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 (manmade) 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

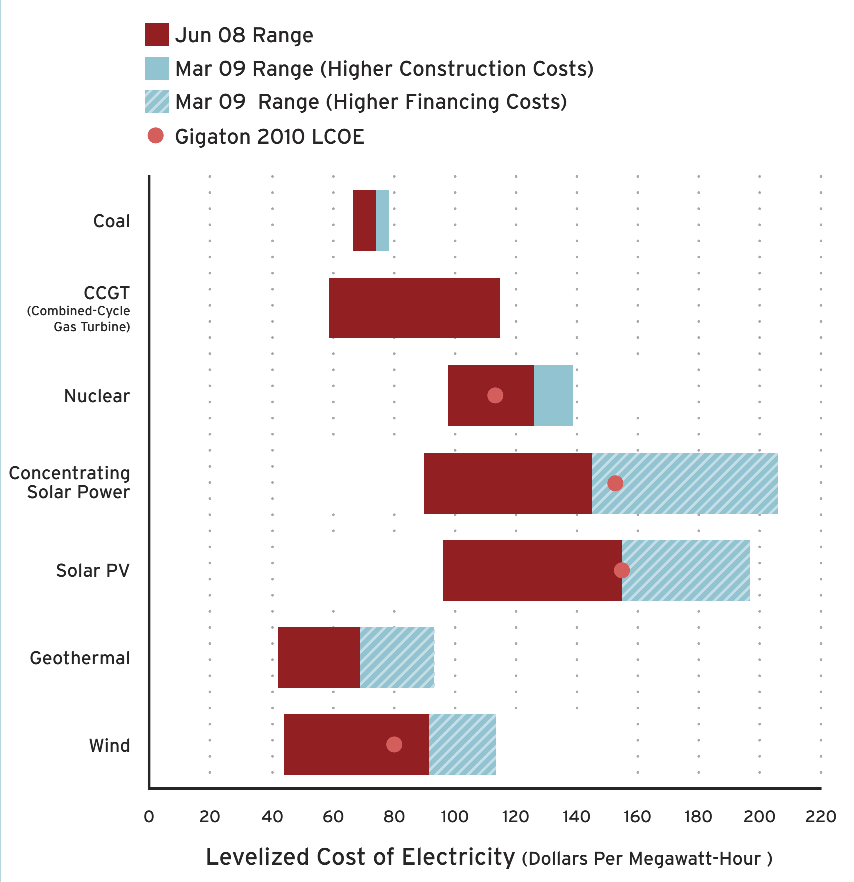
Clean energy sources including wind, geothermal, and solar power already compete with the price of natural gas as an electricity source in some cases, especially where grid infrastructure is available. As shown in Figure 1, wind and geothermal are cost competitive today with new coal-fired generation.[9]

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



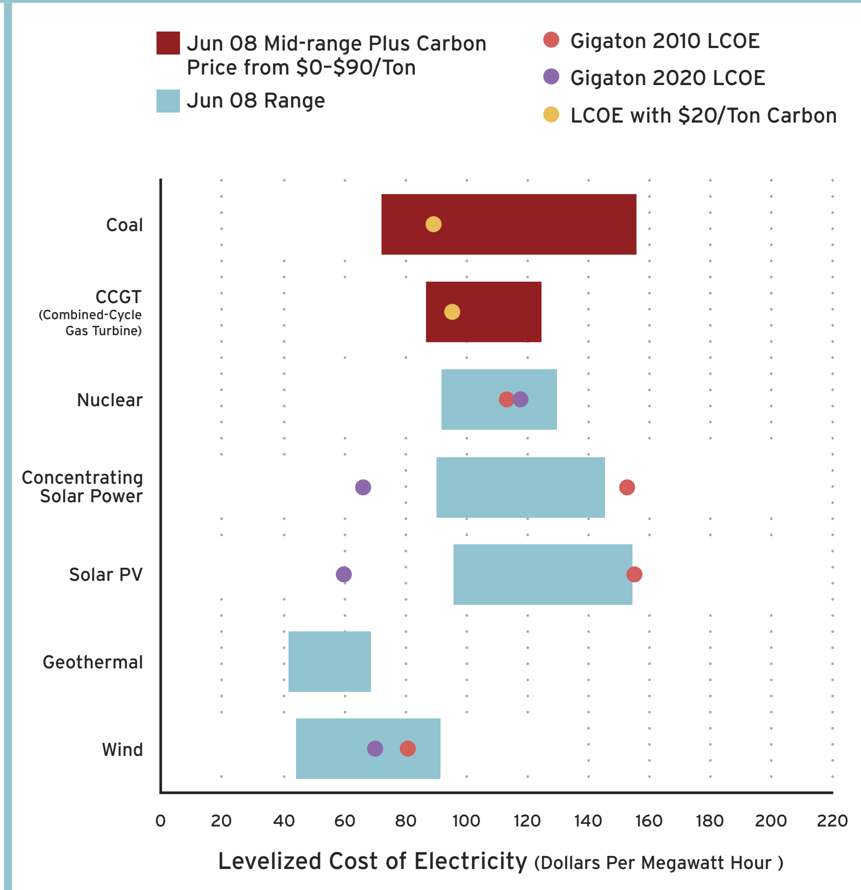


FIGURE 1. Levelized Cost of Electricity (LCOE) for New Clean Energy Generation vs. New Fossil-Fuel-Based Generation Today in the U.S. The LCOE for new clean energy generation is already competitive with new fossil-fuel-based generation in many cases. Notably, an increase in financing costs for clean 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

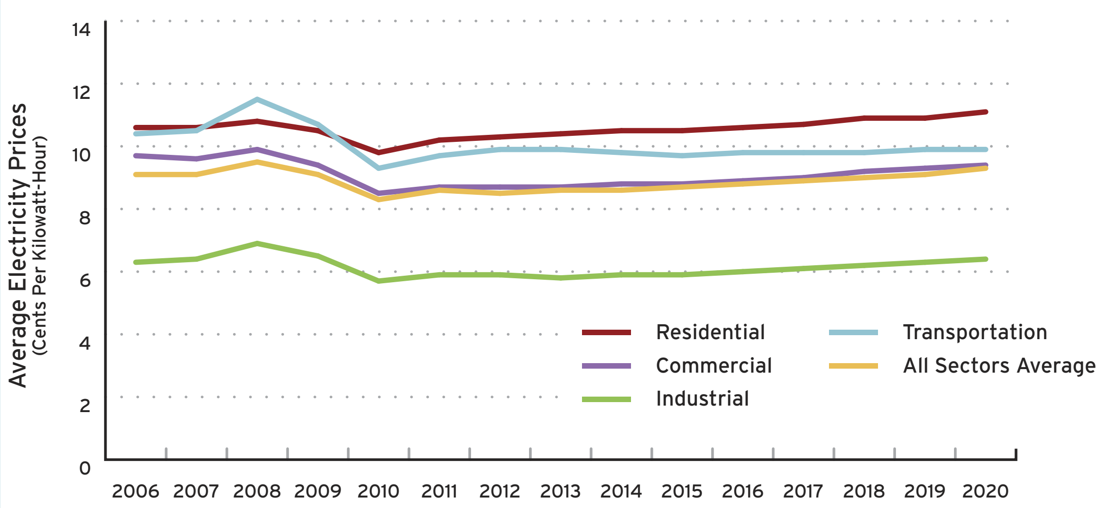


FIGURE 3. Electricity Price Projections Through 2020. Source: EIA, 2009[18]

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.

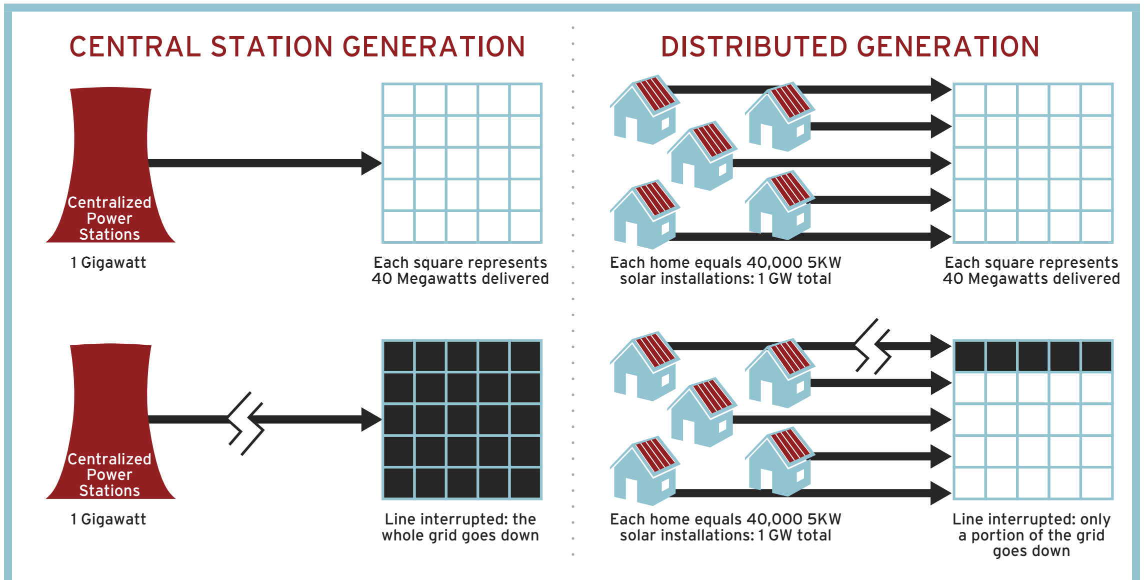


FIGURE 4. Effect of a Power Outage Under Centralized Generation Versus Distributed Generation. Distributed generation helps avoid widespread power outages.

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

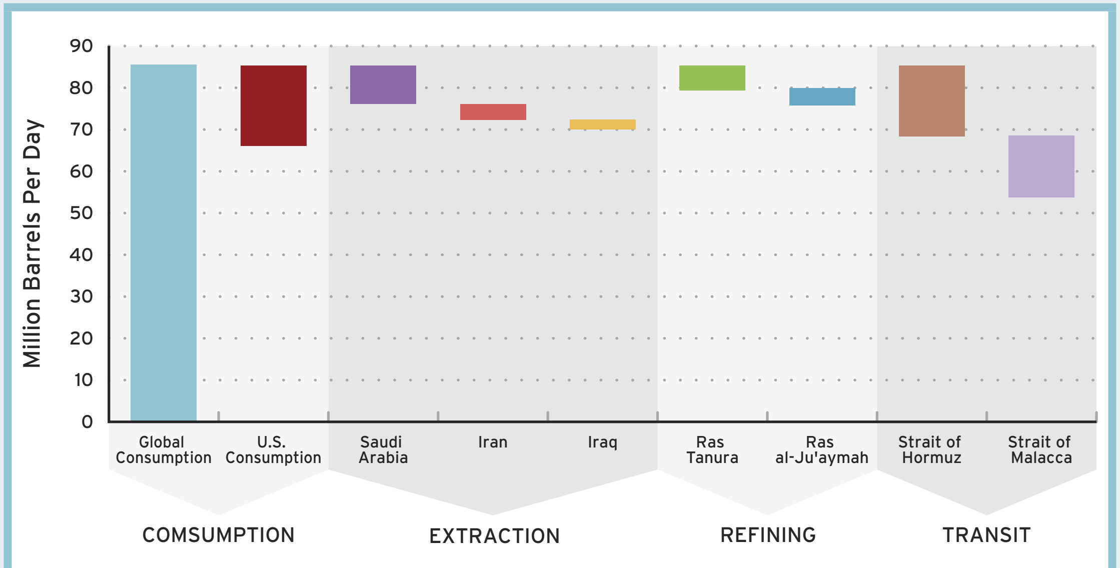


FIGURE 5. Origin and Routing of Global Oil. Oil passes through a number of choke points on its way to its final destination.

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

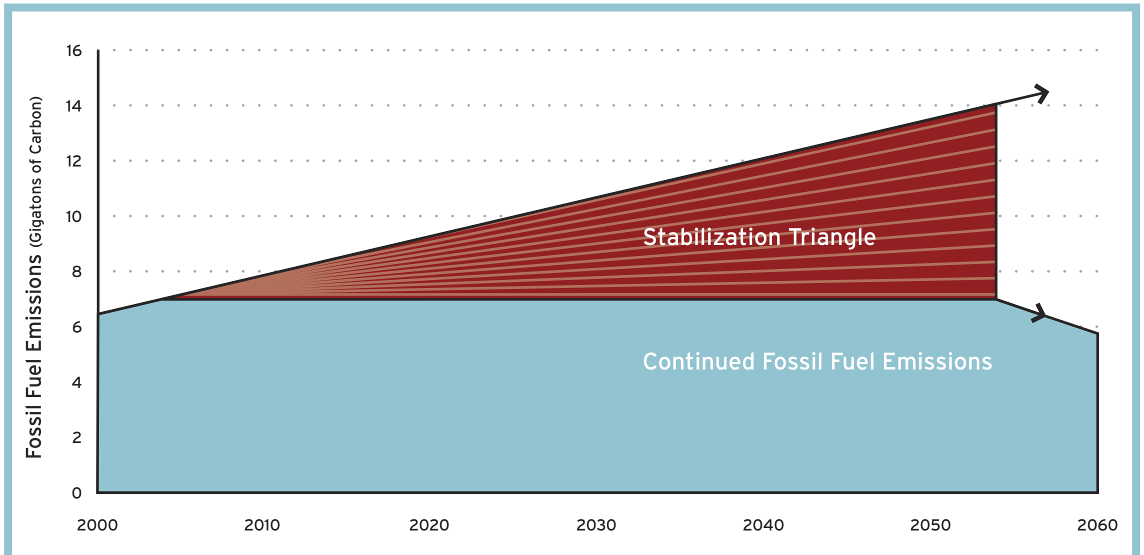


FIGURE 6. Stabilization Triangle Illustrating Emissions that Must be Avoided Annually to Prevent Global Temperature Rise. Note: 1 gigaton of carbon equals 3.76 gigatons of CO_2e. Source: Pacala and Socolow, 2004.[22]

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.

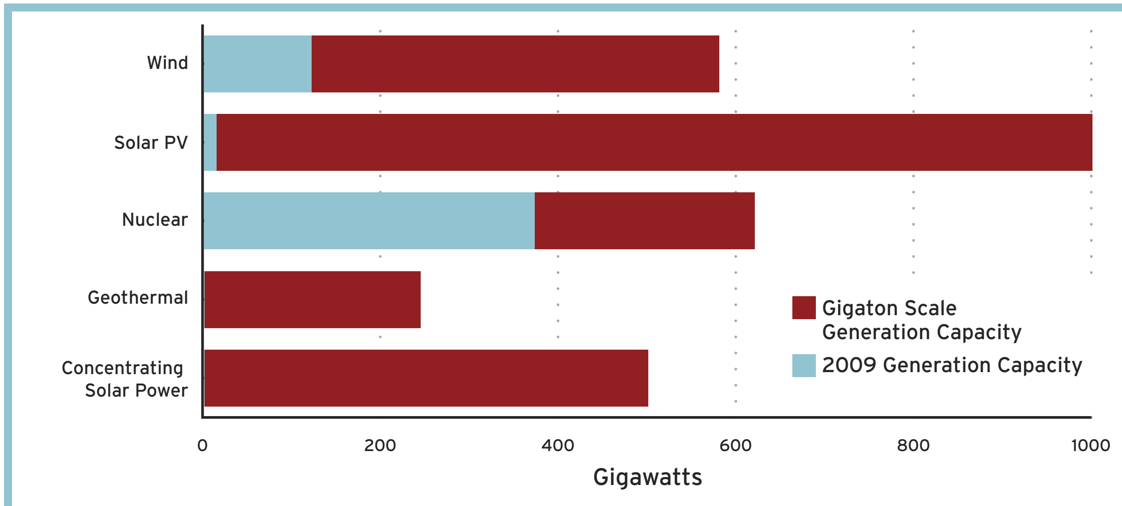


FIGURE 7. Scale-up for Gigaton Clean Energy Generation Technologies by 2020.

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.
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8. EIA. 2009. See 2.
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.