had been received, representing 28.8 GW of generation in 14 distinct projects.[30] Loan guarantees, like liability caps, do not automatically trigger federal outlays; they shift risk from shareholders and ratepayers to taxpayers nationwide but without significant cost except in the event of loan default. However, the Congressional Budget Office has rated the likelihood of default on new nuclear loans as "very high — well above 50 percent... Because the cost of power from the first of the next generation of new nuclear power plants would likely be significantly above prevailing market rates, we would expect that the plant operators would default on the borrowing that financed its capital costs." [31] It is difficult to quantify the economic impact of loan guarantees. IEA estimated that loan guarantees effectively reduce the cost of electricity from nuclear plants to utilities by 1.2 cents per kWh while DOE officials say the guarantees have reduced debt costs to utility applicants by approximately 3 percentage points.[32,33]

PRODUCTION TAX CREDITS

Governments can offer production tax credits, paying nuclear plant owners a subsidy per unit of electricity sold. EPACT 2005 authorized a tax credit for energy produced by nuclear plants at 2.1 cents per kWh and a reward for the first 6 GW of new plants as a reward targeted at "first movers." The provision caps claims at $125 million per year for each GW of generation capacity.

ACCELERATED CAPITAL DEPRECIATION

The U.S. Modified Accelerated Cost Recovery System, established in 1986, allows businesses to deduct the depreciation of assets from their tax burden based on a rate specified in the tax code for particular asset classes. Current Internal Revenue Service rules allow depreciation of nuclear plants over 15 years compared to 7 years for natural gas generation and 20 years for other steam generation technologies. When compared to the standard 20-year schedule for other generation technologies, the 15-year nuclear depreciation time frame reduces the cost of electricity to nuclear plant owners by approximately 0.2 cents per kWh. However, changing the depreciation schedule to the rapid 7-year period currently used for natural gas would lower nuclear costs by an additional 0.5 cents per kWh. Plant owners must have sufficiently high profits to deduct the full asset depreciation each year, however. A 7-year schedule could overwhelm many plant owners' balance sheets, given the large asset values assigned to nuclear plants.

WASTE DISPOSAL

In the U.S. most civilian spent nuclear fuel is stored on site at each nuclear power plant in pools or dry casks. The industry could continue to operate in this manner for some time, but on-site storage can stir local opposition, pose security and environmental risks, and add to plant costs. Financial markets take progress toward a generalized waste storage or disposal solution into account in evaluating nuclear plant risk and pricing capital for expansion.

Any expansion of nuclear energy entails a long-term commitment to manage radioactive waste. Disposal solutions could mitigate the risk of, and opposition to, expanding the industry. There is no viable short-term (5- to 10-year) option currently on the table. One of President Obama's first acts on taking office was elimination in his budget of all but minimal funding for the Yucca Mountain disposal site.[34] The president and Energy Secretary Steven Chu said the administration would begin looking for a new long-term solution to civilian nuclear waste. A single waste repository site on the scale of Yucca Mountain would not end the debate over waste disposal as Yucca Mountain's statutory and physical capacities were both limited.

RENEWABLE PORTFOLIO STANDARDS

Some utilities have lobbied heavily for qualifying nuclear power under Renewable Portfolio Standards (RPSs) that would allow utilities to meet renewable electricity mandates and avoid RPS penalties by building nuclear plants. However, including a mature, central-station technology priced in the billions of dollars runs counter to the original intent of RPSs: to support smaller, novel, and renewable technologies. This policy change would also significantly alter the definition of "renewable." A proposed alternative is a separate "advanced technology portfolio standard" that could include nuclear and similar large-scale technologies such as coal gasification plants with capture and sequestration.

TECHNOLOGY INNOVATION

Nuclear reactor technologies have been maturing for half a century. Thus, incremental learning and optimization, rather than revolutionary innovation, will likely drive cost reductions in the 2010 to 2020 gigaton time frame. Major technology innovations are highly unlikely to affect the industry before 2030.

Construction of hundreds of new nuclear power plants and fueling and reprocessing facilities imposes greater responsibilities for security and careful accounting of nuclear materials. A successful terrorist attack or an outbreak from the proliferation regime could have dire consequences, including for nuclear investors and the goals of energy and climate security. Possible solutions include internationalizing the fuel cycle — retaining tight controls over enrichment and reprocessing facilities while leasing fuel to any nation.

Interactions with Other Gigaton Pathways

Although future generations of nuclear reactors might have more flexibility in output, current reactors produce relatively constant output and thus can provide only baseload power. As a result, nuclear power is a good complement to peaking generation sources that can ramp output up and down quickly to meet changing demand. However, nuclear reactors cannot increase their output to compensate for changes in variable sources, such as solar and wind power. One of the more creative options for increasing nuclear plant flexibility involves using nuclear plants to electrolyze hydrogen during low-demand periods, then burning that hydrogen in peak-demand hours.[35] Such flexibility and added grid-storage options could increase the value of nuclear power on a dynamic grid characterized by significantly higher levels of renewable generation.

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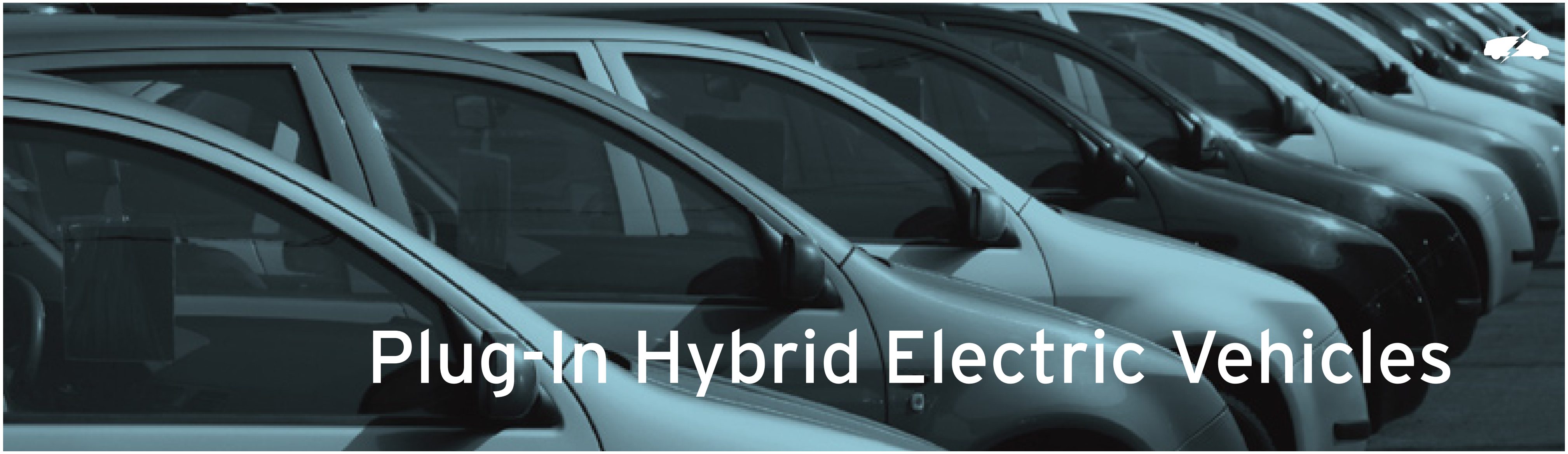
GIGATON THROWDOWN



Plug-In Hybrid Electric Vehicles

MAIN POINTS

- PHEVs cannot achieve gigaton scale by 2020; every new car starting in 2010 would have to be a PHEV to meet the gigaton goal by 2020, making this pathway all but impossible.
- An aggressive scale-up to 5 million PHEVs would create more than 204 thousand jobs in the battery industry, for an investment of $1.9 trillion.
- Innovations that reduce the cost of batteries and of vehicle retrofits would have a major impact on this pathway, as would business models to finance up-front costs of vehicles.
- The vehicle sector in general is by far the most capital-intensive sector of those examined in this report; it is also a source of major job creation.

Overview

Eliminating a gigaton of carbon dioxide equivalent (CO_2e) emissions from the global transportation sector by 2020 would be a monumental challenge, amounting to cutting about ⅙ of all of transportation-related emissions that would be expected in a "business as usual" (BAU) scenario where present-day trends continue unchanged.

A potential strategy for a transportation-sector gigaton emissions reduction would involve a major national and international program with four key initiatives: 1) rapidly introduce electric-drive vehicles (EDVs) to global automobile markets, 2) leverage heavy investments in EDV battery production with government support, 3) improve the fuel economy of all new vehicles as rapidly as possible, and 4) accelerate the retirement (or possibly electric-conversion) of the least-efficient older vehicles. The most promising focus is the light-duty vehicle (LDV) sector, which is responsible for a large percentage of transportation emissions, but efforts in the medium- and heavy-duty vehicle sectors could also yield significant emission savings. The synergy between reducing carbon dioxide equivalent (CO_2e) emitted by electricity generation and increasing the numbers of EDVs is also important for lowering emissions because EDVs recharge by plugging in to the electricity grid.

The magnitude of the required shift in the types of vehicles on the road is clear in a recent analysis for the International Energy Agency (IEA), which estimates that if new LDVs were immediately introduced worldwide that were 30% more efficient than current vehicles, the CO_2e reductions by 2020 compared to a BAU scenario would be about 500 megatons, or half of what is required to meet the gigaton goal.[1] Thus, achieving a full gigaton reduction would require introduction of even more efficient vehicles, such as plug-in hybrid electric vehicles (PHEVs) or fuel-cell vehicles (FCVs), and/or dramatically altering the motor vehicle fleet by accelerated scrapping of existing vehicles and increased introduction of more efficient new vehicles. To do this, a large amount of money would have to be provided to aid consumers in buying new efficient vehicles and scrapping their existing less-efficient vehicles.

To meet the gigaton goal with a strategy based on PHEVs alone, more than 350 million PHEVs would need to be in service globally by 2020, with more than 100 million in the U.S. This is roughly the total number of new LDVs expected to be added to the global fleet in the next 10 years, implying that every new LDV worldwide would need to be a PHEV. This number is not possible based on any reasonable vehicle introduction and ramp-up strategy. For comparison, the Obama Administration has proposed a total of 1 million PHEVs in the U.S. by 2015.

A fairly simple "back of the envelope" calculation highlights the challenge. Conventional vehicles produce about 450 grams of CO_2e per mile, while PHEVs with a 20-mile electric range might produce something like an average of 220 grams per mile if powered with electricity made from advanced combined-cycle natural gas power plants, and about 150 grams per mile if powered by near-zero-greenhouse-gas renewable power. Assuming that, by 2020, we are looking at power produced with average emissions similar to those of advanced combined-cycle natural gas (with considerable renewables but some older, legacy coal and natural-gas plants), the emission reductions compared to BAU vehicles would be about 230 grams CO_2e per mile. To achieve 1 gigaton of emission reductions, we would need about 360 million PHEVs, or nearly half the LDVs on the road in 2020. If by 2020 half of the PHEVs could be recharged with electricity produced with an emission factor similar to combined-cycle natural gas and half could be recharged with much cleaner wind and solar power, the number of PHEVs needed for a gigaton of reductions would be about 315 million — still a very tall order.

Even though the gigaton target appears unattainable by 2020 with current PHEV technology, innovation and carbon reduction in the transport sector are critically important, and major reductions can be made in the short term, laying the groundwork for the bigger reductions that will be needed in the 2030 to 2050 time frame. Efforts to dramatically reduce emissions from the transportation sector will require a series of interwoven and sequential steps, related to developing supply chains for improved vehicle components (such as electric motors, power electronics, and advanced batteries), integrating EDVs with utility grids in ways that minimize grid impacts, and developing other systems and infrastructure to enable cleaner vehicles, such as additional charging locations at workplaces and shopping centers. This will all take many years to develop fully, meaning that efforts that begin immediately will pay dividends for years and decades to come. Another fundamental issue that should be addressed is reducing the number of vehicle miles traveled (VMT), for example by encouraging development of mass transit systems, telecommuting, and non-motorized travel, but few experts believe that this could form the core of a gigaton-magnitude strategy by 2020. Improvements in LDV technology are the best hope for achieving the majority of transportation-related emissions reductions that could be expected by that time.

In terms of broader context, it is important to note that the transportation sector con-

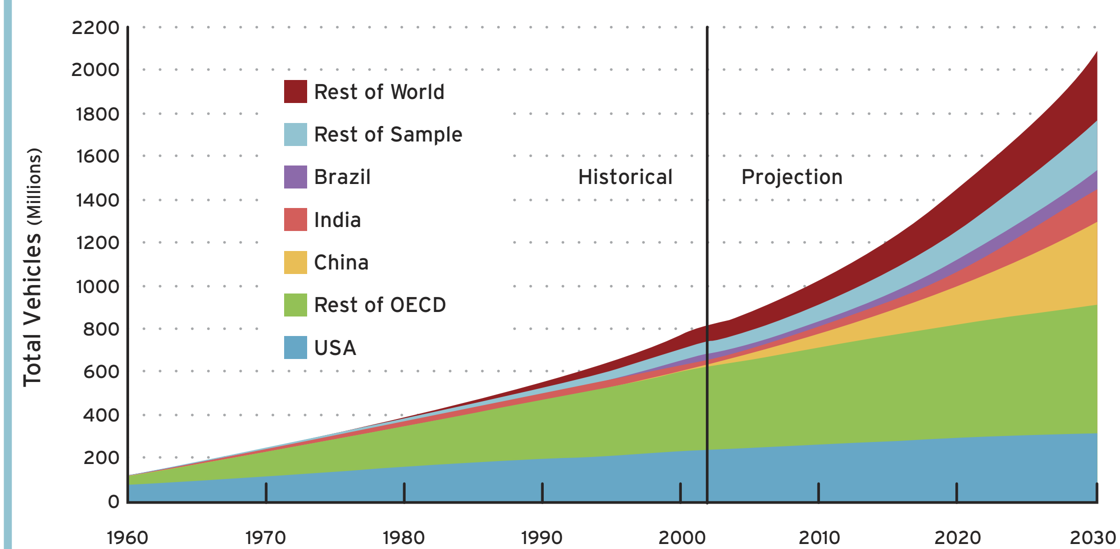


FIGURE 1. Historical and Projected Global Vehicle Ownership. China is the fastest-growing vehicle market. Source: Dargay et al., 2007[8]

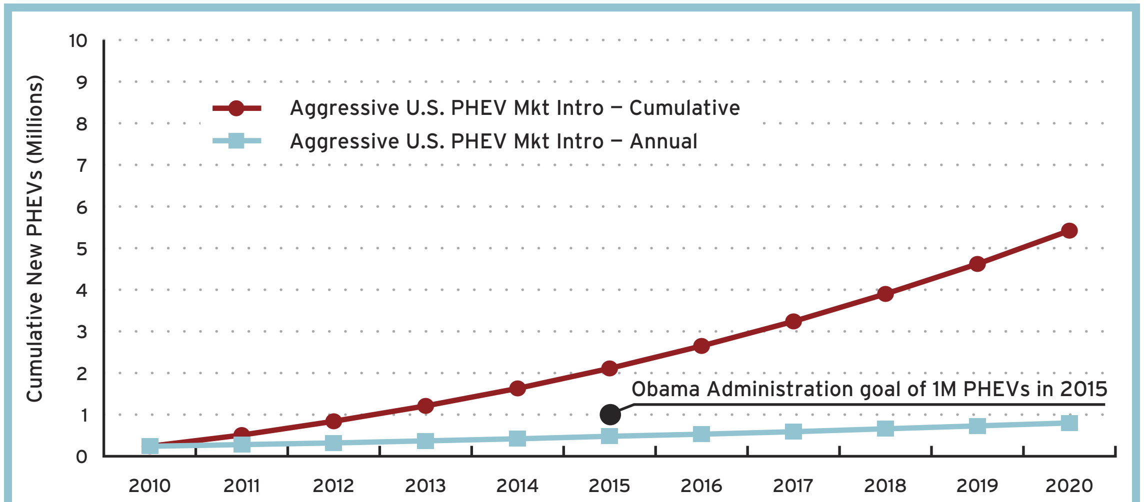


FIGURE 2. Aggressive U.S. Market Introduction Scenario for PHEVs Based on Bass-Centrone Model Estimation and Obama Administration Target for 2015. Source: McManus, 2009.[10]

tributes about 14% of greenhouse gas (GHG) emissions globally, 27% of GHG emissions in the U.S., and almost 40% in California.[2,3] Emissions from the transportation sector are also the fastest growing in the U.S. and globally, so they offer a huge opportunity for targeted reductions.[4] There are currently about 250 million motor vehicles in the U.S. and about 800 million in the world.[5] The number of vehicles in the world is projected to reach 1.6 billion by 2020 and more than 2 billion by 2030. Including trucks, buses, and motorized scooters and cycles with automobiles, there will be a total of more than 2 billion motorized vehicles by 2020, about 60% of which will be cars.[6,7] These projected increases in vehicle ownership make clear the challenge of reducing total transportation-related CO_2e emissions, as well as the huge potential opportunity. Figure 1 shows historical and projected vehicle ownership worldwide.

Figure 2, based on a simplified stock model for vehicles in the U.S. and the potential for PHEV market penetration (using estimates from a "Bass-Centrone"-type diffusion model) shows how challenging it is to rapidly change the characteristics of the motor vehicle fleet by introducing new vehicles with improved technology and better energy efficiency, even under a relatively aggressive scenario.[9] Under this "aggressive" scenario, one might expect a few hundred thousand PHEVs to be sold in the U.S. in the next few years, rising to about a million per year by 2020. This would put about 2 million PHEVs on the road in the U.S. in 2015 (compared with an Obama Administration goal of 1 million) and about 5 million by 2020. For comparison, it took about 9 years for 1 million "conventional" hybrid electric vehicles to be sold around the globe, from 1999 through 2007, with a total of 3.7 million more expected from 2008 through 2012, based on J.D. Power Associates forecasts.

As shown in Figure 3, to achieve gigaton scale with a strategy based on PHEVs, more than 350 million PHEVs would be needed globally. Compared with an "aggressive but possible" introduction strategy in the U.S. that would have about 5 million PHEVs on the road by 2020, this 350 million global figure is really not possible based on any reasonable vehicle

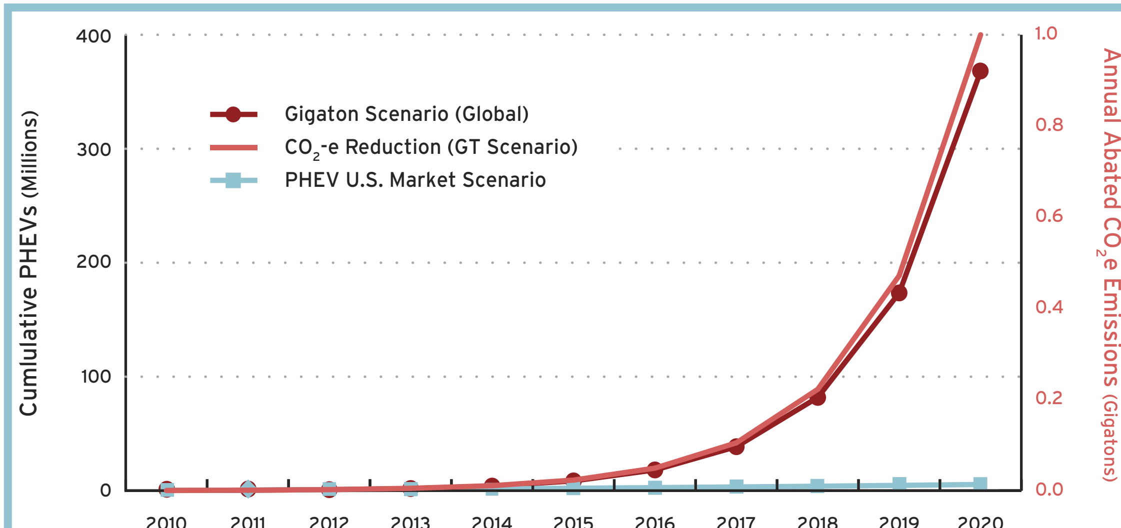
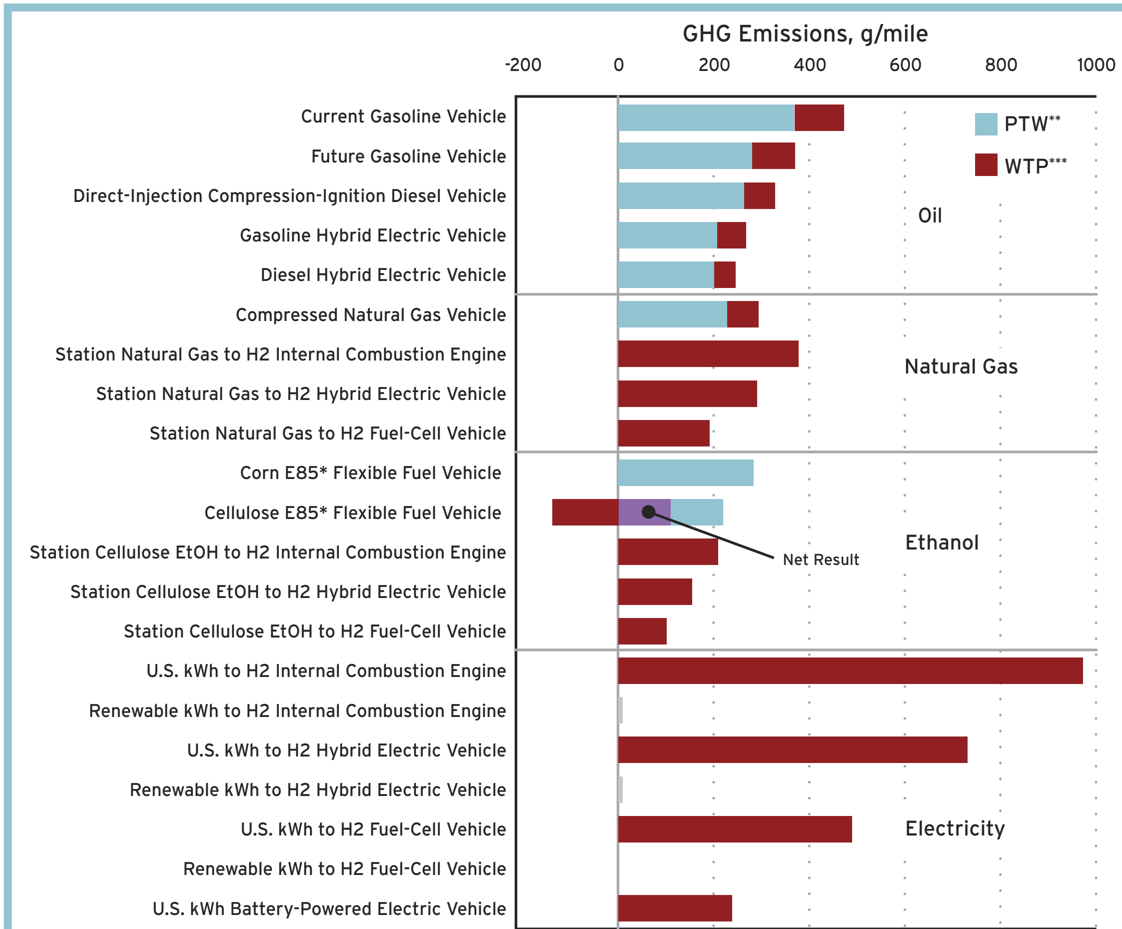


FIGURE 3. Global Gigaton Emission Reduction Scenario from PHEVs Compared with Aggressive U.S. Market Introduction Scenario



*E85: a mixture of 85% ethanol and 15% gasoline (by volume)
**Pump-to-wheel
*** Well-to-pump

FIGURE 4. GREET Model Greenhouse Gas Emissions Estimates for Conventional and Alternative Fuel Light-Duty Vehicles (grams/mile). Source: Argonne National Laboratory, 2007.[11]

introduction and ramp-up strategy. However, in the longer term, by 2040 or 2050 and with more time for new vehicles to enter the fleet, some combination of EDVs that includes PHEVs, battery electric vehicles, and FCVs, could achieve roughly this level of emission reduction (compared with a BAU scenario based on continued dominance of gasoline combustion engine vehicles and only incremental efficiency improvements). This would be especially likely (or perhaps only possible) with supportive government research and development (R&D) and market transformation policies.

Even though the aggressive PHEV market strategy would fall short of meeting the 2020 gigaton goal, it would still produce a cumulative total of about 15 million tons of CO_2e reduction through 2020 in the U.S. alone, compared with a no-PHEV strategy. The actual total would depend on the details of the regions in which PHEVs were mostly introduced and when and how electricity to recharge PHEV batteries was generated. If the aggressive PHEV strategy were extended throughout the Organization for Economic Cooperation and Development (OECD), the cumulative emissions reductions through 2020 could be 40 to 50 million tons of CO_2e. See Figure 5, below, for an estimate of the much larger emission reductions that could be possible in the 2050 time frame.

It is important to note that emissions from EDVs are highly dependent on the source of electricity for recharging vehicle batteries and that the lowest carbon emissions are possible from EDVs that are powered with electricity or hydrogen from renewable sources. By comparison, biofuel vehicles can have highly variable carbon impacts depending on the feedstock and fuel. More efficient conventional vehicles, including those powered by compressed natural gas, can also have significant carbon reduction potential though less than for EDVs and biofuels. Figure 4 shows "well-to-wheel" GHG emission results from Argonne National Laboratory's "GREET" model, in terms of grams of GHGs per mile of vehicle use. The yellow bars refer to "well to pump" emissions (also known as "upstream" emissions), and the purple bars refer to "pump to wheels" or "in-use" emissions.

Although achieving gigaton scale with PHEVs by 2020 is infeasible, it worth noting that the aggressive PHEV market strategy above would cost about $1.9 billion and create roughly 16,000 jobs in battery manufacturing and vehicle construction.

Industry Background

The most promising options for significant efficiency improvements and GHG reductions in the 2020 time-horizon for the LDV sector are hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). Fuel-cell-powered electric vehicles (FCVs) can significantly reduce GHG emissions if the hydrogen that they use (combined electrochemically with oxygen from the air) to produce electricity comes from low-carbon sources, but these vehicles are not expected to be sufficiently commercialized in time to contribute very large CO_2e reductions by 2020.

Electric Drive Industry

All of the world's major automakers are now working on various types of EDVs, and most currently have one or more HEVs on the market.[12] As noted above, global sales of HEVs exceeded a cumulative total of 1 million in 2007, with about 350,000 being sold at that time and about 600,000 expected in 2009. Pure BEVs and FCVs are at earlier stages of commercialization, with only several thousand sold each year, mostly small "neighborhood electric" BEVs; larger BEVs are just re-entering production, and FCVs are still in the early production stage.

HEVs can easily improve efficiency by 10% to 20% or up to about 30% if all of the benefits of hybridization are directed toward increased fuel economy and some redesign options (e.g., decreases in vehicle weight) are pursued. PHEVs and BEVs can make even greater reductions, depending in large part on the local electricity grid and how electric power is produced at the specific time of day when vehicles are plugged in to recharge. For example, in the U.S. and California, PHEVs can reduce well-to-wheels GHG emissions by about 29% and 40%, respectively, depending on vehicle design, charging behavior, and utility grid power generation mix (results from Argonne National Lab's GREET Model version 1.8b).[13]

PHEVs and BEVs are expected to cost more than conventional vehicles to purchase but potentially less to operate. The cost increment for a PHEV or BEV over a conventional vehicle is highly variable depending on the size of the battery, design of the vehicle, and other factors, and may well decline in the future with decreased battery costs. At present, PHEVs are expected to cost \$5,000 to \$15,000 more than conventional vehicles, again mainly depending on the size and type of battery and how much actual or theoretical "zero emission" range the vehicle has.

Industry Growth

The key issue for PHEVs and BEVs is the development and production of suitable batteries. The old adage that "the devil is in the details" applies to EDV battery requirements. Depending on the type of vehicle (HEV, PHEV, BEV, or FCV), the battery requirements are significantly different. Key parameters include the trade-off between energy and power density (typically expressed as "specific energy and power," in terms of watt-hours per kilogram or "Wh/kg" and watts per kilogram or "W/kg"), cycle life and calendar life, abuse tolerance, charge/discharge efficiency, self-discharge rate, and manufacturing cost. Developing a battery for any particular EDV design requires optimizing across all of these parameters for that particular application, inevitably trading off some benefits for others. In general, batteries for PHEVs and BEVs will need to be able to withstand much deeper charge-discharge cycling than batteries for HEVs and FCVs (where battery "state of charge" is kept within a fairly narrow range). This creates particular challenges for battery longevity.

New lithium-based batteries currently cost in the range of \$500 to \$700 per kWh; costs could drop by half in the near future as production volumes increase. But the inclusion of the "battery management system" (BMS) for battery cooling (called "thermal management") and voltage monitoring pushes costs over \$1,000 per kWh for the size battery packs needed for PHEVs. As a result, vehicles using these battery types could easily have cost premiums of \$10,000 or more each, compared with similar gasoline vehicles. Incentives are currently in place in the U.S. and other countries to help to reduce this cost differential and make lithium-battery vehicles more attractive to consumers, but this cost barrier could be a major problem, depending in part on gasoline and electricity costs, which will determine how much money consumers could save over time by buying vehicles that rely at least partly on electricity. With low gasoline prices, having fallen from about \$4 per gallon during the summer of 2008 to less than \$2 per gallon early in 2009, it is difficult to maintain manufacturer and consumer interest in electric vehicles. But few believe that gasoline prices will stay low once the 2009 economic downturn eases, and higher gasoline prices will likely renew interest in these vehicles.

Another tricky issue is the potential market for PHEVs and BEVs. Consumers who purchase these types of vehicles need two important things: 1) a safe place to plug in vehicles overnight to recharge, and 2) driving patterns that lend themselves to the use of these vehicles, which need to be recharged after a certain number of VMT. Drivers who typically travel relatively short distances each day are the best candidates for PHEVs and BEVs.

Achieving Gigaton Scale

Although achieving gigaton scale by 2020 is a very tall order, aiming for that level of reduction could put us on a pathway to achieve the even deeper reductions in GHG emissions that are needed for 2050 and beyond to avoid climate destabilization.

Scaling the Industry

As noted earlier, a major issue with a rapid scale-up of EDVs is the availability of advanced electric vehicle battery packs in the numbers needed for this scale of transition. The current global production capacity of advanced lithium-based battery packs in 2009–2010 is probably on the order of 10,000 battery packs. Achieving gigaton scale with a strategy based largely on a massive introduction of EDVs would require about 1,000 times this many batteries in the near term, growing to about 10,000 times as many by 2020. This implies a massive investment in battery production capacity at a time when battery designs are still being improved and perfected to the point where commercially acceptable PHEVs and BEVs can be produced.

More generally, PHEVs and other EDVs are technologies that can scale fairly rapidly, with typical automotive volumes of several hundred thousand units per year for individual popular models (e.g., the combined U.S. and Japanese sales of the Toyota Prius are around 275,000 to 300,000 per year), and the ability to incorporate electric drive technology into many vehicle models. The rate of scaling is mainly limited by the growth of supplier networks and supply chains, the dynamics of introducing new vehicles — with 15-year lives — into regional motor vehicle fleets, and the economic and market response constraints on the demand side.

Given all the transportation sector dynamics described above, it is much easier to see large reductions in LDV emissions by 2050 than by 2020, especially because a significant percentage of new vehicles sold today will still be on the road in the next 10 years. For example, a recent Electric Power Research Institute/Natural Resource Defense Council (EPRI/NRDC) study concludes that under the most optimistic U.S. scenario assessed — high PHEV fleet penetration and low electric sector CO_2 intensity — 612 million megatons of emissions could be reduced annually by 2050. (See Figure 5.) Extrapolated globally, these emission reductions could be on the order of 2 to 3 gigatons annually, based on optimistic assumptions about fleet penetration and GHG intensity in the electric power sector.

In the near term, it is interesting to consider the capital expenditures needed to scale the EDV industry and the jobs created, even for the more modest "aggressive U.S. PHEV introduction" scenario discussed above, let alone for the type of trajectory that would in theory be needed to achieve 1 gigaton of reductions by 2020.

Capital Investment

Figure 6 shows the estimated capital expenditures needed to expand battery production capacity for the U.S. PHEV market introduction scenario that results in about 5 million vehicles in the market by 2020. Capital expenditures are $125 million to $225 million per year, for a total of about $1.9 billion from 2010 through 2020. These estimates assume a capital expense of $3,000 per battery pack produced, based on industry sources.

The capital investment needed to produce batteries varies significantly around the world; a few estimates have been released. In Europe, Johnson-Controls/Saft is planning to build a pilot battery plant for 15 million Euros (about $23 million) that would produce 5,000 battery packs per year.[15] Scaled up to a production level of 1 million packs per year (for a production level that might be expected in the 2015 to 2020 timeframe), that represents a capital investment of about $4.6 billion. In Japan,

ANNUAL GREEHOUSE GAS EMISSIONS REDUCTIONS FROM PHEVS IN THE YEAR 2050

2050 ANNUAL GHG REDUCTION (MILLION METRIC TONS)		ELECTRIC SECTOR CO_2 INTENSITY		
		High	Medium	Low
PHEV FLEET PENETRATION	Low	163	177	193
	Medium	394	468	478
	High	474	517	612

FIGURE 5. Longer-Term Greenhouse Gas Reductions from PHEV Introduction Scenarios in the U.S.
Source: EPRI/NRDC 2007.[14]

meanwhile, Yuasa is partnered with Mitsubishi on batteries for a small EV called the MiEV. These packs may be somewhat larger than those needed for PHEVs. The estimated cost for the Yuasa battery plant is 14 billion Yen (about $130 million) to produce 20,000 packs per year by 2012.[16] Again scaled up to 1 million packs per year, the battery plant capital cost would be about $6.5 billion. These estimates suggest that the $3,000 per battery pack estimate used to produce Figure 6 may be somewhat optimistic as capital expenditures may be more like $4,500 to $6,500 per pack. Again, however, these expenditures vary significantly in different settings around the world, so Figure 6 should therefore be regarded as illustrative.

Also, it is worth noting that significant development of battery pack assembly plants would be needed in addition to the scale-up in battery cell and module production plants. For example, General Motors was reportedly planning to spend $30 million on a plant to assemble battery modules — produced in Asia — into complete battery packs for the Chevy Volt vehicle.

There also is some question about the availability of lithium to support a dramatic expansion in the use of lithium-based batteries for EDVs. About 70% of the world's lithium is currently produced in South America, and that region holds about 80% of the known reserve base (about 13 million tons globally), but there are considerable lithium deposits in other parts of the world as well, including China, North America, and Australia.[17] One market assessment suggests that there will not be a shortage of lithium for battery applications, but that sharp increases in demand in the 2010 to 2020 time frame could cause prices to increase.[18] Another study suggests that up to 12 billion EDVs could be produced with the current supplies of lithium based on lithium-manganese based electrodes, but another study suggests this figure could be as low as 200 million with other assumptions (mainly related to the size of batteries and the utilization rate of lithium). However, we note that only about 10% to 20% of the cost of lithium batteries is directly related to the cost of lithium, suggesting that potential price increases may not be that serious an issue as long as they are not too dramatic. Certainly, lithium availability overall would not be a major constraint until 2040 or so, by which time other competing battery technologies such as sodium-nickel-chloride, metal-air, or other as-yet-unknown ones may be sharing or even dominating the market.

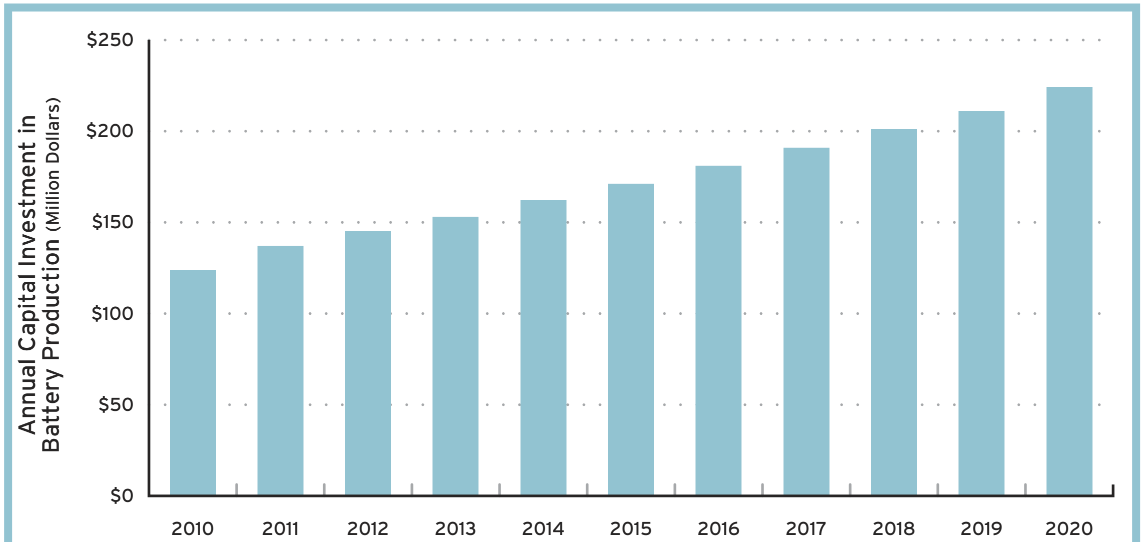


FIGURE 6. Annual Capital Investment in Battery Production. Minimum total capital expenditures needed to expand the battery industry for the aggressive scenario (5 milion PHEVs by 2020) is an estimated $1.9 billion.

Jobs in the Electric Vehicle Industry

The expansion of a PHEV battery industry would entail additional manufacturing and construction jobs. Figure 7 shows an estimate of these jobs, again based on the "aggressive PHEV market introduction" scenario described above for the U.S. The manufacturing jobs estimate assumes that initially about 45 battery packs can be produced per manufacturing employee, rising to 64 packs per employee by 2020 (based on industry sources). The construction jobs estimate assumes that each million dollars of capital expenditure produces 10 construction jobs.

Challenges to Accelerated Deployment

In addition to scaling up battery production capacity, widespread introduction of PHEVs would require:

- Further development of supply chain relationships between battery manufacturers and automobile manufacturers

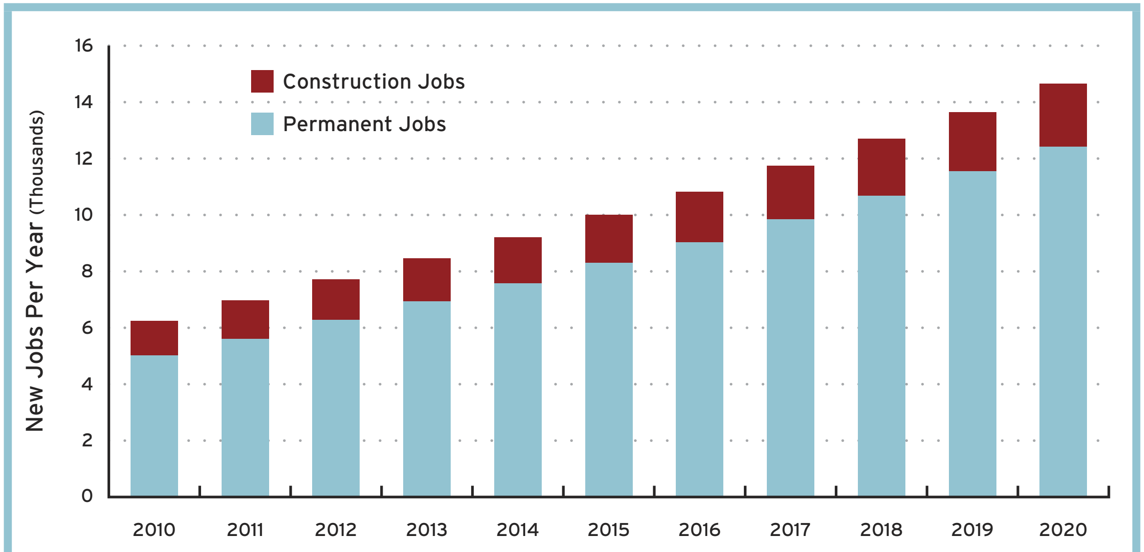


FIGURE 7. Jobs Created in the PHEV Battery Manufacturing Industry. Battery manufacturing and construction jobs for "aggressive" PHEV market introduction in the U .S. total 121 thousand jobs.

- Efforts to place "smart meters" in households to help to manage electrical loads for local utilities, in order to maximize the capacity factor improvement for utility grids (by increasing power sales at night when there is excess capacity) and to minimize the need for additional power generation facilities
- Education and outreach campaigns to help consumers identify who are best candidates for PHEV purchase, given driving patterns and ability to recharge the vehicles

Of these, the consumer education effort should not be taken lightly as PHEVs will not be ideally suited for all drivers, and consumers who purchase PHEVs but become unhappy with them could have a negative effect on development of the market. As noted above, drivers with access to home recharging locations (to take advantage of cheap off-peak power) and relatively short commute distances are the best candidates for PHEV adoption.

With regard to PHEV grid impacts, this is a critical question that depends on the structure of the local power generation and distribution system, consumer driving and charging patterns, and the types of electricity rates and tariffs charged to PHEV owners. One California-focused study found that up to 6 million PHEVs could be economically charged off-peak, and as many as 3 million on-peak. However, by the time market penetration reached 1 million, the state's peak load could increase by about 2% and start to require the addition of new generating capacity.[19] Driver behavior and charging patterns, currently under study at UC Berkeley in a "real world" PHEV test program, are clearly critical to this question, along with the ability to minimize grid impacts using innovative strategies. These include "smart" electricity meters that would optimize for off-peak charging, price signals that would give consumers the incentive to shift charging away from grid peaks, and the ability for PHEVs to interact with utility grids in complicated ways known collectively as "vehicle to grid" (or "V2G") power where real values and services can be supplied to the utility grid using the storage and discharge capacity of the PHEV batteries.

Technology Innovation

Fundamental to the PHEV story is that a new family of batteries with lithium-based electrodes offers a promising combination of energy and power density, and their durability ("cycle life") could far exceed that of the lead-acid and nickel-metal hydride batteries that have previously been used. Furthermore, other types of batteries currently under development could exceed the performance of the lithium chemistries and/or be much lower cost. The further development and especially cost reduction of these new batteries is critical to commercialization of PHEVs that will be attractive to consumers.

On the down side, some types of lithium batteries are highly reactive and can catch fire although new materials and monitoring systems are being developed to reduce these dangers. These batteries require sophisticated BMSs that add considerably to their overall cost. A host of established and new companies are racing to produce EDV battery designs offering the best mix of characteristics for different vehicle designs, and to scale up production. The production scale-up is a significant challenge for the rapid turnover of the vehicle fleet to replace as many vehicles as possible that are designed to reduce CO_2e emissions.

Game Changers

Studies of the economics of PHEVs have found that reducing the cost of PHEV batteries is critical to their ability to achieve cost-effective GHG reductions compared with other strategies. With current battery prices, PHEVs require very low-carbon electricity to be cost effective, or significant government subsidies to lower costs to consumers. For example, one study found that battery costs below about $500 per kWh can lead to reasonably cost-effective PHEVs for GHG abatement, depending on the carbon-intensity of the electricity generation and the value of the carbon reduction per ton.[20] The study further found that if battery costs for PHEVs could reach $200 per kWh, then PHEVs could be cost effective for consumers and society even absent the consideration of GHG benefits and the method of generation.

As noted above "V2G" is a concept that could significantly alter the PHEV commercialization story by improving the economics of PHEV ownership and their impact on utility grids. While potentially complex to coordinate and administer, V2G could allow PHEVs to supply real value to utility grids in the form of utility grid "ancillary services" (e.g., grid frequency regulation, "spinning reserves," and voltage support), peak load-shifting, and emergency back-up power. The value of these services could be in the range of a few hundred to up to a few thousand dollars per vehicle per year, depending on the types of services considered and various underlying assumptions.[21]

Additional concepts that could help to facilitate market transformation include accelerated scrapping of the least-efficient older vehicles (discussed below) to increase the introduction of more efficient new vehicles, conversion of existing conventional vehicles to electric-drive, and innovative ownership and financing schemes such as battery leasing to help alleviate the "first cost" hurdle for consumers. Conversion of conventional vehicles to PHEVs is quite complicated; only HEVs with significant electrical power (e.g., the Toyota Prius and Highlander) can be readily converted to plug in. However, conversion of certain conventional vehicles to all-electric "BEV" operation is more possible, in which case the combustion engine driveline is completely removed. Innovative vehicle ownership and financing models can help to reduce first cost barriers to vehicle purchase by spreading these costs over time and offsetting them with operational savings from increased vehicle efficiency and lower fuel costs. Similar to programs that allow homeowners to pay for solar photovoltaic systems over many years rather than with up-front payments, these types of programs could help to expand the EDV market, particularly as market penetration expands beyond the most eager "early adopters" and into broader market segments.

Public Policy

In California, the "Pavley Law" calls for reducing transportation sector emissions to 1990 levels by 2020, which amounts to an annual reduction of about 32 million metric tons of CO_2e. If similar rules were extended across the U.S., annual reductions would be on the order of 257 megatons by 2020, and, if extended across the OECD, annual reductions of approximately 500 to 600 megatons would likely be possible by 2020 (reductions would be somewhat less than proportional because the rest of the OECD already drives more efficient vehicles than the U.S.). This falls somewhat short of the gigaton goal, but it shows that approaching this goal could be possible with a concerted global effort.

Public policy can also support an increase in the rate at which older vehicles are scrapped and provide incentives for purchases of vehicles with high efficiency and low GHG emissions. Several U.S. senators have introduced a bill for a program of this type, the "Accelerated Retirement of Inefficient Vehicles Act of 2009." This so-called "cash for clunkers" program would reimburse drivers with a credit of up to $4,500 when a vehicle with fuel economy of less than 18 miles per gallon (mpg) is scrapped (based on mpg ratings used for corporate average fuel economy [CAFE] program compliance), and a new or used vehicle with a fuel economy 25% or more greater than the CAFE target for that vehicle class is purchased. Vehicles eligible for purchase would have to have a retail price of $45,000 or less and be of model year 2004 or later. Vouchers could also be used toward transit fares from participating transit agencies.[22]

Other types of public policies that could help to support the introduction of advanced vehicles, in addition to the GHG fleet emission standard and accelerated vehicle scrapping programs discussed above, include financial support and loan guarantees for manufacturing investments as well as public policies to make vehicle purchases more attractive to consumers. One idea for consumer-side policy is a "feebate" program, in which purchasers of vehicles with lower-than-average GHG emissions would receive a rebate, and purchasers of vehicles with higher-than-average GHG emissions would pay a fee. Unlike more typical clean-fuel vehicle incentive programs that require government revenues, feebate programs could be revenue neutral, even net of administration costs. Such programs have been tried previously in Canada and France and are currently being explored by California and Massachusetts. These types of "market pull" programs could be critical to ensuring that the advanced technology vehicles — once produced — are actually purchased and introduced into the vehicle fleet as soon as possible. For other types of strategies and policies that can help to reduce GHGs from the transportation sector, see the review in Shaheen and Lipman (2007).[23]

Interactions with Other Gigaton Pathways

Unlike some other strategies, efforts to electrify the motor vehicle fleet can have a significant synergistic effect with efforts in other sectors, particularly electric power generation, to reduce GHG emissions. Some of these other strategies, such as those based on the expanded use of natural gas or other lower-carbon liquid or gaseous fuels, could more easily achieve modest near-term emission reductions than are possible with EDVs but do not have the same potential for deep, long-term reductions that are possible from vehicle emissions reductions. So, in combination, electric vehicles and other strategies could achieve both the short- and long-term GHG reductions needed. It is also important to note that PHEVs and BEVs can help to facilitate the penetration of intermittent renewables in utility grids, particularly wind power, which can be available at night when plug-in vehicles would likely be charging. EDVs can also act as storage for utility grids more generally, helping to even out power flows, improve grid capacity factors, and provide utility grid "ancillary services" such as frequency regulation and spinning reserves. Taken as a whole, it is much easier to visualize a future electricity infrastructure based heavily on renewable sources of electricity if there are also significant numbers of EDVs in the system. Finally, EDVs such as HEVs and PHEVs can also have a synergistic relationship with biofuels where the combustion engine portion of the EDV drivetrain could operated on a biofuel rather than gasoline. These "zero gasoline" vehicles would still have some combustion emissions from the tailpipe, but these could be low on a fuel-cycle basis depending on the biofuel and the way it is produced.

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Solar Photovoltaics

MAIN POINTS

- Solar PV can achieve gigaton scale by 2020 for an investment of $2.1 trillion, creating more than 1.5 million direct jobs and enhancing energy security through distributed power generation.
- At current growth rates solar PV is on track to abate half a gigaton of CO_2e by 2020 and be cost competitive with current electricity prices within the next 5 years.
- Solar PV is already price-competitive for peak power rates in a number of markets.
- Successful policies, grid integration, and storage are critical to scaling PV.
- Enough rooftop space exists in the U.S. alone to achieve gigaton scale.

Overview

Solar photovoltaic (PV) technology converts sunlight directly into electricity by means of semiconductors. To mitigate 1 gigaton of carbon dioxide equivalent emissions (CO_2e) per year, cumulative solar PV installations would have to reach 1,000 gigawatts of peak power (GW_p) by 2020.[1] In 2008, cumulative U.S. PV installations reached 1 GW_p, providing less than 1% of consumed electricity. Globally, installations in 2008 totaled 14 GWp. Between 2006 and 2008, the industry experienced a 50% global growth rate, with demand rising from 2 GW to 3 GW between 2006 and 2007 and to 4.5 GW between 2007 and 2008. If this growth rate could be sustained, a worldwide gigaton target would be reached by 2022. The economic slowdown of 2009 has led to a more conservative estimate for 2009 growth of closer to 15% although growth could recover with economic stability. Meeting the gigaton challenge by 2020 would require an accelerated growth rate of 46% post-2009 and capital investment upwards of $2.1 trillion. Of particular recent importance is the growth of utility-scale PV projects — some over 100 megawatts (MW) for a single solar farm — and aggressive clean energy policies, such as more serious discussions of carbon prices and the introduction of feed-in tariffs in a number of nations, and discussions at both the state and federal level in the U.S.

The costs for solar PV have been falling, and with the alleviation of a past supply bottleneck in silicon, the most common semiconductor used in today's solar cells, PV is on track to be a cost-competitive electricity source.[2] Although PV is forecast to reach grid parity within the next 5 to 10 years and thus to be competitive with other electric power options, significant hurdles, including technical and materials constraints, must be cleared to allow rapid expansion. If these hurdles can be surmounted, PV will be a very attractive technology. Policies and regulations that have benefited PV in the past will need to be extended to support gigaton-scale ramp-up. Investment in stable policy support and expanded installations will have several benefits beyond bringing down cost. The distributed nature of PV power has security benefits, allowing those served to avoid the effects of power outages in a grid failure. PV is also insulated from fuel price shocks.

Solar PV's ability to provide peak power makes it attractive for meeting daytime power needs when electricity demand is highest. Peak power is the most costly; at peak power rates in the most expensive electricity markets in the U.S., such as California, solar PV is cost competitive today.

Without storage, solar PV is off line at night and when sunshine is unavailable, e.g., during cloudy periods. In the future, as higher grid penetration levels for solar PV are reached, this intermittency may be a concern for utilities. At current penetration levels, back-up generation is not an issue, but, for high penetration levels of solar PV, the technology may need to be paired with firming generators, particularly in regions with intermittent sunshine. Back-up generation will increase system-wide costs by a marginal amount that has not yet been fully evaluated.

A major shift in markets would be needed to scale PV to the gigaton level. More than 80% of new worldwide solar PV capacity in 2008 was installed in four countries: the U.S., Germany, Japan, and Spain (see Figure 1). Figure 2 shows worldwide historic solar PV installations. Owing to the maturity of the electricity market, total installed demand in the U.S. is projected to rise by only 190 GW by 2020, meaning that the gigaton goal cannot be achieved in the U.S. solely by satisfying new demand with PV or even by replacing much of the existing capacity with solar systems. Expanding PV penetration to meet the gigaton goal would require not only expanding established markets around the world like Germany and Japan but extending deep into emerging markets like China and India. Already the bulk of solar module manufacturing capacity is in China and

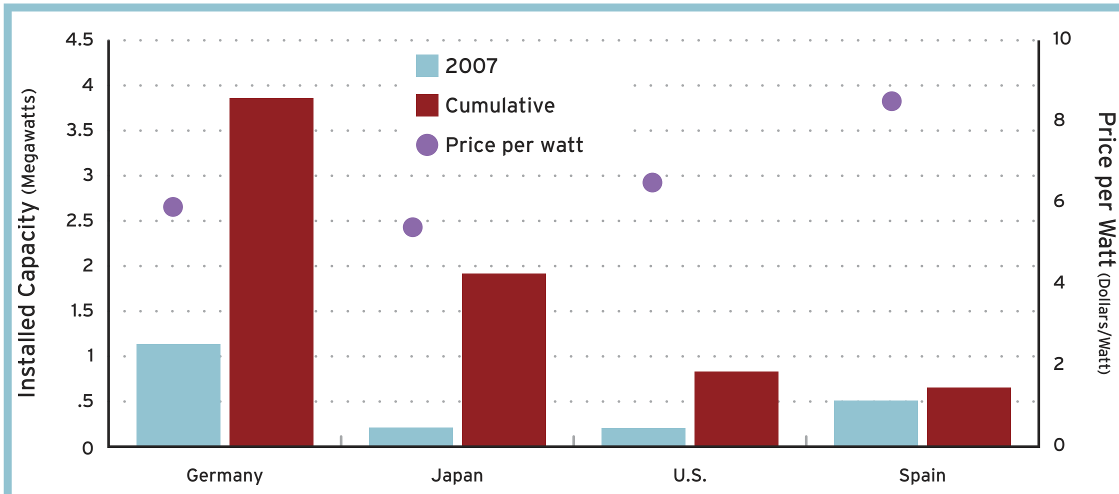

FIGURE 1. Cumulative Solar PV Installations in Germany, Japan, U.S., and Spain. Aggressive feed-in tariffs have spurred adoption in Germany.

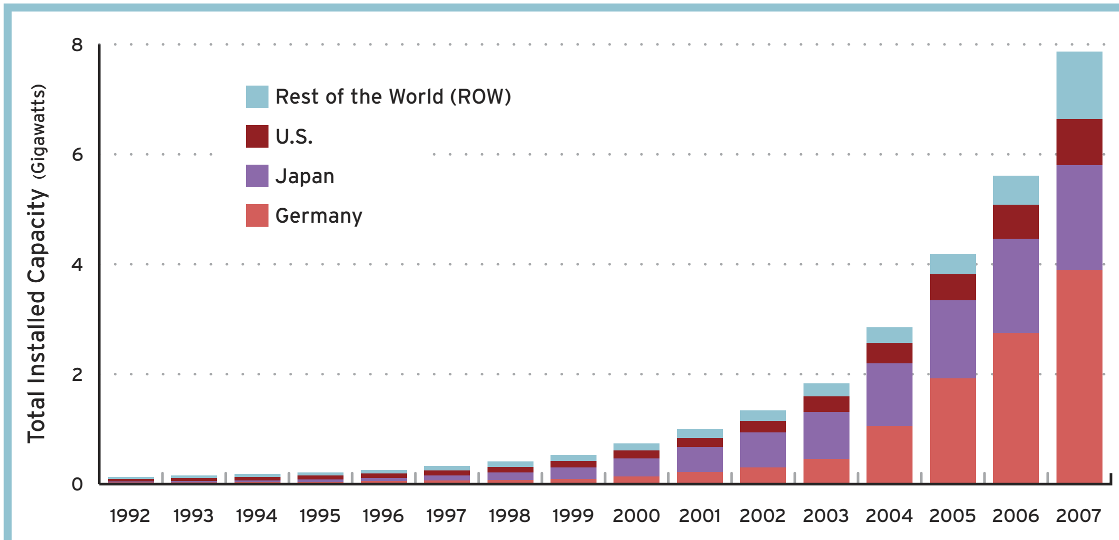

FIGURE 2. Worldwide Historical PV Installations. To date, Germany, Japan, and the U.S. have accounted for nearly 85% of worldwide PV installations. Meeting the gigaton challenge will require expanding the PV market well beyond these three countries.

India although most of what is produced is exported.

A gigaton-scale expansion of solar PV would add an estimated 1.5 million direct jobs.

Industry Background

The solar PV industry has been going through a transformation, with increasing utility-scale developments, an increase in grid-tied installation, and high growth rates.

PV Industry

The U.S. solar PV industry transformed after 2005 when installations became increasingly grid tied. Prior to 2005, the majority of PV installations in the U.S. were off the electricity grid and used to provide electricity in remote locations or for government applications and communications equipment. In 2005, the amount of PV power on and off the grid roughly equalized, with total installed peak capacity reaching 500 MW. Since then, installed capacity has doubled, with 80% of the growth coming from on-grid installations. The vast majority (more than 90%) of worldwide installations are grid tied though exceptions (notably in Mexico and Australia) exist. Grid-tied installations are projected to account for the majority of growth in the industry, implying an urgent need to resolve the issues related to PV's intermittent nature and the associated concerns about grid stability when high levels of PV are incorporated.

PV Technologies

The three major categories of PV technologies are: silicon crystal, thin film, and third generation.

SILICON CRYSTAL

Although the first solar cells were made using selenium, silicon early on achieved energy-capture efficiencies that demonstrated PV's potential to contribute significantly to energy production. Today, silicon is the most commonly used semiconductor in the PV industry, not only because of its physical properties, but also because of its relative abundance as a raw material and the ready transferability of experience with its use from the electronics (particularly microchip) industry. Silicon processing for solar cells is expensive, representing approximately 20% of the total cost of a solar cell.

PV cells built with silicon crystal come in two varieties: mono-crystalline (c-Si or x-Si) and polycrystalline (poly-Si or mc-Si). While c-Si cells utilize silicon wafers cut from a single crystal, poly-Si cells have wafers cut from silicon ingots composed of several different, interlocking crystal lattices. Use of single-crystal ingots is more expensive but produces solar cells with technology-best efficiencies (approximately 18% to 20%). The efficiency rate of today's poly-Si cells typically ranges from 14% to 16%.

THIN FILM

Thin-film PV technologies promise to address the high materials cost of crystalline PV. The general approach is to combine low-cost materials (such as glass or plastic) in significant measure with a small quantity of an expensive but thinly spread semiconductor. This production technique limits the efficiency of individual cells but has the potential to deliver solar power at a lower cost per peak watt (W_p) than crystalline cells. Thin-film technologies are projected by some to become less expensive than crystalline silicon in 5 years.

Embodied Carbon in Solar PV

The operation of solar PV electricity systems emits virtually no greenhouse gases although significant carbon emissions result from the manufacture of system components. The embodied energy in solar PV is high relative to other renewable technologies, in large part because of the energy intensity of silicon processing; silicon is needed for the semiconductors in solar PV cells. The carbon footprint of solar PV depends on the energy source used in semiconductor manufacture. If, for example, renewable energy (say, solar power) were used in the silicon processing phase, PV's carbon footprint could be negligible. Current estimates of CO_2e for crystalline silicon solar PV are 35 grams per kilowatt hour (kWh).[a] This translates into 4.2 to 6.1 gigatons CO_2e to produce 1 terawatt (TW) of PV. The outer bounds of this estimate are 3.1 to 9.2 gigatons. This is a significant amount of CO_2e emissions to be released during the ramp-up of solar PV and highlights a major unresolved concern regarding rapid expansion of the industry under current production methods. Thin-film PV has significantly lower embodied carbon, and further technology advances may help address the embodied carbon issue. The cumulative impact on CO_2e emission over the lifetime of PV operation is net positive; at gigaton scale, approximately 30 gigatons of CO_2e emissions would be abated (assuming a 30-year lifetime of the system).

a Fthenakis, V., H. Kim, E. Alsema. 2008. "Emissions from Photovoltaic Life Cycles." *Environmental Science and Technology*. Vol. 42, No. 6: pp. 2168–2174.

The three principal types of thin-film cells are thin-film silicon; cadmium telluride (CdTe), or "cad-tel"; and copper indium gallium selenide (CIGS). Thin-film silicon panels utilize about 1⁄100 of the silicon required for crystalline cells and use a form of refined silicon that does not contain a large crystalline structure. This lack of lattice structure causes defects in electrical processes but saves refining costs. These thin-film technologies are competing with each other, and with crystalline silicon, on a price-per-Wp and conversion-efficiency basis. Of all the thin-film technologies, CdTe currently has the highest recognized production capacity. Many companies are pursuing CIGS as an avenue to low cost at higher efficiency

THIRD GENERATION

Various low-cost, low-efficiency alternatives to crystalline silicon, thin-film silicon, cad-tel, and CIGS are being researched, but none has emerged in the PV marketplace. Examples of third-generation PV technologies with thin films that use combinations of materials capable of converting sunlight to electricity include: light-absorbing organic dyes, nanostructure silicon, gallium arsenide, and other combinations of materials such as iron, sulfur, and copper. Although it is possible that some of these technologies may come to market in the 10-year gigaton time frame, the uncertainty surrounding their costs and ability to scale led us to omit them from this analysis.

Industry Growth

During the past decade, the solar PV industry grew an average of 40% annually. Trailing Germany, Japan, and Spain in 2007, the U.S. had the fourth-largest PV market in the world and installed 200 MW that year. (Worldwide installations that same year were 2.2 GW.) Several state and federal policies are in place or in the works to encourage PV installations on commercial and residential rooftops, but so far the largest growth in the U.S. has come from utility-scale installations. California leads the U.S. in cumulative installed capacity, but other states, including Colorado and Nevada, are experiencing greater relative expansion of PV installations.

Achieving Gigaton Scale

Development of new global markets and substantial capital investment in the solar supply chain — including solar panel manufacture, labor training, and semiconductor raw materials processing — will be required to reach the gigaton goal.

Scaling the Industry

To meet the 1-gigaton carbon reduction goal, solar PV will have to undergo an annual global growth rate of 46% post-2009. At the current industry-projected growth rate of 15%,

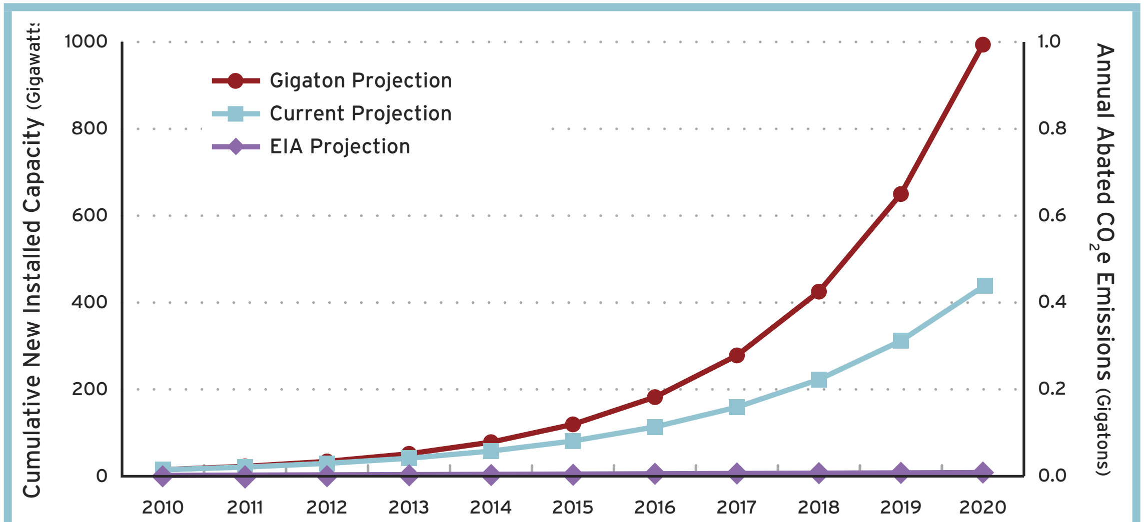

FIGURE 3. Growth in Solar PV Generation Capacity. Additional solar PV capacity required to annually conserve 1 gigaton CO_2e by 2020. A cumulative global capacity expansion of nearly 1,000 GW is needed to achieve the gigaton goal. Source of EIA projection: EIA, 2009.[3]

PV TECHNOLOGY ASSUMPTIONS FOR C3 MODEL[4]

Technology mix: 75% x-Si and 25% thin film (CIGS, CdTe, a-Si); 100% flat plate

Cost Reductions: Learning rate = 0.2 (module costs decrease by 20% as cumulative production doubles); balance of system (BOS) costs decrease by 7%/year

Rooftop-to-utility-scale ratio: 3:1

Debt/equity ratio: 50:50

Interest rate: 5%

the industry would install around 400 GW by 2020, or roughly 40% of the gigaton target. U.S. Energy Information Administration (EIA) projections for 2020 fall dismally short of that goal. Figure 3 shows the PV growth rate required to achieve the gigaton goal, compared to the current growth rate and EIA projection.

Capital Investment

The total direct investment needed to scale up solar panel production to 1,000 GW over the 10-year gigaton build-out period from 2010 to 2020 is estimated to be $1.8 to $2.5 trillion (2008 U.S. dollars). This estimate comes from a cost of conserved carbon (C3) model informed by historical trends, current commodities pricing, and projections of future resource constraints. The total production costs are a function of several factors, including the technology mix of crystalline silicon PV and thin films and the degree of utility-scale deployment. For this model, it is assumed that 75% of the gigaton expansion would be achieved using crystalline silicon and 25% would be thin film. Balance of system (BOS) components (such as inverters and mounting) and labor are assumed to undergo a fixed, annual price drop. The model was run with average 2007 per-watt prices at $6 for crystalline silicon and $4 for thin-film technologies.[5] The recent steep drop in PV prices was not factored into this analysis and would result in lower capital investment.

The 2020 cost also depends on learning curve assumptions based on the experience of the crystalline silicon PV world during the past 40 years. Decreases in module cost per watt were modeled largely by means of an experience curve, which aggregates a variety of cost drivers.[6] For a pessimistic case, a progress ratio of 0.18 was assumed, implying that costs drop by 18% every time capacity expands. The build-out investment required to reach the gigaton goal under this scenario is $3.2 trillion; with a more optimistic progress ratio of 0.23, the required investment is $1.2.[7] Figure 4 shows the annual capital investment in new PV plants that would be needed to meet the 2020 gigaton goal.

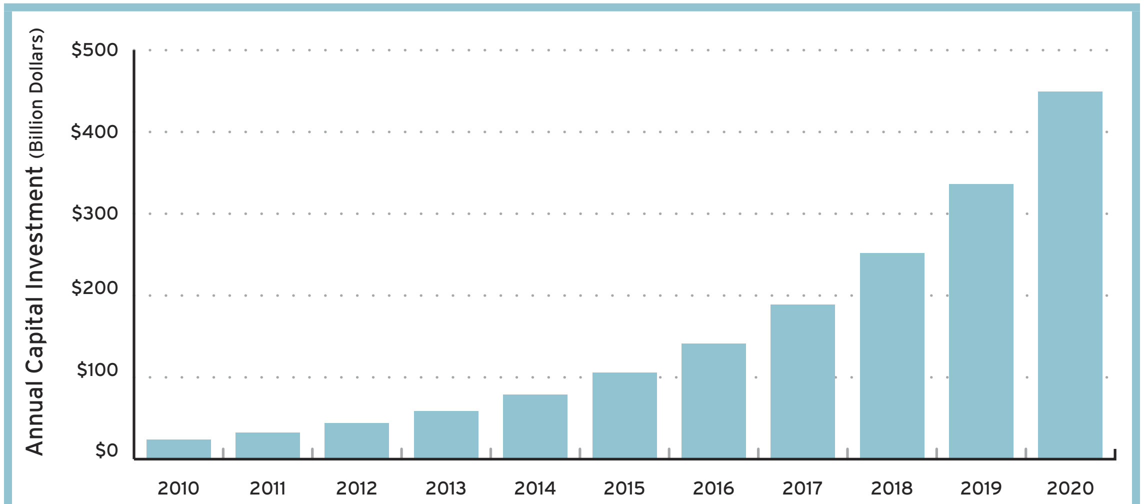

FIGURE 4. Annual Capital Investment in Solar PV Generation Capacity. Capital investments to support the gigaton growth trajectory illustrated in Figure 1. Total capital investment over the 10-year period totals $2.1 trillion; additional capital investment in transmission will be required to support the gigaton expansion.

The general challenge with solar PV is reducing the levelized cost of electricity (LCOE) to a point that PV is the preferred source of new electricity around the world and PV's cost is ultimately low enough that it makes economic sense to decommission or repurpose fossil-fuel power plants. The LCOE for solar PV currently ranges from $0.23 to $0.32 per kilowatt-hour (kWh) for residential solar systems and is below $0.20 per kWh for commercial installations.[8] The U.S. Department of Energy has set a target price range of $0.13 to $0.18 per kWh for solar electricity in 2010 and $0.08 to $0.10 per kWh in 2015 and estimates that meeting those goals will result in the installation of 5 to 10 GW of PV in the U.S. by 2015 and 70 to 100 GW by 2030. Under the rapid build-out scenario for the gigaton trajectory, the C3 model predicts the LCOE of solar PV will be at $0.06 per kWh by 2020. This would render it competitive with the wholesale price of natural-gas-fired electricity in most developed countries but not competitive with current wholesale coal-fired electricity in developing countries like China and India. At these prices, however, solar PV will be competitive with retail prices throughout most of the U.S. and the developing world.

JOBS IN THE SOLAR PV INDUSTRY

Rapid expansion of the solar PV industry will require a substantial increase in the number of workers trained to manufacture and install solar panels. A recent meta-analysis of "green-collar" jobs created by the American renewable energy industry found that approximately two jobs are created over the lifetime of each peak megawatt (MWp) of PV installed.[9,10] Based on this analysis, an estimated 1.5 million appropriately trained people would be employed to meet the challenge of increasing PV capacity over the next 10 years by about a thousand-fold to meet the gigaton goal. Figure 5 shows new jobs created per year in PV installation and operations and maintenance from a gigaton scale-up.

Challenges to Accelerated Deployment

Scaling solar PV more rapidly than today's trend poses a number of challenges. The near-term problem is that the price of solar electricity is still higher than most competitive fossil-fueled electricity. As PV prices fall and adoption increases, utility concerns about grid stability and PV's intermittent nature may impede rapid deployment. Another barrier to rapid deployment (and an area where supporting policy can play a role) is the land requirement for large solar PV arrays. Finally, materials constraints pose challenges to ramping up the supply chain and may ultimately restrict the amount of thin-film solar that can be manufactured.

CAPITAL COST

Because the bulk of the costs of a solar PV system are paid up front, capital structures and financing play a large role in how solar PV will scale. Different elements of the market — residential, commercial, and utility — have different requirements and will require different financing mechanisms. Utility-scale installations follow a process similar to traditional centralized electricity production.

Residential and commercial installations will be important contributors to meeting the 1,000-GW goal. These distributed systems avoid electricity transmission costs and enable a large and diffuse pool of individual investors to participate in developing the PV sector. However, at an installed cost of $6 to $8 per Wp, a standard rooftop system ranging from 2 to 10 kilowatts (kW) in size costs tens of thousands of dollars. Having to pay this amount up front, as dictated by the usual financing scheme, deters many businesses and homeowners from purchasing systems. Solutions include financial instruments created by the private sector and public policy.

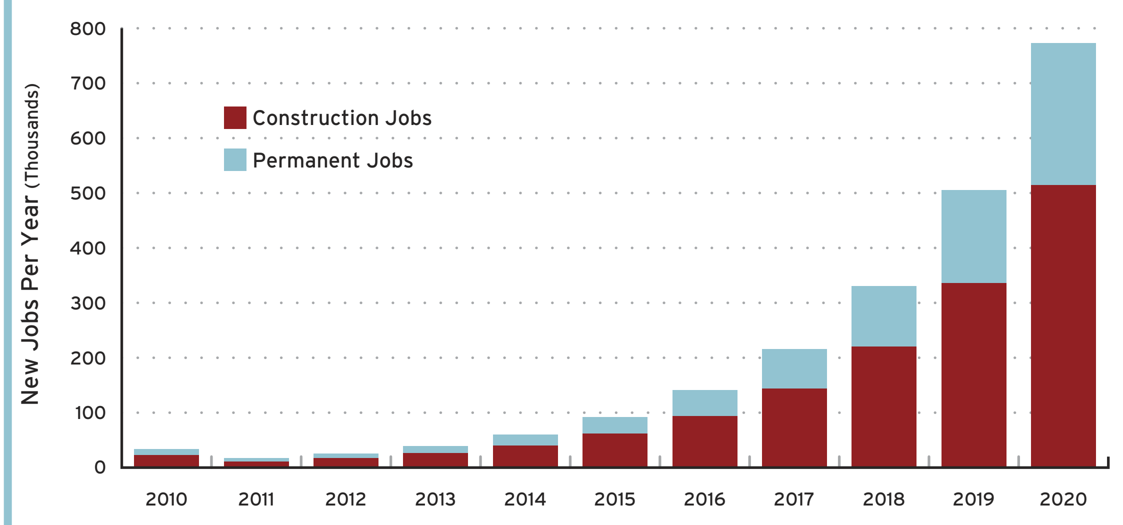

FIGURE 5. Jobs Created in the Solar PV Industry. An estimated 1.5 million new direct jobs would be created over the 10-year gigaton expansion period.

MATERIALS CONSTRAINTS

The different solar PV technologies utilize different materials to generate electricity from sunlight; the scarcity of some of these materials could ultimately slow or constrain scale-up of several of the technologies. Silicon-based PV faces no fundamental materials constraint although gigaton scale will require extensive expansion of foundries and refining capacity. Assuming a continuation of the recent trend of increasing production and availability of silicon for PV, a business-as-usual (BAU) scenario has a ceiling of 380 GW of c-Si installed by 2020. Reaching 1,000 GW by 2020 would require increasing projected solar-grade silicon production by 150%. Scaling to a gigaton with thin-film silicon would require a smaller ramp-up of silicon production.

Cadmium telluride PV production currently has space to grow but is likely to face materials constraints and price increases as it scales. A 1-watt CdTe cell produced today requires about 0.11 g of Te (or about 110 metric tons per GW).[11] Tellurium is a scarce element (crustal concentration of 0.005 ppm, rarer than platinum) that is traditionally recovered as a waste byproduct from copper mining. The current market demand for tellurium is small enough (estimated to be 500 metric tons per year) that it can be met entirely using the waste stream from copper mining. If larger quantities of tellurium are demanded than are currently produced as a byproduct from copper mining — which is likely the case if a large scale-up takes place — then there would need to be significant investment in and development of tellurium mines. The cost and feasibility of this is a major uncertainty.

The currently identified reserves of tellurium worldwide (47,000 tons) are more than adequate to meet the 250-GW gigaton goal for thin film; also, as commodity prices for quality tellurium increase, additional exploration and mining are likely to uncover additional reserves.[12,13] The question is how to access these reserves and what the effect of more expensive tellurium (mined versus recovered from copper processing) will be on the price of CdTe. If the price of tellurium is too high, then CdTe prices will also go up, making it less competitive.

ASSUMPTIONS ON TELLURIUM USAGE FOR 250 GW CDTE PRODUCTION

- Usage of Te in grams per watt (g/W) drops ⅔ by 2020 (9% annual decrease).
- Worldwide copper production increases by historical rate (4%/year since 1994).
- Te extraction from copper refining reaches 100% efficiency by 2020 (7% annual improvement)
- Worldwide demand for non-PV uses of Te remains constant (due to more efficient use or substitution)

The first mine primarily devoted to tellurium is currently under development in China. As demand for Te rises, many more mines and locations can begin to process copper mining waste for Te, and more efficient recovery methods (which exist today but are considered tedious and expensive) will become economically attractive. Tellurium deposits in other locations, such gold mines and lead/zinc mines, become attractive with an increase in the price of tellurium. Attention is already being given to each of these sources; CdTe producer First Solar recently acquired the rights to a lead/zinc mine in Mexico for the recovery of tellurium supplies. Further, there is potential for mining exploration devoted solely to Te. Iron-manganese oxide crusts, formed on rock surfaces 400 to 4,000 meters deep in the ocean, include Te at average concentrations of 50,000 times terrestrial levels, and there is speculation that they might also offer a solution to supply constraints.[14]

Deployment of CIGS technology may also be checked by limited reserves, in this case of indium. At the current utilization rate of 50 metric tons (tons) of indium per GW of CIGS, the estimated world indium reserves (about 6,000 tons) will not provide material for more than 120 GW of PV, presuming that no indium is devoted to other purposes.[15,16] Most indium is used in the liquid crystal display (LCD) industry. It is possible but not predictable that the LCD industry will move to a different material system. Without that shift, the LCD industry can absorb an increase in price far more easily than the CIGS industry. If CIGS has to compete with the LCD industry, it could face limited access to indium, restricting CIGS contribution to less than 120 GW. This constraint may be alleviated by innovation on another front: a shift to a combination of alternative materials, such as zinc and tin which have already shown promise, to replace indium in PV systems.[17]

ROOFTOP AND LAND-AREA REQUIREMENTS FOR SOLAR PV

Depending on assumptions regarding cell type and efficiency and insolation, 1,000 GW of PV panels can cover a surface area of 6 to 9 billion square meters (2,300 to 3,500 square miles, roughly the size of Delaware). According to recent estimations, the U.S. alone has about 6 to 10 billion square meters of appropriately oriented and exposed residential and commercial rooftops. It is unlikely that a solar build-out would focus entirely on rooftop solar, and satisfying the gigaton goal will doubtless entail utility-scale arrays on undeveloped land. Studies concerning the impact of converting land for siting large-scale solar facilities are scarce and cannot be widely generalized; however, concerns cited often include disruption to habitat and species dynamics and interference with rainfall and drainage patterns.

Technology Innovation

Some of the innovations that will make PV an economically viable technology will develop as a result of technological advances that depend on research and development (R&D) and time. Other innovations leading to declines in price will be directly tied to experience with scale-up of the technology. Recent analysis finds that increasing the scale of panel manufacturing facilities accounted for more than 40% of cost reductions from 1980 to 2001, suggesting that aggressive production planning can lead to significant cost decreases.[18]

There are two general ways to improve solar PV's competitiveness as an electricity generator: either increase the amount of electricity produced per module or reduce the cost of a complete operating system. Manufacturers must balance these two demands. For example, although technology currently exists to increase the efficiency of solar cells by more than 40% and to expand capacity factors to 27%, this technology also raises costs significantly.

Dramatic cost reductions are occurring in the solar PV value chain. Increasing scale generally reduces costs across all categories. Innovation plays a major role in all phases but especially in improvements in the amount of energy per installed solar module, which could result from technology development at any of the stages in the value chain. Figure 6 illustrates the cost concentration in the PV value chain.

Although much attention is focused on driving down the cost of solar panels, cost reductions can be realized from other components that make up BOS. Cost savings could come from multiple sources, for example: more effective power electronics, including the potential for integrating inverters onto panels; solar concentrators constructed from relatively inexpensive materials; tracking devices that reorient a panel throughout the day to follow the sun's movement; and more cost-effective mounting systems that reduce planning and installation time.

Game Changers

Game changers are not required to achieve gigaton scale because solar PV is already on a steep cost-reduction curve; however, some innovations would further accelerate adoption of solar PV, making it even more competitive with existing fossil-fuel electricity.

A major game changer for solar PV would be development of cost-effective storage. Storage increases PV's output by banking power so that it can be made available even when the sun isn't shining, but current storage technologies are very expensive. A major expansion of demand-response technology and a smarter grid capable of shifting loads and power sources would have an effect on PV similar to the effect of development of cost-effective storage.

Public Policy

Electricity from distributed PV systems is currently more expensive than electricity from conventional energy sources. As a result, distributed PV systems would not be economically viable in most markets without government support. The focus of policy has been to provide sufficient incentives to ensure that solar electricity is cost effective. The long-term goal is to increase capacity, accelerating the learning curve and bringing solar costs down to eventually transform the solar market and

	SILICON PROCESSING	SILICON INGOT & WAFERING	CELLS	MODULES AND OTHER COGS[a]	FINANCING & SALES	INSTALLATION	SHIPPING, WARRANTY, & OPERATION
Cost (% of Total)	20%		8%	15%	15%	40%	<1%
Cost ($/watt)	$0.80/watt		$0.30/watt	$0.60/watt	$0.60/watt	$1.70/watt	<$0.05/watt
Cost Drivers	Electricity, foundry equipment, materials		Equipment, Materials	Glass & other materials	Risk premium	Labor, power electronics, steel/ aluminum	Labor

FIGURE 6. Value Chain for Crystalline Silicon Solar PV. Costs are concentrated in the silicon refining process and the installation phase for the standard module technology. Thin-film technologies benefit from avoiding most of the cost of the first two steps on the left of the value chain.

[a] COGS: Cost of goods sold

eliminate the need for incentives. This goal is within reach.

A carbon tax that raises the price of conventional electricity can help PV achieve grid parity even faster and contribute to reaching this goal sooner. Based on the average carbon intensity of the U.S. grid, a carbon tax of $50 per ton CO_2e would add about $0.0285 per kWh of electricity, and a carbon tax of $100 per ton CO_2e would add $0.057 per kWh to the price of electricity in the U.S.[19] Conventional electricity prices range from $0.058 to $0.167 per kWh. At a carbon premium of $200 per ton CO_2e, solar PV is competitive with coal, the least expensive source currently on the grid.

In addition to a carbon tax, other general policies would encourage solar PV expansion, including renewable portfolio standards. A number of solar-specific policies could also accelerate growth in the PV industry, including pre-approved siting, utility demand-side management programs, feed-in tariffs, net metering and time-of-use electricity pricing, consumer buy-downs, and financing incentives.

PRE-APPROVED SITING

Advance government assessment and approval of land for utility-scale PV could rapidly accelerate deployment. Such a program would include an advance Environmental Impact Statement (EIS) to ensure that the land meets environmental requirements. A similar program has been operated for hydrothermal on federal lands.[20]

DEMAND-SIDE MANAGEMENT PROGRAMS FOR UTILITIES

Concerns regarding grid stability with higher penetration of solar PV can be partly addressed through implementation of demand-side management (DSM) programs that enable utilities to quickly and easily shed load. Features of DSM programs can include refrigerator controls to allow temperature resetting, general appliance controls, and thermostat regulation.

FEED-IN TARIFFS

A feed-in tariff is a guaranteed premium rate for electricity generated by renewable sources. For a specified period of time, utilities are required to purchase electricity from those sources at a fixed price above the prevailing spot market price for electricity. The premium rate reflects the environmental and climate benefits of electricity generated from sources other than fossil fuels. Utilities are allowed to pass on to consumers the extra cost, spread equally, through a charge on electricity bills. Feed-in tariffs reduce the payback period on a solar system and lower uncertainty for investors by guaranteeing a price level and providing market stability. As a result, they can drive sizeable growth in installations and associated cost reductions. However, one danger of such programs is the risk of setting the premium rate too high. Furthermore, feed-in tariffs do not guarantee that a specific amount of new capacity will be installed.

NET METERING AND TIME-OF-USE PRICING

Net metering allows owners of solar generators to sell any excess electricity to the grid and receive credit for it at the retail price. Similar to the feed-in tariff, net metering provides a financial benefit to solar system owners, albeit a smaller one, by allowing them to offset the cost of electricity. As part of the Energy Policy Act of 2005, all public electric utilities in the U.S. are required to make net metering service available to the customers they serve, upon request. Net metering is currently available in 44 states and Washington DC.[21]

As previously noted, solar PV systems can only generate electricity during the day when the sun is shining. In addition, they produce more electricity when the sun is shining more intensely. Solar PV has the advantage that this production pattern coincides with peak electricity demand in states like California, which consume the most electricity on hot summer days. Most PV electricity is therefore produced at times of peak demand when the value of electricity is high. However, the valuation of solar PV uses a flat rate — the average wholesale cost of electricity — which tends to undervalue the power provided to the grid.[22] One way to address this discrepancy is to implement a time-of-use pricing system, under which the rate paid for electricity varies depending on demand. According to one study analyzing multiple California locations, the valuation of solar PV power should be 29 to 48 percent greater than its valuation at a flat-rate tariff; a pricing system involving two rates, one for peak hours and one for off-peak hours, reduces the misvaluation of solar PV electricity to approximately zero.[23] Time-of-use pricing can contribute to the proper valuation of the benefits of PV electricity and improve its payback time and cost effectiveness.

CONSUMER BUY-DOWNS

In contrast to the European approach, U.S. solar PV policy has focused mostly on buy-downs, usually involving tax credits and rebates to consumers to reduce up-front installation costs. The largest rebate program is in California, which provides a rebate of $2.50 per watt to consumers who install sys-

The German Experience with Feed-In Tariffs

Feed-in tariffs are the most prevalent global renewable energy policy and have driven rapid solar growth in several European markets, notably Germany where a comprehensive renewables policy, including guaranteed grid interconnection and an aggressive feed-in tariff, has stimulated a spectacular increase in annual installations.[a] In 2000, a feed-in tariff was set at 0.51 Euros (€) per kWh for PV electricity and guaranteed for 20 years. The policy drove rapid expansion of the PV industry, with installations increasing from 9 MW in 1999 to 150 MW in 2003. The tariff was raised in 2004 to €0.574 where it has remained, increasing annual installations from about 150 MW in 2003 to 1,200 MW in 2008.[b] An important feature of the German program is that the feed-in tariff for new PV systems is reduced by 5% each year, encouraging cost reductions over time. In 2008, German utilities paid a tariff of between €0.35/kWh and €0.47/kWh, depending on the size and type of system, for solar electricity from newly installed PV arrays. The monthly extra cost per household as a result of the solar electricity tariff is currently about €1.25.[c] Figure 7 shows the increase in PV systems in Germany from 1998 to 2007.

The success of the feed-in tariff in Germany has encouraged adoption of similar policies in many other European countries. Six U.S. states have introduced feed-in tariff bills, and eight more states have considered or are considering similar legislation although none has passed as of this writing.[e]

a. KEMA. 2008. *Exploring Feed-in Tariffs for California. California Energy Commission,* Publication number: CEC-300-2008-003-D.

b. International Energy Agency (IEA) PVPS. 2007. *Annual Report.*

c. European Photovoltaic Industry Association and Greenpeace. 2008. *Solar Generation V – 2008: Solar electricity for over one billion people and two million jobs by 2020.*

d. IEA PVPS. 2007. See b.

e. Rickerson, W. F., F. Bennhold, J. Bradbury. 2008. *Feed-in Tariffs and Renewable Energy in the USA – a Policy Update.* North Carolina Solar Center, Heinrich Boll Foundation, and World Future Council. May.

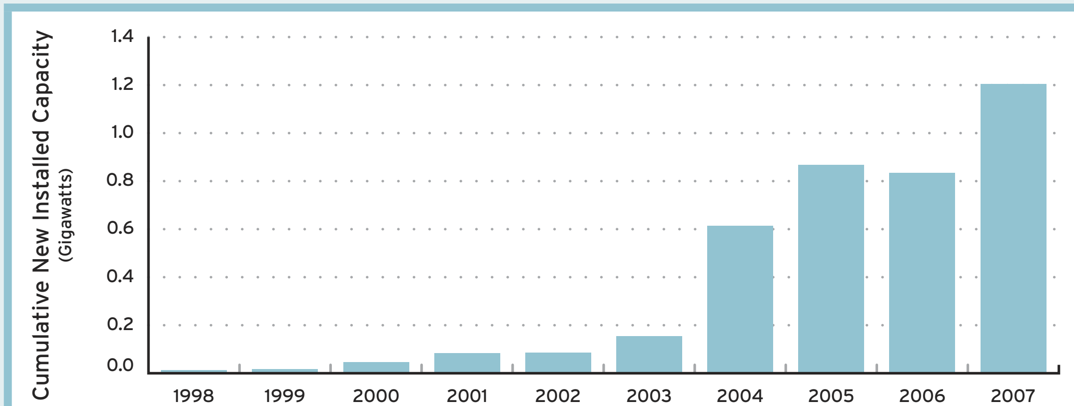

FIGURE 7. Development of Grid-connected PV Capacity in Germany. Source: IEA PVPS.[d]

tems smaller than 70 MW. For a 4-kW system, the total amount of the rebate is therefore $10,000 (on top of any federal tax credit). This incentive scheme helps address one of the biggest hurdles to increasing demand for solar PV: the high up-front cost. The total cost of the solar system is also reduced.

Rebates can be very effective in stimulating solar growth, as demonstrated by Japan's experience. Beginning in 1994, Japan started offering consumers an up-front rebate to assist in the purchase of solar systems. Incentives were specified over a 10-year period, declining over time, which reduced investment risk for manufacturers and provided an incentive to reduce costs. Today, Japanese manufacturers dominate the industry (48% worldwide market share in PV modules in 2006), and the Japanese PV market was the largest in the world until 2004.[24]

The scheduled decline in the Japanese rebates was a crucial policy feature because it encouraged PV manufacturers to seek cost reductions that they could then pass on to consumers. Evidence from California, by contrast, suggests that heavy subsidies can dampen the motivation of installers to provide, and or customers to seek, lower installed costs.[25] Recognizing the reduced cost to consumers, manufacturers have little incentive to compete on the basis of price. Finally, another criticism of rebate policies is that they are provided on a capacity rather than performance basis, lowering the incentive to consumers to invest in more efficient but expensive systems and in maintenance.

In addition to rebates, tax credits can also provide an incentive for solar installations by covering a portion of the cost. Currently, consumers who install residential solar electric systems can receive a federal tax credit for 30% of the cost of the system.[26]

SOLAR FINANCING INITIATIVES

Bond Rate Financing Federal and state initiatives to secure low-interest-rate financing for solar PV can significantly spur adoption. As already mentioned, at an installed cost of $6 to $8 per W_p, a standard solar system can cost tens of thousands of dollars. For most homeowners and business, the up-front investment required to purchase a solar system is an insurmountable obstacle. One way to solve the problem is to offer financing schemes for solar installations. For example, Berkeley FIRST is a program offered by the City of Berkeley, California that allows property owners to borrow money from a special fund to install solar PV systems. This special tax bond is financed by a private partner. Homeowners repay the loan over 20 years through an annual special tax on the property tax bill. Such financing schemes can dramatically reduce the up-front investment required to install solar systems and thereby increase the adoption rates of PV.

Power Purchase Agreements Power purchase agreements (PPAs) are another means of addressing the barrier of high up-front capital outlays. Under a standard PV PPA, the site host leases surface area (often roof space) to the power provider. The provider takes full responsibility for purchasing, installing, and maintaining a PV system on that space, and sells the generated electricity to the host at a contract rate for a set period of time (typically 15 to 25 years). Like a municipal financing program, a PPA shifts the large and immediate out-of-pocket expense from individual investors to a larger institution and relieves the PV host of concern for engineering considerations. Although to date most PV PPAs have been arranged for commercial hosts, there is a developing residential market. The viability of the PPA model is in part sustained by the federal Investment Tax Credit for PV, which covers 30% of the cost of commercial and residential system installations and was recently uncapped and extended through 2016.[27]

WORKFORCE DEVELOPMENT AND TRAINING PROGRAMS

Among the biggest challenges facing the growing PV industry is the severe shortage of qualified workers. As the industry is expanding at a rapid pace, jobs are being created in design, manufacturing, sales, logistics, installation, operations, maintenance, and other areas. Despite job availability and attractive wages, few solar-specific training courses exist to support an industry seeking qualified personnel. The courses that are available do not provide standard or industry certification. As a result, solar employers are experiencing increasing difficulty in finding qualified solar workers.[28] Building a large and skilled employment base is a major prerequisite for future PV growth.

RESEARCH AND DEVELOPMENT

Real public and private investment in energy R&D has steadily declined in the recent past, falling from 10% of the total U.S. R&D budget in the mid-1980s to 2% two decades later.[29] As there exists a strong correlation between R&D funding and patenting in both the PV industry and in the broader energy sector, it can be inferred that the telescoping of research budgets has a negative impact on innovation and hobbles efforts to improve the performance and economics of technologies like PV. Reversing the trend of declining energy R&D budgets would likely stimulate advances that would make meeting the gigaton challenge more feasible.

Although increasing R&D funding would be a boon to the PV industry, the public benefit of that expenditure would be magnified if increased budgets were well coordinated with dissemination efforts. Starting in the late 1980s, the Japanese Sunshine solar energy program paired increased R&D funding with deployment efforts and consumer education. The result was a rapid build-out of PV and an average annual price drop of 10% (better than California's peak annual price decline of 5%), demonstrating the effectiveness of coupling a "technological push" and a "demand pull."[30]

Interactions with Other Gigaton Pathways

Building-integrated photovoltaics (BIPVs) are a promising strategy for reducing PV system installation costs. BIPVs are PV systems that replace standard building components such as roof tiles or facades. Costs savings come from two sources: 1) the reduction of materials needed to construct the building (e.g., solar panels replace shingles), and 2) the blending of building construction and PV installation labor. Though buildings can certainly be retrofitted with PV panels, greater cost reductions and better system performance are achieved when PV systems are incorporated into building plans at conception.

In many areas where wind blows most steadily at evening and night, solar and wind resources are complementary. With appropriate grid infrastructure, utilities can combine these resources to provide continuous energy to customers.

Notes and References

1. Also known as "nameplate capacity." The term "peak" signifies that the given wattage refers to the maximum output of the generator. This is to be distinguished from average wattage (GWa), which encompasses reductions in output from times when the power generator is either not operational or otherwise producing less than its maximum technical capacity.
2. Between roughly 2003 and 2008 shortages in the supply of silicon forced up prices and led to a leveling out, or even a slight increase in the cost of solar PV.
3. Energy Information Administration (EIA). 2007. *International Energy Outlook*.
4. The C3 model is a "cost of conserved carbon" model developed at the Renewable and Appropriate Energy Lab (RAEL) at the University of California, Berkeley.
5. The model is most sensitive to assumptions regarding learning rate and initial cost per watt, with a 2% adjustment in learning rate and a $0.30 change in starting costs having the same effect of doubling the deployment of thin-film technologies.
6. Nemet, G. 2006. "Beyond the Learning Curve: factors influencing cost reductions in PV." *Energy Policy.* Vol. 34, No. 17.
7. Optimistic scenarios apply a learning curve with a ratio of 0.77 and balance-of-system (BOS) materials costs decreases of 10%/yr and a 50% installation percentage of thin films and utility-scale systems. More conservative forecasts predict an annual system price decrease of 5% and a 10% installation percentage of thin films and utility-scale systems. Mid-range values are based on a combination of 0.82-learning ratio curve and 6% annual BOS cost drop and a 25% penetration of thin films and utility-scale systems.
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13. Because the size of the tellurium market today is relatively small, a few unreported sources and/or production from countries not included in the USGS survey have a dramatic impact on the total supply.
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15. Deutsche Bank, 2007. See 11.
16. USGS, 2008. See 12.
17. Katagiri , Hironori, et al. 2007. "Enhanced Conversion Efficiencies of Cu2ZnSnS4-Based Thin Film Solar Cells by Using Preferential Etching Technique." *Appl. Phys. Express* 1 (2008).
18. Nemet, G. 2006. See 6.
19. The EIA estimates the carbon intensity of the average U.S. blend of electricity at 5.7×10^{-4} metric tons CO_2e/kWh.
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22. Borenstein, S. 2005. Valuing the Time-Varying Electricity Production of Solar Photovoltaic Cells. University of California Energy Institute, CSEM WP 142.
23. Borenstein, S. 2005. See 22.
24. Western Governors Association. 2006. *Solar Task Force Report*. January.
25. Wiser, R., M. Bolinger, P, Cappers, R. Margolis. 2006. *Letting the Sun Shine on Solar Costs: An Empirical Investigation of Photovoltaic Cost Trends in California.* Lawrence Berkeley National Laboratory, Report LBNL-59282 / NREL/TP-620-393000. January.
26. Solar tax credits were extended to 2016 with the "Emergency Economic Stabilization Act of 2008," signed into law in October 2008. The credits are available for systems placed in service from January 1, 2006 through December 31, 2016. The tax credit is for 30% of the cost of the system, up to $2,000. After December 31, 2008, this $2,000 cap will be removed for PV systems (but not solar water heaters).
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Wind

MAIN POINTS

- Wind is on a pathway to exceed gigaton scale by 2020 and attract $1.38 trillion in investment.
- Current projections show wind delivering approximately 1.5 gigatons of CO_2e reductions in 2020.
- There is enough wind resource available for many times annual global energy consumption.
- There is enough wind resource available for more than 4 times projected annual global energy consumption in 2020.
- Wind could be cost competitive with fossil-fuel generation without subsidy in the next 10 years.

Overview

By virtue of favorable economics, vast resources, and fast deployment, wind power offers the largest near-term carbon abatement opportunity of any energy source. Capture and conversion of wind to electricity has improved significantly in recent decades, and wind power is growing faster than any other large-scale source of carbon-free electricity. In the U.S., Europe, and China — markets with much of the world's electricity demand — wind power is already the first or second most common form of new generation capacity added to the grid.

Global installed wind capacity of 560 gigawatts (GW), a little more than half a terawatt (TW), could avoid 1 gigaton of carbon dioxide equivalent (CO_2e) emissions, assuming uniform displacement across the global emissions mix.[1] With a constant annual growth rate of almost 14% — less than half the 28% annual growth of the last 12 years — wind power's CO_2e abatement would reach a gigaton sometime in 2020. There is no shortage of wind resources to meet and exceed this goal. Roughly 72 TW of economically viable wind resources are estimated to exist on land alone, amounting to more than 4 times projected total world energy demand in 2010.[2]

Wind power is the only large-scale, low-carbon generation technology that approaches cost competitiveness with existing fossil-fuel generation. Capacity-weighted wind power prices already are at or below annual average U.S. wholesale block rates at nearly two dozen locations nationwide.[3]

The overall competitiveness of wind still depends heavily on policy support and subsidies such as the production tax credit (PTC) in the U.S. and renewable power quotas in China's Renewable Energy Law. But if current cost reduction trends continue and energy markets begin operating under a moderate carbon price, then wind power could be competitive without subsidy by 2020. The downsides of wind development — noise, visual intrusion, low capacity factor, high land intensity, and wildlife impacts — are balanced by co-benefits that include free, domestic fuel; modularity and easy scalability; very low life-cycle carbon emissions; conservation of fossil fuels and water; availability for centralized or distributed generation; and increased energy security.

Total investment required to reach the half-TW level globally from 2010 to 2020, with 10% real cost reductions and some improvement in capacity factors, would be just over $827 billion in undiscounted 2006 dollars, not including finance charges. Using U.S. median transmission costs and assuming those costs remain constant over time, total global transmission costs would add about $127 billion.[4] If capital costs, transmission costs, and capacity factors are assumed flat over time — no technological gains, economies of scale, or other cost reductions — it would take almost a year longer to obtain a gigaton of CO_2e abatement through wind power, and total costs including transmission would be $1.14 trillion.

If wind development remains on a likelier trajectory, as in the Global Wind Energy Council's moderate scenario revised for 2008 growth, then capital requirements in 2020 will be $1.38 trillion plus $210 billion in transmission, for a total of $1.6 trillion. These figures may underestimate necessary transmission investment overall, especially in China and India, and are based on assumptions that all renewable energy support policies remain in place, no significant new political opposition arises, and all renewable targets are achieved.

Reaching gigaton scale would take roughly 185,000 to 370,000 wind turbines. For comparison, U.S. factories turned out 300,000 military aircraft between 1939 and 1944 for World War II. Manufacturing these turbines by 2020 could create more than 1.3 million direct jobs, with an additional 560,000 jobs in installation, operations, and maintenance. The land footprint would be an estimated 113,400 square kilometers — about 3.1% of the land area in the U.S. or about 1% of the combined land area of the U.S., China, and the European Union (EU) — for the use of 2-megawatt (MW) turbines on flat, windy land.

Significant, near-term barriers to continued rapid growth for wind power include managing variability at increasing penetrations and greater need for transmission. Wind resources often are far from load centers, and uncertain transmission siting and permitting can slow wind farm development. Wavering policy support — the on-again-off-again tax credits in the U.S. are a prime example — can stymie investment and development. Pricing carbon can stimulate wind development without other support policies, but the combination is especially effective. Our analysis suggests that typical Class 4 wind sites would become widely competitive at U.S. wholesale electricity prices if carbon prices were in the range of $42 to $56 per ton of CO_2e, without tax credits or other subsidies, though other estimates based on very low, sustained natural gas prices can range almost twice as high.

Regardless of policy support on the supply or demand side, wind power is unlikely to continue to grow at current rates without addressing transmission and grid integration. The challenge of wind variability presents opportunities for innovation in storage, operations, and transmission that are shared by many other renewable and conventional energy sources. Although wind accounts for less than 5% of total energy in Europe and less than 3% in the U.S., utilities in Denmark, Germany and the U.S. Midwest and Southwest are finding large-scale wind produces vast energy at moderate costs. Expanding transmission and improving the coordination of renewable and conventional generators over larger regions, in concert with carbon pricing, hold significant promise for large-scale carbon emissions abatement.

Industry Background

The wind industry has the largest installed base of any non-hydro renewable technology today. It is also on a significant growth trajectory.

Wind Industry Growth

During the past decade, the global wind industry has accelerated to a compound annual growth rate of 28%.[5] In the largest markets, wind in 2008 grew faster still: U.S. developers added 50% to the nation's installed wind capacity, and China more than doubled its capacity for the fourth year in a row. No nation ever has installed as much wind in a single year as the U.S. and China did in 2008. Those installations pushed global capacity over the 100-GW threshold earlier than most industry projections; by the end of 2008, wind stood at about 120.8 GW, or about ⅕ of the way to 1 gigaton of abatement.[6] More than 85% of existing and new wind projects are in Europe, the U.S., and Asia. If current annual growth rates were sustained — a trajectory at odds with projections by all reviewed industry forecasts — global wind capacity could grow to more than 2.4 TW and deliver more than 4 gigatons of CO_2e abatement by 2020, mostly in China.

Recession's Impact on U.S. Wind Development

After years of being lobbied for a dependable PTC, the U.S. Congress delivered a string of extensions, and the U.S. wind industry has ridden the 2.1-cent-per-kilowatt credit through 4 consecutive years of record-breaking growth and a huge expansion in the U.S. turbine manufacturing base. But by late 2008, the recession's impact on financial markets became more telling, and both debt and equity markets for wind shrank dramatically. A recent survey of 18 large banks and institutional investors that once invested regularly in U.S. wind projects found only four remaining.[7] Investment houses such as Lehman Brothers that once played big roles as tax-equity investors in wind have ceased to exist. GE Financing is turning down wind projects. In a larger sense, a shrinking economy means fewer corporate entities have the sizable positive balances and therefore the tax appetite for investment in 10-year tax credits. At the same time, banks reportedly have increased their debt rates on wind projects, resulting in an overall increase in the cost of capital of 50 to 200 basis points or 0.5% to 2% higher annual interest.[8]

Recession's Impact on European and Asian Markets

Europe and China have driven wind development by mechanisms that so far are less heavily impacted by the recession's blows to the financial sector than has been the case in the U.S. The primary policy tool in Europe is the feed-in tariff, a guaranteed payment for grid-connected power above wholesale market rates. China has auctioned off wind concessions in select wind-rich areas, based in part on the lowest electricity prices tendered by the developers, all of which have been state-owned companies. These subsidized prices remain in effect for the first 30,000 "full load" hours of a project lifetime, after which the project receives wholesale electricity prices for the regional grid. The effect has been a patchwork tariff system, with developers in the same region sometimes receiving significantly different prices. China's powerful National Development and Reform Commission has devised a new feed-in tariff system partly intended to harmonize regional prices for wind electricity. But perhaps the most significant apparent driver for both wind development and domestic wind-turbine manufacturing in China has been the Renewable Energy Law of 2006, which mandates that grid operators all purchase a set percentage of renewable generation and build the necessary transmission lines to connect successfully tendered wind concessions. For these and other reasons, China at this writing is expected to install as much as 10 GW of new wind projects in 2009 and could surpass the U.S. as the world leader in new wind development.

Line-Up of U.S. Wind Projects

In the U.S., more than 300 GW of proposed wind projects are lined up in regional interconnection queues, chiefly in the Midwest, the Mid-Atlantic and the West (Midwest Independent System Operator [ISO], Electric Reliability Council of Texas, PJM, California ISO, Southwest Power Pool, and Bonneville Power Administration). These represent the largest volume of proposed additions to the U.S. grid from any energy source. For 2008 applications through mid-October, the capacity of proposed new wind projects is 125% of all other

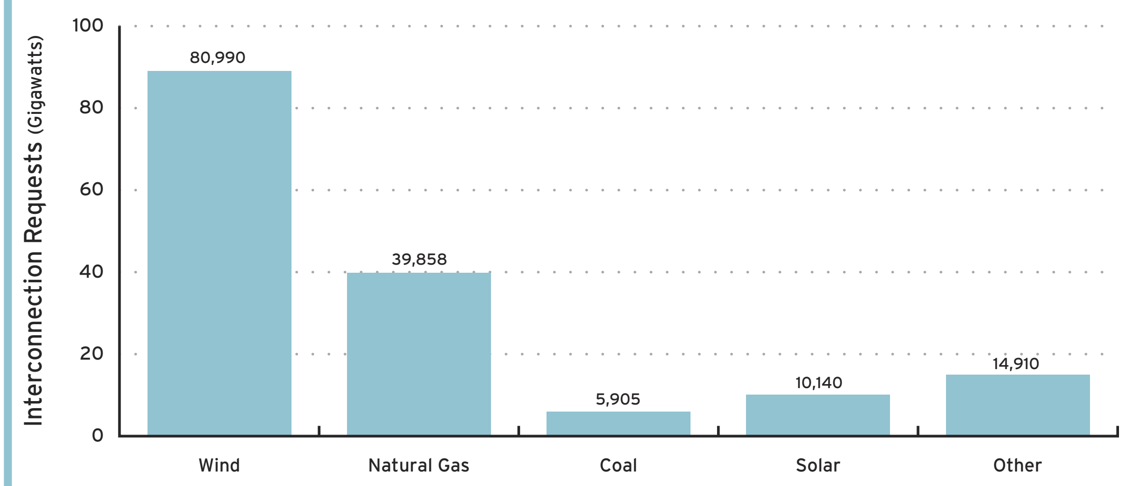

FIGURE 1. Capacity of U.S. Interconnection Requests by Fuel Source for 2008 through October 20, 2008. Source: Exeter Associates, Inc., based on data from Bonneville Power Administration, Western Area Power Administration, and the regional transmission operators and independent system operators.[10]

FIGURE 2. New U.S. Generating Capacity by Energy Source Source: Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2007, U.S. Department of Energy[11]

proposed capacity additions combined; more than twice the proposed additions for of the next largest source, natural gas; and 15 times more than proposed coal additions.[9] Figure 1 shows capacity additions by fuel source for the year 2008, through October.

Historical experience suggests that many of these applications will not result in completed wind projects but instead are "upgrade shopping" — filing several times to discover the least additional cost for tying into the grid — and will withdraw. What the numbers suggest, however, is an order of magnitude of interest in wind in the U.S. that, if translated into built projects, would roughly equal a doubling of current global utility-scale wind capacity and could meet or exceed a quarter billion metric tons of abatement by 2020. The large share of wind in new capacity additions in Europe and the U.S. suggests that this trend already has started. Figure 2 shows new U.S. generating capacity added, by energy source, between 2002 and 2008; wind's increasing share is evident.

The history of the U.S. electric power industry is one "boom-and-bust" saga after another: utilities binged on coal then on nuclear, now on natural gas and wind. Whether wind keeps growing, and what happens to demand and where, will have significant impact on the short-term carbon emissions trajectory for the electric power sector.

Technology Background

Wind is created by differential heating of the Earth and by the planet's rotation. Turbine blades are shaped like airplane wings and function similarly. Movement of wind across the blades generates lift and turns the rotor, spinning a shaft connected to an electric generator. The turbine translates the kinetic energy of the wind into mechanical energy, then electrical energy. The theoretical maximum that a turbine can capture of the kinetic energy in wind is 59.3%, known as the Betz limit.

Three factors determine wind power output: wind speed, rotor sweep, and height. Doubling the rotor diameter quadruples wind power. Increasing the height of the rotor hub allows a turbine to tap faster, steadier winds. Wind power increases as the cube of wind speed, so that doubling wind speed increases available wind power by a factor of eight.

However, increases in rotor diameter and turbine height impose more demanding physical loads on the rotor and tower, which translates into higher capital cost. These capital costs so far have been compensated by returns in power and lower costs per unit of energy produced. To take advantage of these power laws, wind turbines over the past 30 years have undergone rapid expansion in size, with rotor diameter growing eight-fold and towers more than quadrupling in height in exchange for a 200-fold increase in power. (See Figure 3.) As a result of such design changes, the real cost of wind electricity has dropped from about 40 cents per kilowatt hour (kWh) in 1981 to between about 5 cents and 8 cents per kWh in 2006.[12]

Inside the nacelle (the housing for the gearbox, generator, and other moving parts behind the rotor) the rotor axis spins typically at 8 to 24 revolutions per minute (rpm) for utility-scale wind turbines. In the most common, indirect-drive systems, a gearbox translates that rotational energy to a shaft spinning at hundreds of rpm, which drives a generator.

Automated yaw motors steer turbines to face the wind and actuators optimize blade pitch for ideal angle of attack at a given wind speed. Large, utility-scale turbines begin producing

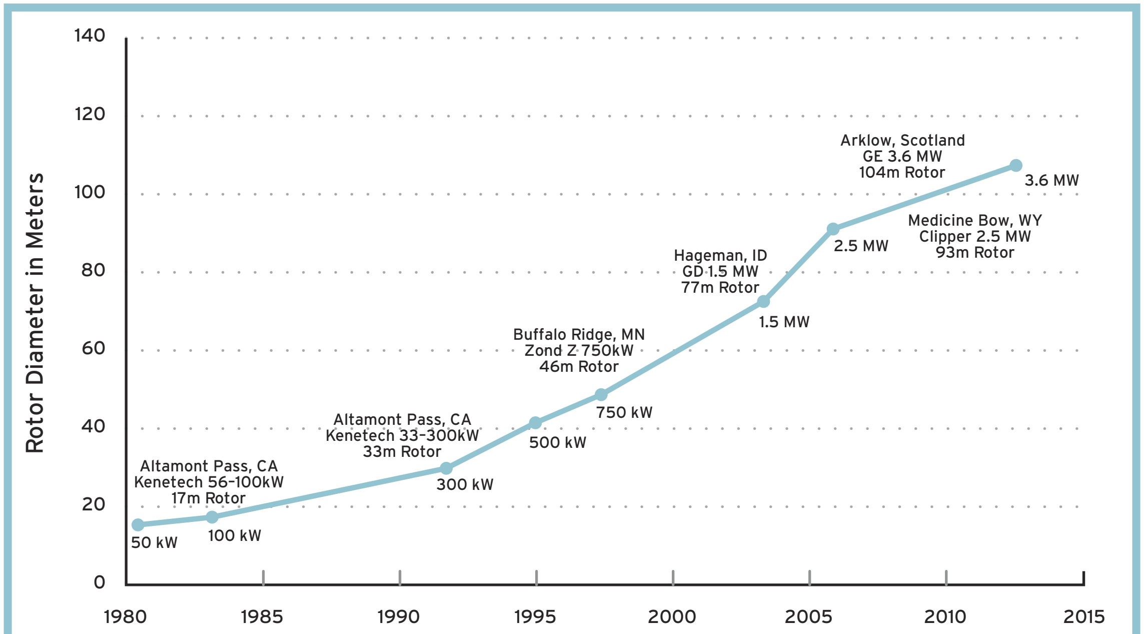

FIGURE 3. Increases in Rotor Diameters through Time. Turbine designers have raised rotor height and sweep in exchange for a 200-fold increase in power Source: NREL[13]

power at a cut-in speed of about 4 meters per second. Pitch controls automatically feather the blades and stop power production when wind exceeds a cut-out speed of generally 20 or more meters per second.

For economies of scale, wind turbines are aggregated into wind plants or farms ranging up to a few gigawatts in capacity. Turbines are networked by power collection cables that terminate at a substation. Voltage is stepped up at the substation to interconnect to the grid at a higher voltage.

Early wind turbines were one step removed from windmills and not especially efficient or mechanically robust. Today, wind farms can have hundreds of highly reliable turbines. Turbine failure rates are comparable to failure rates of conventional power plants. Forced outages for electrical or mechanical problems with individual wind turbines are about 2% onshore and less than 5% offshore, compared to 3% to 9% for conventional, fossil-fuel plants and 2% to 3% for nuclear plants. All newer turbines are designed with low-voltage fault ride-through, so that a wind farm will keep generating on its own when the electricity grid encounters trouble.

The harnessing of wind power has reached industrial scale. Multi-megawatt turbines with 100-meter towers and rotors and nacelles weighing more than 100 metric tons are common.

Because wind is driven by temperature differences, climate change could reduce surface wind energy production by heating the Earth's poles more intensely than temperate and equatorial regions where most demand is located. The research community is divided over whether there is preliminary evidence that U.S. wind speeds already are beginning to decline[14] and whether the impacts of climate change on wind are likely to be more mixed, with net velocity increases in some areas.

The same effect may augur well for very high altitude wind power. We do not evaluate high-altitude wind here because it is our assessment that resolving regulatory, technological and economic questions before scaling up high-altitude wind will take most of the next decade. Over time, however, the growing temperature differential between the troposphere and the stratosphere could enhance the productivity of very high-altitude wind.

Offshore Wind

Offshore wind development is enormously attractive because ocean breezes blow steady; strong; unimpeded by trees, hills, and buildings (very low surface roughness); and in close proximity to large coastal cities where building new power plants and transmission lines is particularly challenging. As a result, some of the world's most power-hungry cities are, in grid terms, islands of heavy demand tied to high wholesale power prices by geography, transmission congestion, or bad planning. In theory, offshore wind farms can relieve that congestion and deliver power from the seaward side of cities at capacity factors of 45% or more. That's roughly ⅓ better performance than onshore facilities in the same wind class.

The wind is generally 90% higher in speed offshore than on land, according to one global study.[15] The National Renewable Energy Laboratory (NREL) estimates the U.S. offshore resource out to 50 nautical miles on the coasts and the shorelines of the Great Lakes at more than 900 GW. About 60 GW is available in shallow waters within 20 miles of shore and accessible by turbines on ordinary pile-driven foundations, with conventional transmission lines. The remaining 840 GW would be much costlier to tap but comes with other advantages.

Deep offshore wind developments are appealing because they offer limited visual and noise impact and somewhat fewer infrastructure constraints than onshore facilities face (e.g., offshore facilities avoid the length/height limits that roads and cranes are beginning to impose on transport and installation of towers and blades). As a result, deep offshore wind farms can use larger, more efficient wind turbines without people hearing or seeing them.

Europe has been developing offshore wind for 15 years and has about 1.5 GW installed at more than 25 projects. Another 20 GW of installations are planned through 2020. The rest of the world is frontier territory for offshore wind.

Because of the harsher, less accessible marine environment and the high cost of undersea transmission, offshore wind farms are vastly more expensive than their onshore counterparts. The distribution of costs is also different. Deep offshore wind farms are designed for punishing marine conditions — including ice impacts, gales, typhoons, and hurricanes — and costs increase with distance from shore and depth of installation.

For these reasons, deep offshore wind development is not considered likely to make a significant contribution to capacity growth within the 2020 gigaton time frame, and shallow offshore development is expected to be slow outside of Europe.

Adverse Impacts of Wind Development

Wind development can have a number of adverse impacts. Wind farms can extend over vast areas of land and ocean. Turbines produce low-frequency noise and shadow flicker. Turbines can impair wildlife habitat and, especially when poorly sited, kill birds and bats through collisions. Turbines can also interfere with radar.

The land requirement for wind farms is dependent on the turbine capacity, with larger turbines requiring less area. For instance, moving from a 2-MW turbine to a 3-MW turbine would reduce the land area requirement from about 113,400 square kilometers — about 3.1% of the land area in the U.S. or about 1% of the combined land area of the U.S., China, and the EU — to 77,000 square kilometers, or about 0.6% of the combined land area of the U.S., China, and the EU. Wind farms would be widely distributed if a build-out occurs. However, the actual footprint of turbines, access roads, and other infrastructure is 5%, or significantly less, of a wind farm's actual area. Dual and multiple land-use arrangements are typical, with lease payments to farmers, ranchers, ski areas, and other landowners averaging $5,000 per year per turbine. Farmers find that wind power works with multiple crop rotations.

Noise comes from either mechanical sources within the nacelle or airflow past the blades, the latter driven by the number of blades and tip speed. Higher tip speed translates into greater efficiency but higher noise. The efficiency/noise tradeoff is optimized in modern turbines, which can have multiple noise settings in onboard software. The volume of low-frequency turbine noise three football fields away from an onshore wind farm falls in the same range as bedroom-to-household noises.

Wind turbines can kill birds and bats — especially when newly installed — but the number of associated avian deaths is lower than from many conventional power sources and substantially lower than those caused by buildings and housecats. In the U.S., wind turbine-caused avian deaths total an estimated 7,000 to 40,000 a year, including both birds and bats.[16] By comparison, an estimated 5 million to 50 million birds are killed each year by U.S. communication towers, 130 million to 1 billion are killed by collision with high tension wires, and an estimated 97.5 million to 975 million are killed by windows.

Compared with other energy sources, wind turbines result in an estimated 0.279 avian deaths per gigawatt hour (GWh), versus 0.418 avian deaths per GWh for nuclear power (from uranium milling ponds and collisions with cooling towers and other infrastructure), and 5.18 avian deaths per GWh from coal-fired power (from mountaintop mining to collisions and, most of all, climate change).[17]

By one estimate, total bird mortality due to wind turbines amounted to 0.003% of total anthropogenic (human-caused) mortality of birds in the U.S. in 2003.[18] If bird habitat were uniformly distributed on land and global anthropogenic bird mortality due to wind turbines scales with land area, then abating 1 gigaton of CO_2e emissions using wind power could be expected to kill 850,000 to 3.5 million birds a year, or cause about 0.2% of estimated global anthropogenic bird deaths. As noted above, meeting the gigaton goal also would mitigate global warming. It would also reduce air pollution mortality for humans and animals.[19]

Potential radar interference has led U.S. aviation, homeland-security, and defense agencies to stall several gigawatts of new wind installations. For line-of-sight radar, wind turbines generate signals in which aircraft or to some extent weather patterns can be lost, shadowed, or misidentified. There are workarounds, however, including the use of software filters that compensate for the steady signature of turbine motions and transmission of data streams from wind farms to radar stations. An elite panel of scientific advisors to U.S. defense agencies suggested recently that the conflict also presents an opportunity to upgrade the nation's radar infrastructure, changing out older radar that inhibits carbon-free energy security while "significantly" increasing the security of U.S. airspace.[20]

Achieving Gigaton Scale

According to current projections, wind will surpass gigaton scale by 2020. Scaling up to meet projections will present a number of challenges, and will also create economic opportunity in the form of new jobs and industry expansion. Figure 4 shows several wind power industry growth and CO_2e emissions reduction projections.

Scaling the Industry

In a little more than 2 years, the supply chain for wind power has exploded, expanding well outside Europe to employ tens of thousands in China, the U.S., and elsewhere. From 2005 to 2006, China and the U.S. put several policies in place that launched domestic manufacturing in force and moved European turbine makers to establish new manufacturing capacity in both countries. The most important of these policies were China's Renewable Energy Law, wind concession set-asides for China's domestic manufacturers, the expansion of state renewable portfolio standards (RPSs) in the U.S. and extension of the U.S. PTC.

Until 2005, the U.S. and China each could claim one wholly domestic turbine manufacturer.

China's turbine manufacturing base now numbers more than 40 firms, including domestic and foreign companies and joint ventures.[21] Foreign players include most of the world's 10 largest: Vestas (Denmark), Gamesa (Spain), GE (USA) and Suzlon (India), with Acciona and REpower engaged in joint ventures. By 2006, domestic manufacturers such as Sinovel Windtec, Goldwind, and Dongfeng Electrical Machinery had grown to supply 41.3% of the Chinese market and were expected within 2 years to approach 60% of the domestic market.[22]

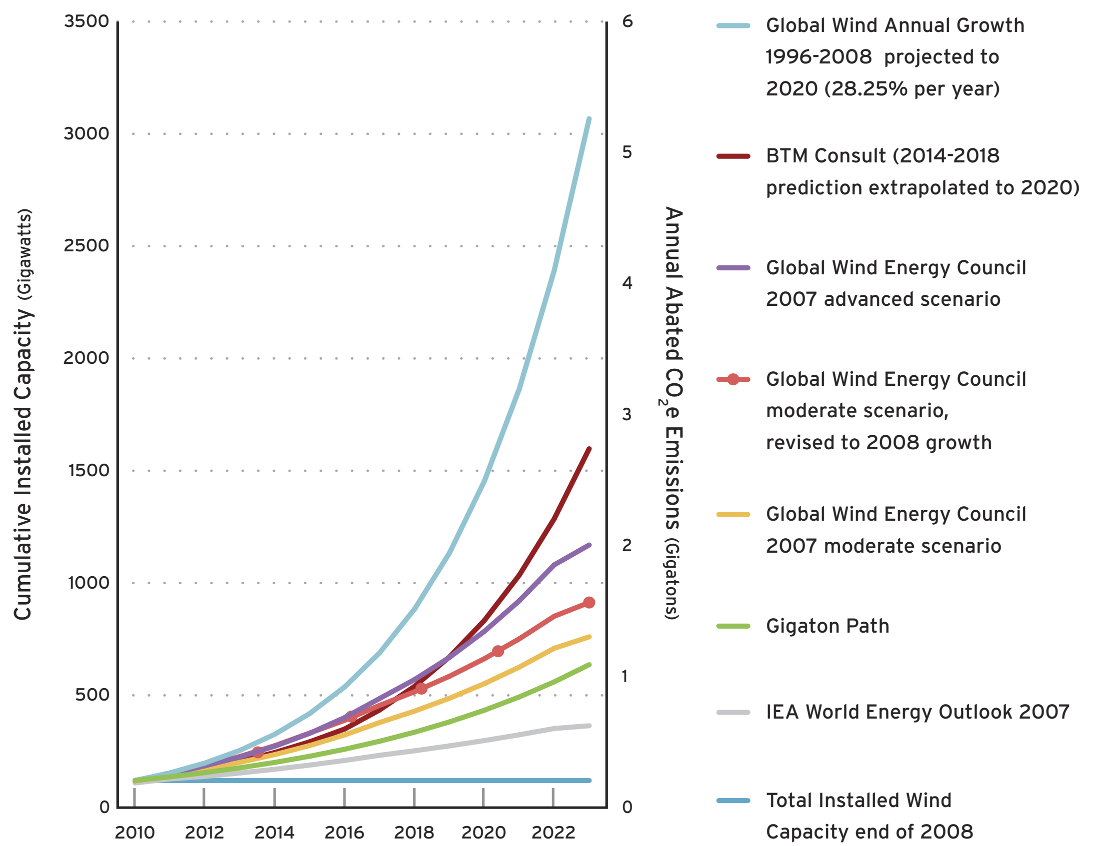

FIGURE 4. Growth in Wind Generation Capacity. Expansion pathways for wind vary for different projections.

In the U.S., 11 new factories make blades alone, and more than 70 new and retooled factories are dedicated to the wind industry, many of them recently retasked from the auto industry. U.S.-manufactured turbines, whether by companies that are headquartered in the U.S. or headquartered abroad, are expected to account for half of new U.S. installations in 2009. After years of tight supplies and elevated turbine prices, supply bottlenecks have disappeared; the U.S. market now is overloaded with turbines, and crates of components are piling up at U.S. ports.

Commodity inputs are not expected to be a constraint for near-term wind development; most material inputs for wind farms other than copper have declined in price recently with the impact of the 2009 recession on commodity demand. However, prices for certain commodities could rise considerably depending on the coincidence of technological choices and a global wind boom. Balsa wood remains a common frame for fiberglass blades, and there is some risk of global price competition. Fiberglass itself is made of sand, but it takes almost 8.5 tons of fiberglass for every megawatt of turbine capacity, and manufacturing enough blades in the U.S. alone to meet 20% of energy demand by 2030 would require ⅕ of the nation's fiberglass-making capacity. The resin that infuses the glass fibers is a petroleum product, so its price responds to the price of oil. If permanent magnets were to prevail over wound rotors as the technology of choice inside turbine generators, there could be significant price pressure on rare-earth metals such as lanthanum.

Capital Investment

The gigaton analysis for wind power relied heavily on data used in the joint 20% Wind by 2030 report issued by the U.S. Department of Energy in 2008, updated for capital costs and financing assumptions. At the time of this writing, wind capital costs are uncertain because project demand is contingent upon the uncertain availability of both credit and government subsidy in the U.S. and to a lesser extent in Europe. For our middle-cost case, we have used an overnight cost of $2,000 per kW.

We assume that new wind generation supplants energy from the full global generation mix, with composite emissions starting at 600 grams (g) CO_2e per kWh and trending downward over the study period to 550 g CO_2e per kWh. In practice in U.S. markets, wind electricity in the short term competes on the margin with natural gas, which has lower emissions intensity than other fossil-fuels. Over the longer term and at high penetrations, wind energy displaces baseload generation and emissions. Displacing gas alone would delay achieving the gigaton goal by about a year.

The model employs a discount rate equal to the weighted average cost of capital because this approach more closely mirrors the calculations of a developer (rather than using a social discount rate). The model is highly sensitive to the choice of discount rate and by extension to the relative proportion of debt and equity financing in wind farms. We have used a 50/50 share even though wind financing arrangements are highly diverse. Figure 5 shows the annual capital investment from 2010 to 2020 for wind to achieve gigaton scale.

Like most power sources, wind qualifies for accelerated depreciation, but the model does not take depreciation into account. We also include a nominal cost for grid integration.

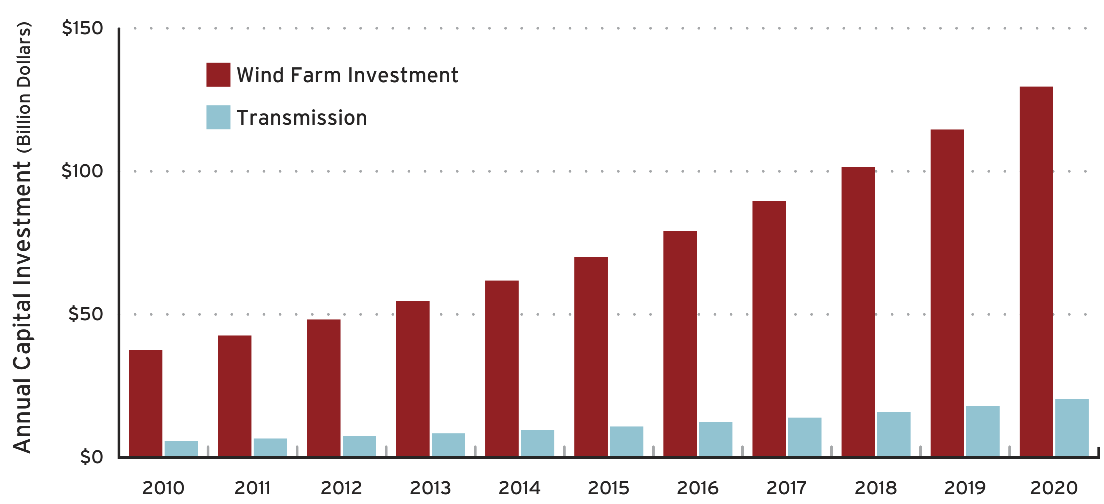

FIGURE 5. Annual Capital Investment in Wind Generation Capacity. The gigaton trajectory investment over 10 years totals $1.4 trillion.

For these reasons, the resulting levelized cost of wind energy is slightly elevated. The components and course of the levelized cost of wind electricity over time are shown in Figures 6 and 7, for the following assumptions: 10% cost reductions from learning, a capacity factor of 36%, 8% debt interest, a 13% return on equity, and a project lifetime of 25 years.

Annual and cumulative costs for wind farms and transmission are shown in Figure 7 for a moderate-cost scenario.

Jobs in the Wind Industry

Based on surveys of its members, the European Wind Energy Association estimated direct jobs in the European wind industry at 108,600 in 2007, of which 59% were in turbine and component manufacturing. The majority of jobs are in Germany, Denmark, and Spain.

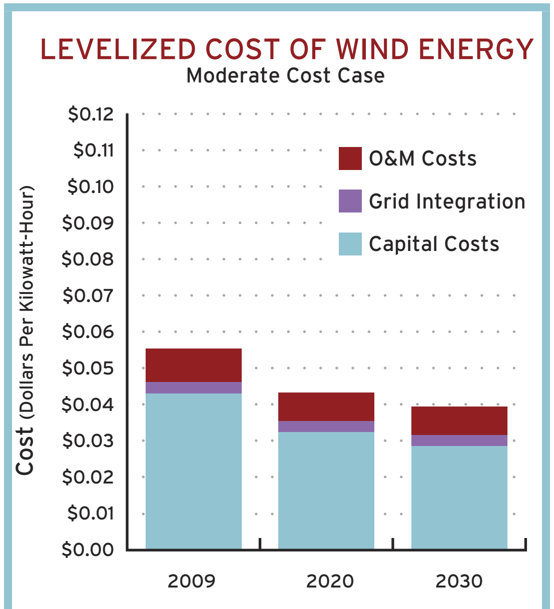

FIGURE 6. Levelized Cost of Electricity from Wind for Three periods: 2009, 2020, and 2030.

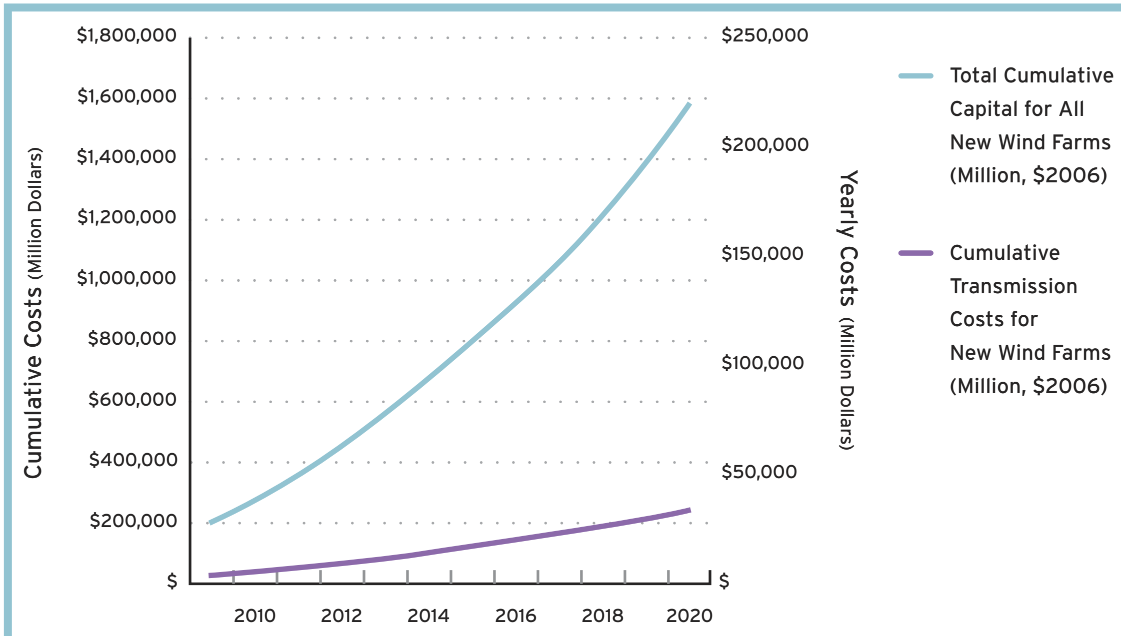

FIGURE 7. Cumulative Investment in Wind Farms, 2010 to 2020. Note: numbers are based on current Global Wind Energy Council (GWEC) projection.

Wind-industry jobs in the U.S. took off in 2006 and had been growing until the credit crisis of late 2008 stalled new U.S. wind development. The American Wind Energy Association estimates employment industry-wide at 85,000, with 35,000 jobs added in 2008 to 2009. The jobs span manufacture of all large components, from steel plates for towers and heavy forgings for foundations to blades, rotors, and nacelles, as well as high-tensile bolts and fasteners.

Using a breakdown of turbine components and identification of potential manufacturers via the North American Industrial Classification System in 2004, researchers with the Renewable Energy Policy Project (REPP) concluded that every GW of new wind installed produced an average of 3,000 full-time jobs in manufacturing, 700 in installation, and 600 in operations and maintenance.[23,24] Projected job growth was concentrated in the 20 most heavily populated U.S. states that had lost 76% of manufacturing employment since 2001.

Based on the REPP estimate for the U.S. market, scaling up global installations to the capacity required to avoid a gigaton of CO_2e emissions annually by 2020 would generate 1.3 million manufacturing jobs and 560,000 installation and operations and maintenance jobs. Figure 8 shows labor requirements needed to scale wind to 1 gigaton.

Challenges to Accelerated Deployment

The two key challenges to large-scale wind deployment are expanding transmission and dealing with the variability inherent to wind.

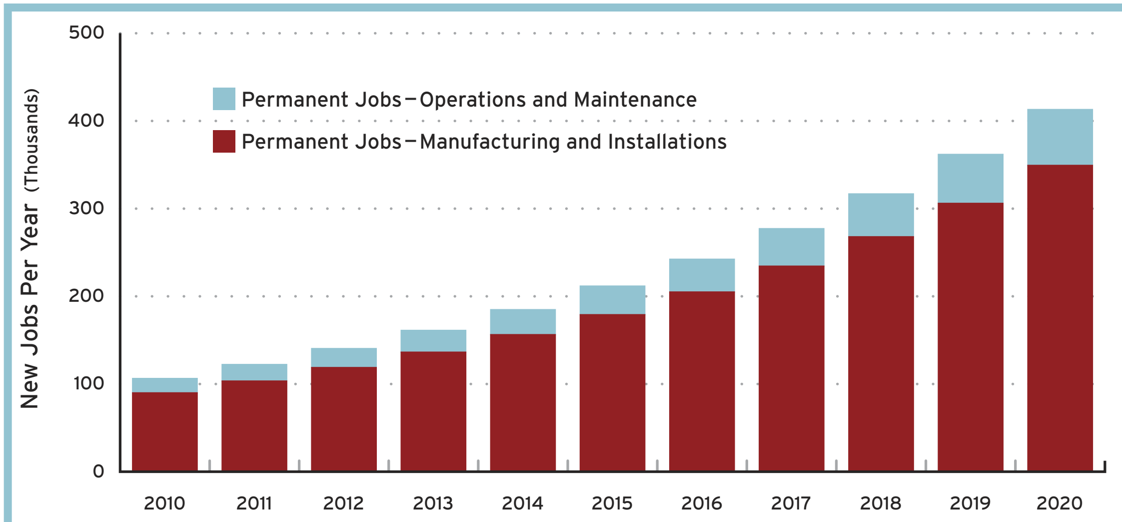

FIGURE 8. Jobs Created in the Wind Industry. Hundreds of thousands of jobs would be added over the 10-year build-out for gigaton scale.

TRANSMISSION

Transmission is the vital key to unlocking the greenhouse gas emissions abatement and energy security potential of wind and other low-carbon energy sources. Without a significant increase in transmission investment, policies to increase renewable electricity will matter less and less because the most profitable sites that combine high resource density with close proximity to electricity demand already have been or are being developed. In the U.S. and Europe, for example, virtually all of the high-quality onshore Class 6 wind sites near cities have been developed. Financial incentives such as feed-in tariffs and PTCs are necessary now to justify exploiting the larger quantity of moderate quality Class 4 resources near load.

Wind-rich areas remain within and on the coasts of virtually every nation leading the rise of wind power. But in most cases very little transmission capacity exists for moving that power to large urban loads, leaving significant, high-quality wind power stranded, untapped. If the transmission system were expanded to devote a fraction to wind, many gigawatts of Class 5 and 6 wind sites would become developable. Absent transmission investment, most new capacity will have to be subsidized and probably at an increasing rate.

If the best wind is distant from demand, won't markets automatically secure transmission up to the most efficient level of supply? Not really, and part of the explanation in the U.S. comes from utility deregulation and the separation of economic incentives for generation and transmission. The firms making the power often are not the firms moving the power. Also, many states hold considerable influence over transmission decisions but have little incentive to attend to electricity demand or generation outside their borders.

Below is a summary of estimated transmission needs and costs for U.S. wind power. In reading this summary, keep in mind that national and regional transmission studies are highly assumption- and scenario-driven, so that the costs below are bracketed by wide ranges reflecting different policy choices:

- In 2008, the U.S. Department of Energy's 20% Wind Energy by 2030 Report put at $20 billion the cost of adding 12,000 miles of new high-voltage line to help access 293 GW of new wind capacity.
- In 2007, the utility American Electric Power drew up a network with 19,000 miles of 765-kilovolt lines to integrate about the same amount of wind. The estimated cost was $60 billion or $25 billion in net present value terms.[25]
- Preliminary work by the Western Wind and Solar Integration Initiative suggests that transmission costs for adding 31 GW of onshore wind and solar resources to the western grid could be $3.4 billion.[26]
- Preliminary analysis of the Texas portion of the U.S. grid, which leads most of the world in the pace of wind installations, calculates the cost of adding 12 GW to 24 GW at $3.3 billion to $6.7 billion, respectively. The state's ratepayers are expected to recoup those costs in saved fuel.
- Preliminary analysis of integrating enough wind to meet 20% of energy on the eastern U.S. grid by 2024 – chiefly 229 GW of onshore wind in the Midwest — calls for 15,000 miles of extra-high-voltage lines at a cost of $80 billion.

For our analysis, we drew on a survey of 40 U.S. transmission studies, performed by Lawrence Berkeley National Laboratory and Exeter Associates, and spanning a period between 2001 and 2008. Researchers found a vast range of transmission costs from $0 per kW to more than $1,500 per kW. The median was $300 per kW or in energy terms, $15 per megawatt hour (MWh). Using the last figure, we calculate transmission costs off adding 440 GW worldwide at about $155 billion. This figure almost certainly underestimates global transmission cost for the gigaton case because it is based on a mature U.S. grid. However, the difference is substantially mitigated by lower labor and commodity costs in China and India where much of the new transmission investment is needed. Some offshore wind development almost certainly will be required to meet the gigaton target and will be accompanied by higher transmission costs for installing or upgrading coastal lines or installing an underwater transmission backbone.

A note of caution: it costs $1 million to $5 million per land mile for the high towers, large substations, and heavy, multiple cables needed to keep very-high-voltage line losses to just a few percent over long distances. The low capacity value of wind compared to less variable energy sources makes it difficult for wind alone to economically justify privately financed clean-energy superhighways, so new means of financing or bundling projects for transmission are under development.

VARIABILITY

Wind is highly variable. Turbine power output ramps up and down with wind speed on every time scale, from seconds to seasons to years. This variability has implications for cost and is a dominant factor in any large-scale expansion of wind power. But wind is one of many sources of variability on the grid; others include demand, transmission congestion, and the availability of other generation. Because wind amounts to a zero-cost fuel, grid operators often treat wind energy as a "must-take" resource and so operate the grid to the net load, i.e., demand minus wind generation and other sources of variability, which is less variable than wind alone (see Figure 9). For this reason, the U.S. Utility Wind Integration Group concluded that ramping conventional power plants up and down in response to every movement of wind is neither necessary nor cost effective.[27]

Any penetration of wind increases net-load variability and can reduce system reliability unless back-up generating capacity is added to compensate for the added variability and maintain system balance. The added costs of these reserves rise with wind penetration but vary from place to place, depending on such factors as the size of the system and the diversity of its generation and storage assets.

So far, multiple wind-integration studies in Europe and the U.S. suggest that variability accompanying wind penetrations up to 20% of system demand brings moderate uncertainty and added system cost of less than 10% of the wholesale value of the added wind energy.[29] Adding wind, that is, results in net savings from the substitution of free fuel for natural gas, i.e., an energy source with zero marginal cost for an energy source with among the highest marginal costs on most systems. Preliminary studies of deploying wind at 20% of system energy show savings of more than $20 billion a year on the Eastern Interconnect and about $10 billion a year on the Western Interconnect.

Thus, wind power can act as a hedge against fuel-price volatility and the prospect of

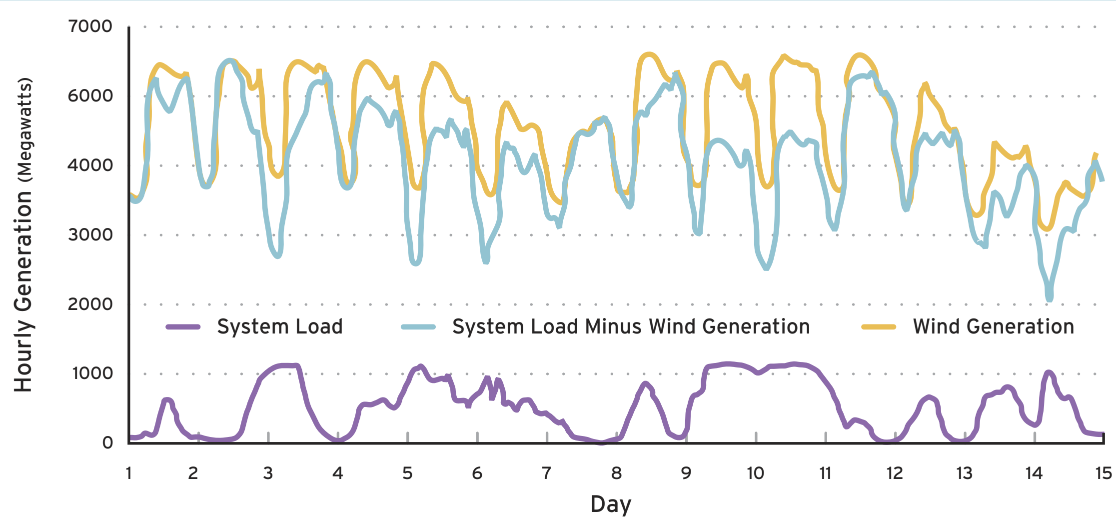

FIGURE 9. Hourly load shapes with and without wind generation. Net load (blue) is less variable than wind generation. Source: NREL, 2008.[28]

carbon pricing. By relieving demand for fuel, wind energy can indirectly ease fuel prices.

The cost and operating implications of wind penetrations above 20% are still being studied. Variability of net load rises, along with the need for back-up generation or reserves and the costs of contracting for those reserves. But some studies suggest that these system-balancing costs can flatten, depending again on the size of a control area and the flexibility of its generation, storage, and transmission resources.

If grid operators employ high-fidelity weather forecasts in their control rooms to support accurate scheduling decisions, overall system costs will be lower in the day-ahead and hour-ahead markets, with a state-of-the-art wind forecast delivering 80% of the savings of perfect foreknowledge. Studies in New York and California have shown annual savings up to $100 million from using state-of-the-art wind forecasting to inform markets and operations.

As noted, the cost of adding more wind to the grid is typically lower for larger control areas with more diversity and flexibility in grid assets. For example, wind power in a single Western U.S. state may swing up or down by as much as 50% of installed wind capacity, but across the entirety of the Western Interconnect wind power will swing up or down by less than 20% in the same hour. As Archer and Jacobson observe, the more that geographically distinct wind farms are interconnected, the more they behave as a single wind farm with steady wind.[30] Consolidating smaller control areas into larger ones combines this advantage of reduced correlation in wind speed among interconnected wind farms with the availability of more resources for smoothing the variability in wind power.

Grid operators can select among many resources to manage system balance, and increasingly those options include energy storage using batteries, capacitors, flywheels, pumped hydro facilities, hydrogen, compressed air in geologic formations or plug-in hybrid electric vehicles (PHEVs). Storage allows smoothing of energy generation and shifting of its use to a desired time period. All storage options are expensive, and all but the higher-performing batteries entail significant round-trip energy loss. But, by smoothing and shifting net load, storage allows effective use of renewable energy and higher penetrations than would otherwise be economical, resulting in more carbon abatement.

If plug-in hybrid electric vehicle (PHEVs) or battery electric vehicles (BEVs) are used, the economics and abatement potential of storage can improve. Access to a high-performance battery is considered a sunk cost of obtaining a transportation service, so that the cost of renewable storage narrows to the electricity used and the extra burden of charge-discharge cycles on battery lifetime. In this fashion, PHEVs can enable emissions reductions from both grid and vehicle. Researchers at the University of Delaware, Stanford University, and elsewhere have calculated abatement potential from storing wind energy in plug-in or full electric vehicles up to 32.7% of total U.S. CO_2e emissions.[31]

INTERMITTENCY

Intermittency, or losing wind power entirely, has diminished as a concern with improved turbine technology, the growth of wind farm size, and the interconnection of multiple wind farm sites on transmission networks. Early wind farms were seen as prototypes and set to trip off-line easily and quickly. Today, wind farms are larger, more sophisticated and more trusted. Unlike conventional power plants, they are composed of hundreds or thousands of independent generators that can ramp up and down steeply but don't go off-line instantaneously. Given the variation in wind across geographically separated but interconnected farms, according to the Utility Wind Integration Group, the cessation of all wind generation in a region is "not a credible event."

Technology Innovation

Wind turbines are unattended, stand-alone generators that have been part of the grid for only about 30 years. Hundreds of thousands of turbines have been installed, but no clear technical consensus has emerged regarding the ideal capacity for an onshore turbine or wind farm. The increases in scale that have characterized wind power's evolution are expected to continue for offshore turbines but to stabilize for onshore turbines in the future.

Ever-longer blades and wider-diameter towers are becoming difficult to transport on land, and so is obtaining large enough cranes to erect turbines. Designers also are running into another corollary of wind power: although power increases as the square of rotor diameter, the mass of material in the rotor — along with weight and cost — increases with the cube of the rotor diameter unless other modifications in materials or design are made. At some point then, scaling up the size of turbines can become a losing economic proposition.[32]

In recent years, turbine designers have used simulation tools, wind tunnels, and new materials to break the cubic mass-diameter relationship and deliver longer, lighter blades at a linear increase in cost. How long this will continue is not clear, but research is ongoing into ways to relieve loading and trim weight so that blades can grow longer. Other performance gains for future turbines are expected from more sophisticated sensors to read oncoming wind, more refined digital controls to optimize the angle of attack over the length of the blade, and new blade materials to resist fouling from dirt and insects.

Technologies and approaches under investigation to improve wind-power productivity include:

- Deploying short-range lidar (a light-based analog of conventional radar) on the rotor nose to sense changes in oncoming wind and adjust the blade pitch for optimal power capture
- Coupling sensors on the edges of turbine blades to processors, actuators, and flaps on the trailing edge to ease loading on the rotor while carving the most power out of the wind
- Using hybrid carbon-composite/fiberglass, ultra-high tensile, nanofilament blade materials to reduce weight, stiffen blades, and resist loading
- Using novel laminates and blade shapes to obtain passive resistance to wind gusts and resulting loads[33]
- Using direct-drive systems, especially to reduce maintenance costs for offshore wind
- Using permanent magnets instead of windings in generators to save weight
- Using lighter, more efficient gearboxes and power converters; new silicon-carbide power electronics may reduce losses and enable a magnitude reduction in mass.[34]

Public Policy

Acquiring wind power's chief benefits — abundant free fuel, energy security, and fast scalable carbon abatement — comes at a significant up-front capital cost of nearly $1 trillion for the gigaton scenario, including $127 billion in new transmission. The scale of investment in wind projects and transmission is large, yet recent studies of global electricity demand and supply conclude that maintaining current levels of service for a growing population will require spending a half billion dollars or more per year on new generation and transmission for the foreseeable future.

STABLE POLICY

The costs and benefits of different incentive philosophies for renewable generation are worth debating, but the most critical precursors for investment and abatement are consistency and stability. To be comfortable betting on wind power, investors must be assured of reliable returns or at least quantifiable risk mitigation. Likewise, people living in wind-rich regions and developers of wind projects would benefit from a reliable set of rules that could guide development and settle disputes over noise and visual and natural aesthetics. These rules could serve as touchstones to protect property values, wind investments, and natural resources, as well as social and ecological interests in climate stability.

Teasing apart the relative contributions of different policies to wind development is difficult. However, the clear surges and sags in U.S. wind development with expiration of the federal PTC in 2000, 2002, and 2004 — coupled with record-breaking growth since — leave little doubt that the trajectory of U.S. wind power is entwined with government support.

Figure 10 illustrates this point: major drops in wind deployment all occurred in years when the PTC expired.

The uncertainty arising from U.S. tax policy translates into higher costs for clean energy infrastructure and reduced emissions abatement for the most extensive and fastest-growing non-hydro renewable energy source. Without a reliable PTC, the wind project financing, supply, and installation pipelines must be ramped up and down, causing demand-supply mismatches and price increases, as happened from 2004 to 2008, prior to the onset of the 2009 recession.

Exchanging the short-term political benefits of renewing the PTC every 2 or 3 years for a longer-term strategy would leverage greater private investment in clean, secure energy supplies. Depoliticizing the PTC could have profound climate and energy-security benefits.

The U.S. Energy Information Administration analyzed the impact of various extensions of the tax credit and found that a 5-year PTC extension would deliver 41% more growth in U.S. wind generation by 2020 than no further extension of the credit. Making the credit permanent could more than double U.S. wind generation by 2020 and more than triple it by 2030.

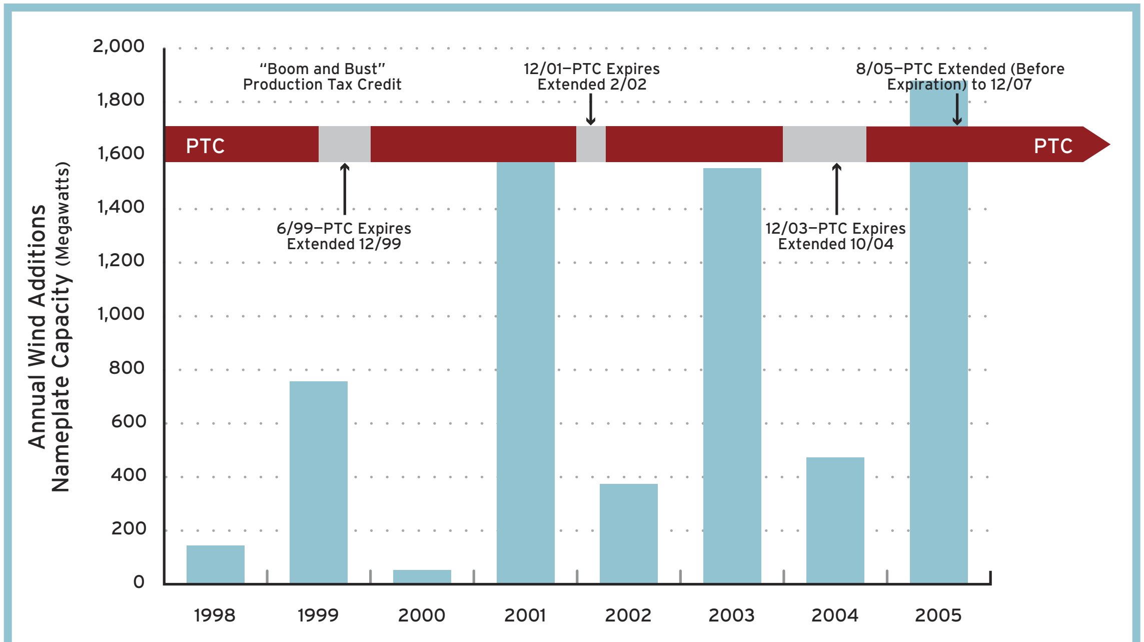

Figure 10. Impact Of Production Tax Credit On U.S. Wind Installations. Source: Black & Veatch, 2007[35]

EFFICIENT ENERGY MARKETS

In the end, policy should aim to remove inefficient market incentives and account fully for the cost of burning fossil fuels. Based on a discount rate equal to the weighted cost of capital for new wind farms with a 2010 capital cost of $2,000 per kW to $2,150 per kW and a range of project lifetimes from 20 to 30 years, we have calculated the carbon price necessary to make wind energy competitive with wholesale electricity prices in the U.S., without a PTC. The carbon adder ranges from as little as $14 per metric ton in the low-cost, low-interest case to as much as $86 per ton in a high-cost, high-interest case. At moderate interest rates and more typical project costs and lifetimes, the carbon price that enables large-scale growth of wind in wholesale markets comparable to those of the U.S., exclusive of transmission costs, is likely to be between $42 and $56 per metric ton of CO_2e without relying upon other subsidies.

TRANSMISSION POLICY

Policy changes are needed to make private financing of renewable transmission more attractive, perhaps by enabling higher rates of return. Alternatively, state or regional entities, such as Texas or the Wyoming Infrastructure Authority, could use ratepayer or bond financing to build new networks, often with more capacity than the nearest-term projects. Texas, California, and other states also are designating competitive renewable energy zones to cluster and anchor new transmission.

Interactions with Other Gigaton Pathways

Many of the same strategies for integrating wind at higher penetration — smoothing net load via storage or demand shifting, firming with natural gas or hydro, build-out of transmission, and better use of forecasts — also enable greater penetration and abatement from other low-carbon electricity sources.

Night-time wind and PHEVs charged at low-load hours are a natural combination. Concentrating solar power plants tend to fill in summer demand peaks when wind can die down. Rooftop photovoltaic panels can perform the same function without transmission congestion or loss. Geothermal plants can help carry the economic justification for transmission of other renewables. Demand response and storage shifts loads to periods of inexpensive wind generation. If carbon pricing provides stronger economic foundations for all of these technologies, a 21st-century network of "smart grid" controls, transmission, and flexible generation can orchestrate their operation as an efficient, diverse electric power system and enable large-scale carbon abatement.

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GIGATON THROWDOWN

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