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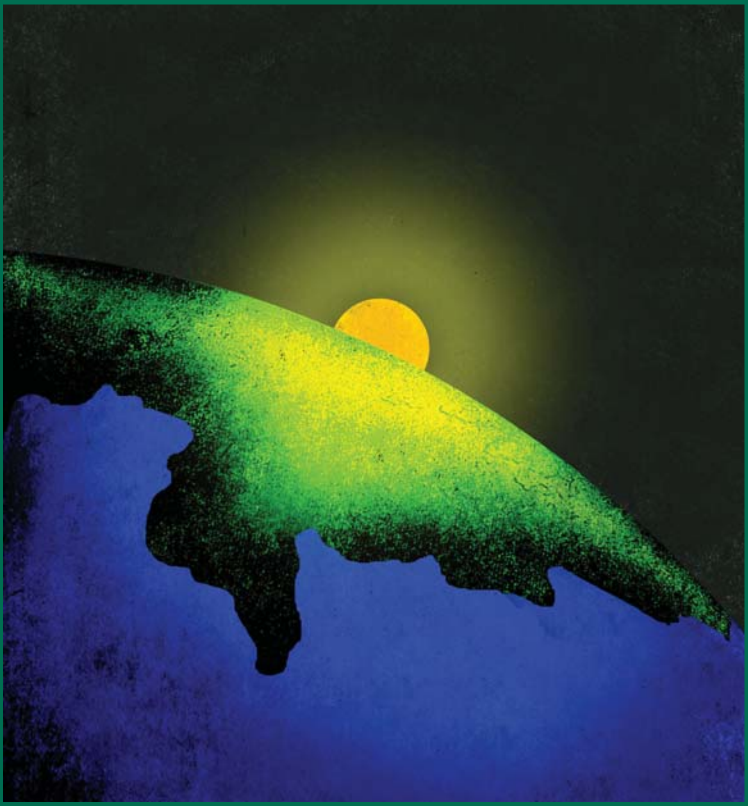
REPORT

What's Next for Alternative Energy?



THE BOSTON CONSULTING GROUP

What's Next for Alternative Energy?

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Executive Summary

Alternative energy saw an unprecedented explosion in interest through much of the last decade. Driving this was a confluence of forces. First, the cost of fossil-fuel-generated energy climbed, driven by surging demand from China, India, and other rapidly developing economies. Second, many countries intensified their focus on enhancing their energy security and reducing their dependence on energy imports. Third, there was growing acceptance worldwide of the need to reduce carbon emissions to combat climate change and its consequences.

This momentum ground to a halt in the second half of 2008, however, with the onset of the global recession and declines in energy prices. Many alternative-energy companies saw steep declines in their share prices and also suffered financial distress, as project-financing difficulties stalled ambitious deployment plans. Although some alternative-energy sectors, for example wind and solar photovoltaic (PV), resumed growth in 2009, a compelling recovery remains elusive.[1] And there are still hurdles. Regulatory support, which remains critical to the development of alternative energy, continues to be highly variable by sector and location. (In India, for example, there is growing support for solar power, while in Spain, subsidies for solar power are decreasing.[2]) Furthermore, the lack of progress on global climate policies has dimmed the near-term prospects for a policy-enabled price on carbon emissions, which could spur demand for alternative energy. In short, alternative energy continues to suffer from uncertainties that muddy the waters for investors.

So what's next? Will alternative energy resume its upward trajectory as the global economy recovers, or will hurdles ranging from lower conventional-energy prices to "subsidy fatigue" and the slow progress of enabling legislation translate into stagnation? Will alternative energy be a useful but ultimately minor element of the global energy mix, or is there potential for it to fundamentally disrupt that mix? Will alternative energy be a niche preserve of entrepreneurs, technologists, and venture capitalists and be relegated to the fringes of the energy complex, or can aspects of it morph into a disruptive mainstream over the next decade? Who will pay and how will the adoption of alternative energy be funded?

The bottom line: conventional energy sources will remain the lion's share of the world's energy mix for at least the next couple of decades. Natural gas will play a major role as a relatively abundant source of lower-carbon energy. Yet technologies in some alternative-energy sectors are approaching inflection points in their development and are on a path to becoming viable on a standalone basis, either completely decoupled from subsidy programs or requiring much less assistance. And there are clearer lines of sight into the barriers that must be surmounted before these technologies can be adopted broadly and to the triggers that could lead to more rapid adoption. These sectors, we believe, could have an impact on the global energy landscape far sooner than is commonly assumed. Other alternative-energy sectors, however, will continue to be no more than visions or promises for at least the next decade. It is vital that companies, governments, and other stakeholders in the energy ecosystem recognize and

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[1] Growth in the development of wind energy, for example, resumed in 2009, driven by stimulus measures and the continuation of subsidy schemes. In other sectors, such as solar PV, strong volume growth in 2009 (an approximately 25 percent increase in PV gigawatts installed) has continued into 2010. This growth, however, was offset by price declines (ranging from 20 to 30 percent for solar PV systems) that were the result of competitive pressures and oversupply.

[2] India has announced its National Solar Mission; Spain recently announced cuts of up to 45 percent in the feed-in tariffs for large-scale PV plants. Similar examples can be found across alternative-energy sectors.

understand the differences among these sectors, revisit their assumptions, and redraw potentially outdated plans and timetables accordingly.

This report focuses on two critical areas that have disproportionate impact on energy and climate considerations. For the first, transportation, our focus is on advanced biofuels and electric-propulsion vehicles. For the second, power generation, we focus on concentrated solar power (CSP), solar PV, onshore and offshore wind, and clean coal through carbon capture and sequestration (CCS).[3] For each of these sectors, we offer a snapshot of where it is currently and assess its prospects vis-à-vis three questions: Can it achieve cost competitiveness with conventional energy by 2020 and be economically viable without subsidies? Once cost competitive, can it overcome barriers to rapid adoption? Can it reach penetration levels by 2025 that disrupt the status quo?

This report's high-level findings, outlined in Exhibit 1, include the following:

Advanced biofuels are moving rapidly down the cost curve and are on a path to becoming cost competitive in the next few years.

- Once they are cost competitive, advanced biofuels will face several structural barriers to rapid adoption, the biggest of which is likely to be the vast investments needed to build the necessary conversion capacities and other infrastructure.

- If these barriers can be overcome, advanced biofuels could significantly disrupt the status quo in fuel markets.

CSP is also moving quickly down the cost curve and could become competitive with conventional generation sources in lead markets even in the next five to ten years.

- By 2020, CSP could provide power at $0.10 or less per kilowatt-hour and be competitive with conventional energy sources.

- Coupled with the ability to utilize thermal storage to provide on-demand power, CSP is a likely candidate to disrupt the status quo in power generation by 2025 if major barriers, such as limitations in transmission infrastructure, can be overcome.

Solar PV's costs are also declining rapidly, and the technology will see accelerated adoption; onshore wind, already cost competitive in many instances, will see steady adoption.

- Without breakthrough declines in energy storage costs, however, inherent challenges posed by the intermittent nature of these technologies will limit their combined penetration to no more than approximately 25 percent of the total power-generation mix.

- Yet even at these levels, these technologies could have disruptive effects on the status quo.

In contrast to onshore wind, offshore wind will struggle to move beyond purely subsidy-driven growth or to reach economic viability on its own before 2020.

- Its growth will be limited to a few regions or countries.

- These are regions and countries that are committed to meeting aggressive carbon-reduction targets but have few other renewable resources.

Electric vehicles (EVs) will become economically attractive for lead market segments by 2020, but broader adoption will require major declines in battery costs.

- EVs are likely to achieve a 5 to 10 percent share of new-vehicle sales by 2020; however, under aggressive assumptions regarding battery cost declines or fuel prices, EVs could become economically attractive to more than 20 percent of some vehicle segments.

- Even with higher adoption rates, EVs are unlikely to become a material part of the vehicle fleet in the coming decade, because fleet turnover is slow.

- If there is insufficient low-carbon power-generation infrastructure, EVs will struggle to be seen as a solution for reducing carbon emissions significantly.

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[3] On the basis of the scope we defined for this report, some sectors—energy efficiency and hydroelectric and nuclear power (two important existing means of low-carbon power generation)—are not covered here despite the important roles they will play in the energy mix. Smart grids and energy storage are considered only from the standpoint of how they might facilitate alternative energies.

Exhibit 1. Several Technologies Are Poised to Reshape the Energy Landscape by 2020; Others Will Have Limited Impact

Potential to become cost competitive by 2020 and to begin disrupting the status quo by 2025

Low ◄——► **High**

Offshore wind

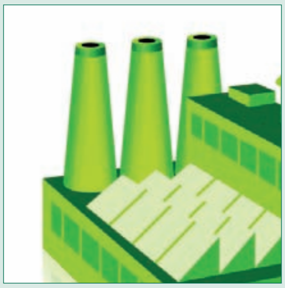
- Offshore wind is unlikely to reach cost competitiveness by 2020
- Wind's intermittent nature means a ceiling on total deployment

Solar photovoltaic

- Solar PV will achieve cost competitiveness by 2015 to 2020 in sunny regions
- The intermittency of solar PV's energy generation will cap its total potential deployment absent breakthroughs in energy storage

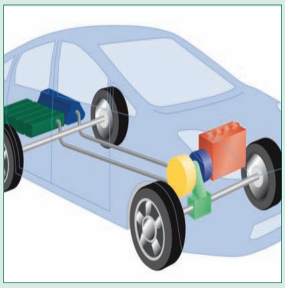
Advanced biofuels

- Advanced biofuels are moving rapidly down the cost curve
- They will be cost competitive in the next few years
- Infrastructure limitations and other barriers to deployment are surmountable
- Converting the vehicle fleet to flexible-fuel vehicles is relatively cheap and easy



Carbon capture and sequestration

- CCS is critical to carbon abatement but is challenged on many fronts and will not be viable without a significant price on carbon emissions
- It is making very slow progress toward large-scale demonstrations, is unproven, and lacks supporting policy frameworks



Electric vehicles

- EVs will become economically attractive for lead market segments by 2020
- Without significant declines in battery costs, long payback periods will be a barrier to rapid growth more broadly
- Even when EVs are economically attractive, fleet turnover will still take many years
- The need for charging infrastructure and grid investments could slow growth
- EVs will need low-carbon power-generation infrastructure to be a solution for carbon emissions reduction

Onshore wind

- The best sites are cost competitive today; the technology is entering a more mature phase of development
- Wind's intermittent energy generation caps its total potential deployment

Concentrated solar power

- With large-scale deployment, CSP will become cost competitive in the 2015–2020 time frame
- CSP is uniquely able to provide on-demand power through cost-effective thermal storage
- Infrastructure limitations and other barriers to deployment are significant but surmountable

Source: BCG analysis.

Clean coal through carbon capture and sequestration will have very slow adoption and won't be viable for the next decade or two.

- However, the technology is vital for cutting global carbon emissions from the vast existing and rapidly growing global coal-fired power-generation fleet and for addressing the energy security concerns of countries such as China.
- There are a number of reasons why it will develop slowly, including the technology's slow progress toward demonstrating large-scale viability and moving down the cost curve.

The fortunes of alternative energy have historically waxed and waned with the price levels of oil, gas, and other energy sources, rising when prices are high only to fall once they retreat. For the most part, the focus has been on the technical feasibility of various technologies, required subsidies, or need for carbon prices to make those technologies viable. We believe, however, that this time is different. The debate is moving to when and how—not whether—alternative energy can move beyond the realm of subsidies to compete with conventional energy sources. For some alternative-energy industries—CCS and offshore wind, for example—real competitiveness is still a distant probability. For others, that reality could be a lot closer than is commonly assumed.

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Transportation

The transportation sector accounts for approximately 61 percent of global oil consumption.[4] At the same time, it produces approximately 23 percent of total carbon dioxide emissions.[5] Advanced biofuels and electric vehicles (EVs) are alternative-energy sectors that offer the promise of reducing carbon emissions from and dependence on fossil fuels used for transportation.

Advanced Biofuels: Accelerating Adoption

Advanced biofuels are significantly different from their first-generation predecessors, such as corn ethanol and biodiesel derived from palm oil and rapeseed feedstocks. In contrast to first-generation biofuels, advanced biofuels are derived from a range of dedicated energy-crop feedstocks (such as switchgrass, energy cane, and miscanthus) that can be grown on marginally productive land (as well as conventional cropland) and do not compete with food crops. Advanced biofuels being developed as substitutes for both fossil-based gasoline and diesel can also achieve emissions reductions of 90 percent or more, while most first-generation biofuels reduce emissions negligibly, if at all.[6] Unlike first-generation biofuels, advanced biofuels are a sustainable energy solution.

The different types of advanced biofuels are in various stages of development, with many different companies involved.[7]

◇ *Biochemical Conversion of Lignocellulosic (LC) Feedstocks into Biofuels.* Examples of LC feedstocks include various grasses (for example, switchgrass and miscanthus), wood, waste residues, energy cane, corn stover, and the bagasse left over from sugarcane crushing. All the sugars that can be extracted from the cellulose and hemicellulose that make up the bulk of energy crops and other plant biomass are biochemically converted (that is, fermented) into ethanol and other gasoline substitutes such as biobutanol.[8] (Compared with ethanol, biobutanol has superior properties as a fuel.[9]) The sugars extracted can also be directly converted biologically into advanced biodiesels through sugar-to-diesel conversion technologies. Lignins and other remaining wastes can be used to generate process heat or electricity. Ethanol and butanol from biochemical conver-

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[4] Euromonitor International, Global Market Information Database, 2007.

[5] International Energy Agency, 2008.

[6] A notable exception is first-generation ethanol made from sugarcane. It not only is competitive with gasoline today but also, like advanced biofuels, can reduce carbon emissions by as much as 90 percent.

[7] Other uses for biomass, such as power generation or the production of chemicals, are not included in this discussion. These other uses are synergistic with biofuels production. Examples include integrated biorefineries that can produce fuels, power, and chemicals from diverse sustainable biomass sources. We have intentionally avoided naming or discussing specific companies in this report.

[8] In first-generation biofuels conversion, only the six-carbon, or hexose, sugars (for example, glucose from corn starch) are fermented. In advanced biofuels, biomass is pretreated to separate the cellulose, hemicellulose, and lignins. Enzymatic or acid hydrolysis (the former is the more promising) then liberates both the hexose *and* the pentose, or five-carbon, sugars from the cellulose and hemicellulose, thus increasing the total amount of sugars available for fermentation. However, while common yeasts are sufficient to ferment the hexose sugars to produce first-generation fuels such as corn ethanol, conversion of pentose sugars requires special enzymes and organisms.

[9] Biobutanol has greater energy content and can be blended with gasoline in higher levels than can ethanol, giving it greater compatibility with the current infrastructure.

sion of LC feedstocks are moving into advanced stages of commercialization, whereas sugar-to-biodiesel technologies are in earlier stages of development.

- *Oil Substitutes Derived from Algae Oil and Refined into Fuel Products.* Algae oil has some potential advantages over LC biofuels. Algae reproduce faster than LC energy crops; can be grown virtually anywhere, including saltwater; and absorb large amounts of CO_2. Algae are also highly productive, with an estimated yield of 1,200 to 10,000 gallons of fuel per acre compared with an equivalent yield of 200 to 600 gallons per acre for LC ethanol. Furthermore, algae oil can leverage existing oil-refining and logistics infrastructure and is compatible with traditional internal-combustion engines. Although algae oil technologies hold long-term promise, they remain in the very early stages of development.

- *Thermochemical Conversion of Lignocellulosic Feedstocks into Biofuels.* Plant biomass can be gasified to create "syngas," which, after cleaning, can be converted to ethanol through thermochemical means using catalysts. Large-scale demonstration projects of this process are under way, and the technology is moving into commercialization. Syngas can also be converted to diesel fuel using Fischer-Tropsch processes.[10] Fischer-Tropsch technology has been around since the 1920s, but applications of the technology (including, for example, diesel production from the conversion of syngas from coal or natural gas) are slowed by its high costs and the significant capital required for the large-scale facilities essential to bringing down those costs, which are particularly problematic for biomass.[11] Technologies for converting syngas to ethanol through fermentation using specialized microorganisms are in the early stages of development. Thermochemical technologies that aim to convert extracted sugars from biomass directly to hydrocarbon fuels (including both gasoline and diesel fuel) are also in development.

Achieving Cost Competitiveness and Moving Past Subsidy-Driven Growth. The economic viability of advanced biofuels will ultimately be governed by their ability to compete directly as substitutes for hydrocarbon fuels such as gasoline. LC ethanol, especially, is on the verge of being cost competitive with gasoline: large-scale LC facilities are expected to reach unsubsidized retail-cost parity with $3 per gallon gasoline by 2012 to 2015.[12] The cost declines of LC ethanol are being driven by three factors. (See Exhibit 2.)

Lignocellulosic ethanol is on the verge of being cost competitive with gasoline.

- *Reductions in Enzyme Costs.* Currently, the enzymes used to extract fermentable sugars from LC feedstocks are the most expensive element of the conversion process, costing approximately $0.80 to $2.00 per gallon of ethanol. Enzyme producers and others expect that in the next few years, these costs will decline by 50 percent to $0.40 to $1.00 per gallon, through production scale effects and technology improvements. A major producer of industrial enzymes, for example, expects enzyme prices to fall to roughly $0.50 per gallon in the very near term.

- *Improvements in Feedstock Yield and Quality.* Today, LC feedstocks such as energy grasses and energy cane make up approximately 30 percent (approximately $0.75 per gallon) of the total production cost of LC ethanol. Such LC feedstocks are not yet produced in mass quantities for use as energy crops, but the agricultural life-sciences industry has a well-known track record of delivering steady improvements in crop yields and quality.[13] Plant genomics, breeding, and other technologies are being used to further develop higher-yield

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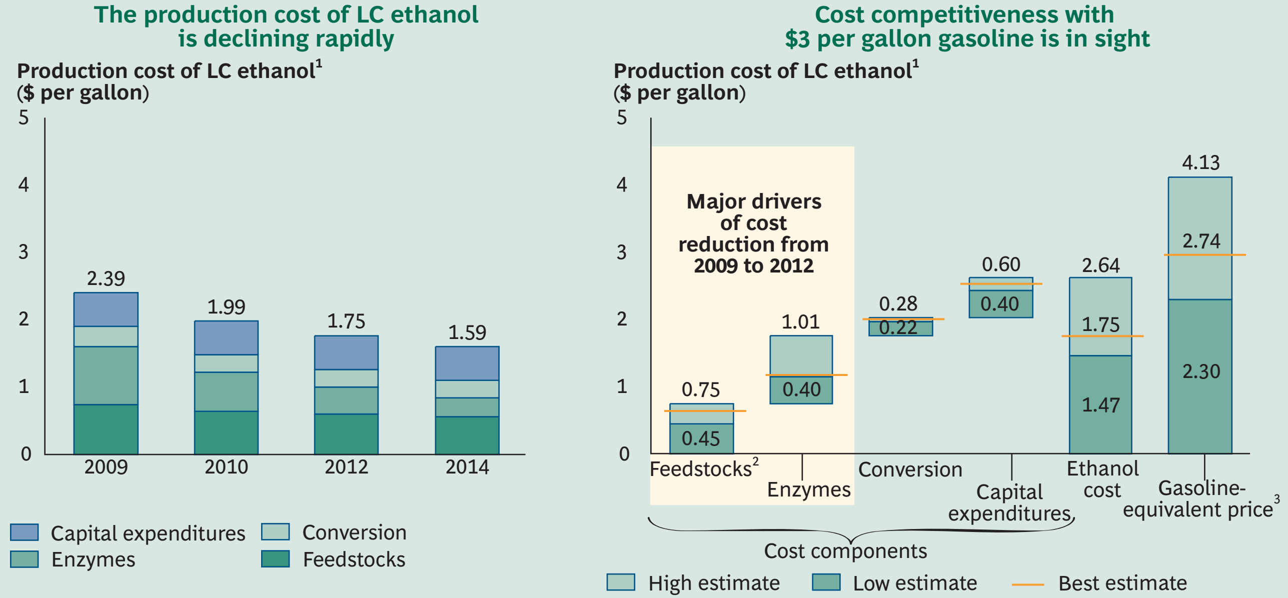
[10] These fuels are also commonly called biomass-to-liquids, or BTL. Syngas—a mixture of carbon monoxide, hydrogen, and small amounts of methane—can also be used to produce dimethyl ether, which can be a blend substitute for liquefied petroleum gas.

[11] Thermochemical pathways are significantly more capital intensive than biochemical options because of the high-temperature, high-pressure operating environment. The large-scale requirements for cost-effective BTL are particularly problematic for biomass, as transportation costs and practical land-use realities generally limit the scale of biomass facilities.

[12] We define a large-scale plant as one that has a conversion capacity of 50 million gallons or more per year. A plant of this size balances the capital investment efficiencies of a large plant with the increased transportation and logistics costs of bringing feedstocks to the plant. These costs are driven largely by fuel prices, crop yields, and the percentage of the surrounding acreage that is dedicated to growing the needed feedstocks. The cost parity estimate is based on the International Energy Agency's forecast of $95 per barrel of oil in 2012.

[13] U.S. corn yields, measured in bushels per acre, doubled from 1970 through 2010, according to the U.S. Department of Agriculture.

Exhibit 2. Ethanol from Lignocellulosic Feedstocks Is on the Verge of Becoming Cost Competitive with Gasoline



The production cost of LC ethanol is declining rapidly

Cost competitiveness with $3 per gallon gasoline is in sight

Sources: U.S. Department of Energy projections; expert interviews; BCG analysis.

[1] Using biochemical pathways.

[2] Based on costs of $45 to $60 per dry ton of LC feedstocks and yields of 80 to 100 gallons per dry ton.

[3] The energy density of ethanol is approximately 65 percent that of gasoline, so approximately 1.565 gallons of ethanol are needed to substitute for a gallon of gasoline.

dedicated energy crops that also have specific desired qualities, such as easier extractability of sugars.[14] This will increase crop yields per acre and drive down feedstock costs by an estimated 20 percent in the next few years, with substantial promise of further improvements in later years.[15]

◇ *Lower Costs from Scale Advantages and Experience Curve Effects.* LC ethanol technologies have had success at the pilot level, and the process of translating this success to an industrial scale is under way in earnest. It is reasonable to expect that the typical scale economies and experience curve effects that will come with commercial-scale plants (for example, biorefineries that produce 50 million or more gallons per year) will further drive down conversion costs. For LC ethanol, the conversion cost per gallon is expected to fall by approximately 20 percent for each doubling of volume from these effects alone.

LC biobutanol is also in the advanced pilot-demonstration stage but likely will lag behind LC ethanol in coming to market. Taken together, these fuels will pose a credible challenge to gasoline. As they become cost competitive over the next few years, they will be attractive substitutes for gasoline in many markets, especially if there is more pressure to lower dependence on hydrocarbon fuels for reasons of energy security or carbon emissions reduction. As noted earlier, biodiesel from LC feedstocks through sugar-to-diesel pathways is in earlier stages of development. However, as the LC ethanol sector ramps up, there will be a much shorter time lag between proof of large-scale technical viability and commercialization (as well as accompanying cost declines).

The evolution of integrated biorefinery complexes is an exciting development that will emerge toward the end of this decade. Much like conventional oil-refining complexes that take in diverse types of crude oil to produce a

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14. Other exciting developments include saltwater- or drought-resistant energy crops that can be grown on land that would be otherwise unusable.

15. Feedstock costs could fall to $45 to $60 per dry ton, with a yield of 80 to 100 gallons per dry ton (a 35 to 40 percent reduction), but, to account for potential delays, we have used a more conservative 20 percent reduction in our cost projections for the next few years.

wide array of refined products, these integrated facilities will further drive cost and other synergies by combining multiple biomass sources to produce desired combinations of various biofuels, biopower, and other bioproducts (for example, chemicals).

The current economics of algae oil—at an estimated production cost of $500 per barrel—keep it far from viable. Achieving favorable economics will require sizable reductions in both capital costs (on the order of 33 percent) and operations and maintenance costs (nearly 70 percent). Estimates of when the technology will finally become viable vary considerably; assuming it happens, our assessment is that it is easily more than ten years away. Similarly, biomass-to-liquids, or BTL, using Fischer-Tropsch technology is plagued by high capital costs, difficulties achieving scale, and other unfavorable economic drivers and is unlikely to be cost competitive by 2020.

Infrastructure barriers need to be overcome for advanced biofuels to gain rapid adoption.

Overcoming Structural Challenges to Rapid Adoption Once Cost Competitive. As advanced biofuels become cost competitive, they will need to surmount several infrastructure-related barriers to gain rapid adoption:

- *Transportation and Storage Infrastructure.* Today, ethanol is blended in small amounts with gasoline. (The widely available fuel E10, for example, is 10 percent ethanol and 90 percent gasoline.) But with conventional-fuels infrastructure, there is a ceiling on the proportion of ethanol that can be blended with gasoline. This ceiling is commonly referred to as the "blend wall."[16] For LC ethanol to gain rapid adoption once it becomes cost competitive, it will need to compete as a *substitute* fuel (as does, for example, E85) and not merely as a mandated minor additive.[17] Adoption of E85, however, will require additional large, dedicated investments in infrastructure.[18] It is estimated that in the United States, for example, creating the infrastructure necessary to support the ethanol portion of the U.S. government's mandate that 36 billion gallons of biofuels be produced annually by 2022 will require incremental investments of $6 billion to $9 billion.[19] Although such infrastructure investments are large in total, they are relatively modest when amortized on a per-gallon basis. It is estimated that these investments would add approximately $0.01 to the per-gallon price of ethanol at the pump and that the E85-specific retail investments would add an additional $0.07 to $0.10 to the per-gallon price of E85.[20]

  Of course, there is a lack of clarity today regarding who would be motivated to make these investments and whether the investments will be wholly dependent on government funding and incentives. But clarity will emerge as the attractiveness of LC biofuels (their cost competitiveness and lower emissions, for example) becomes evident.

- *The Speed of the Transition to Flexible-Fuel Vehicles.* FFVs, designed to run primarily on ethanol or gasoline, are necessary enablers for increased adoption of ethanol, but outside of Brazil, they are a small part of today's global vehicle fleet. (FFVs represent only 6 percent of the U.S. fleet, for example.) The transition of the fleet to a larger proportion of FFVs could happen fairly quickly, however. U.S. automakers already produce more than 40 FFV models at an estimated incremental cost of only $100 to $150 per vehicle. Aftermarket conversions are available at a similar cost. Furthermore, Brazil's experience—FFV sales as a percentage of total light-duty-vehicle sales rose from roughly 15 percent in 2004 to approximately 85 percent in 2009—demonstrates that if the conditions are right, demand can climb quickly and production can ramp up quickly in response.

- *Advanced-Biofuel Conversion Capacity.* For advanced biofuels to become a material part of the fuels mix, a robust feedstock supply chain and considerable amount of commercial conversion capacity will be necessary. But today, there is virtually none. For instance, in the United States, there is an enormous gap between the

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[16] Although the blend wall can be as high as 20 percent ethanol, it is much lower in practice: automakers void engine warranties above the current EPA-sanctioned E10 limit. The EPA is considering raising this limit to E15 (15 percent ethanol and 85 percent gasoline).

[17] E85 is a blend that is 85 percent ethanol and 15 percent gasoline.

[18] Investments will be required in transportation, storage, and retail-station equipment, as well as flexible-fuel vehicles.

[19] Estimates developed for the mandated volumes for 2022 are based on *Infrastructure Requirements for an Expanded Fuel Ethanol Industry,* an original study of the Oak Ridge National Laboratory's Ethanol Project.

[20] Figures represent investments amortized from 10 to 20 years.

capacity necessary to reach the government's 2022 mandate calling for the production of 16 billion gallons of LC biofuels per year (a portion of the 36-billion-gallon total biofuel mandate) and the commitments in place to build that capacity: currently announced capacity plans would be sufficient for only about 2.2 billion gallons. (In February 2010, owing to a lack of production capacity, the U.S. mandates for use of LC ethanol in 2010 were sharply lowered from 100 million to just 6.5 million gallons, but the long-term mandate remains unchanged.) Similarly, there is strong regulatory support for advanced biofuels in the European Union, as well as an increasing emphasis on mandates specific to advanced biofuels based on sustainable feedstocks. But there is a shortage of feedstock and conversion capacity.

Battery costs must decline dramatically for EVs to gain mass-market adoption.

Using the U.S. mandates as an example, we estimate that total investments of $110 billion will be necessary to finance the necessary build-out.[21] However, exacerbated by the financial crisis, the disarray and bankruptcies that plagued first-generation biofuels have created wariness among investors toward significant capital commitments for advanced biofuels. But as the cost competitiveness of and investment case for advanced biofuels become clearer in the next few years, investments in LC biofuels capacity will rise.

Regulatory mandates in the United States, the European Union, and elsewhere are and will be catalysts to overcoming these barriers. If oil prices rise significantly or energy security and climate concerns command greater attention in the future—resulting in added incentives or a price on carbon emissions—the push to overcome these barriers will become more compelling and urgent. In short, the prospects for an accelerated substitution of conventional fuels by LC ethanol and other advanced biofuels over the next five to ten years are quite real.

Reaching Penetration Levels That Disrupt the Status Quo. It is common to hear claims that advanced biofuels will be viable only by 2020, at the earliest, and that they will achieve material growth only well after that. We disagree. We believe that their fundamental economic viability will likely be established over the next few years or certainly well before 2020. Then the pace of adoption will be influenced primarily by how quickly the infrastructure barriers described earlier can be overcome. As a cost-competitive and ultralow-carbon-emissions source of transportation fuel, advanced biofuels will be compelling alternatives to conventional fuels and will compete for a significant portion of the transportation fuel mix (as is the case today in Brazil).

By 2020, advanced biofuels will likely be on their way to being disruptive to the status quo of transportation fuels in markets worldwide. By 2025, they stand to be truly disruptive. A massive expansion would fundamentally reshape the global transportation-fuels market, much as sugarcane ethanol changed Brazil's fuels landscape.

Electric-Propulsion Vehicles: Steady Adoption

Several types of advanced electric-propulsion-vehicle technologies are in development today, including plug-in hybrids, range extenders, and pure EVs. If these plug-in solutions were combined with the use of low-carbon power generation to charge batteries, EVs could reduce carbon emissions in the transportation sector by approximately 90 percent.[22]

The past several years have seen a significant rise in the number of EVs planned for market introduction. Some, such as the Tesla Roadster, which costs more than $100,000, are high-priced niche products. A number of lower-priced alternatives are now entering the market.[23] However, an even broader set of vehicle options will be available worldwide over the next two years. The makers of these vehicles will attempt to surmount a major hurdle to breaking into the mass market: they aim to drive costs down dramatically.

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[21] A recent publication of the U.S. Department of Agriculture, *USDA Biofuels Strategic Production Report,* June 2010, provides another estimate. According to that report, meeting U.S. mandates for advanced biofuels will cost $168 billion (assuming a total of 527 biorefineries, each with an annual capacity of 40 million gallons).

[22] Assuming an electricity generation mix similar to that in France, CO_2 emissions of EVs would be approximately 90 percent lower than those of ICE vehicles powered by gasoline. In regions more heavily reliant on fossil-fuel power generation, the emissions reduction potential is much lower.

[23] Examples include the Nissan Leaf and the Chevrolet Volt.

Achieving Cost Competitiveness and Moving Past Subsidy-Driven Growth. To understand whether and when EVs can achieve cost competitiveness, The Boston Consulting Group has analyzed the evolution of the total cost of ownership (TCO) of both EVs and internal-combustion-engine (ICE) vehicles through 2020.[24] The analysis shows that, in the most attractive market segments and regions, an EV purchased in 2020 will achieve payback in as little as three years, even without subsidies—an attractive time frame for many customers.[25] However, barring major declines in battery costs, the payback for many other market segments will be eight to ten years or longer. Across all segments, EVs could constitute 5 to 10 percent of total vehicle sales by 2020.

It should be noted, however, that TCO comparisons are quite sensitive to the assumptions used for critical lifetime-operating-cost parameters—for example, average number of miles driven per year, oil prices, engine fuel efficiency, and EV battery costs. Using more aggressive assumptions for these parameters shortens the time to achieve EV breakeven and creates a more compelling value proposition for consumers. (See Exhibit 3.)

In summary, we expect EVs to move beyond subsidy-driven growth in certain lead market segments by 2020.

Overcoming Structural Challenges to Rapid Adoption Once Cost Competitive. Even as EV economics become attractive for certain customers, several other hurdles will need to be overcome before the vehicles can achieve a large share of the total car fleet. The lag time to deployment, public charging-station infrastructure, grid infrastructure, advantaged-disadvantaged cy-

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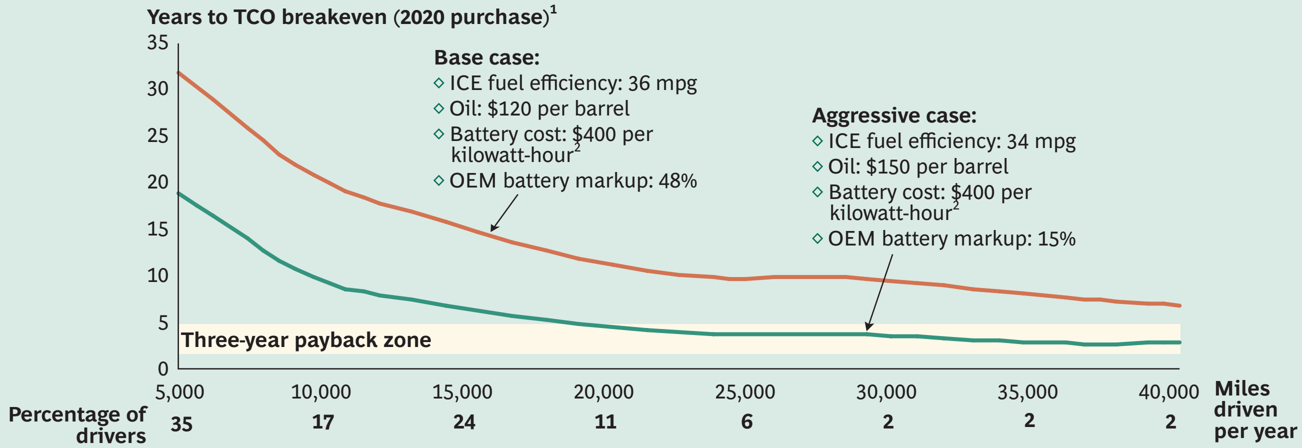
[24] See, for example, *Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020,* BCG Focus, January 2010, and *The Comeback of the Electric Car? How Real, How Soon, and What Must Happen Next,* BCG Focus, January 2009. Given the dramatic differences in types of costs associated with owning an EV (for example, electricity consumed in charging the battery) and owning a traditional ICE vehicle (for example, gasoline), the most appropriate yardstick for comparing costs is the TCO. The TCO captures both the up-front operating costs and the ongoing operating costs in order to determine which type of vehicle is cheaper to operate over the vehicle's full lifetime. BCG will revisit this topic in future reports as well.

[25] The most attractive market segments are those that combine smaller, lighter vehicles with a higher average number of miles driven. The most attractive regions (for example, Europe) are those with the highest fuel prices.

Exhibit 3. Under More Aggressive Assumptions, Electric Vehicles Become Attractive

A shorter time to achieve breakeven could significantly speed adoption



In an aggressive scenario, 20 percent of drivers of C-segment vehicles would realize payback in approximately three years

Source: BCG analysis.
Note: Breakeven figures for TCO do not include purchase incentives. All figures are for North America and North American C-segment (compact) vehicles.
[1] Reflects the net-purchase-price and operating-cost differences between an EV and an ICE vehicle, including taxes.
[2] Represents pack level cost to OEM.

cle, and raw-material constraints pose a few of the most critical hurdles.

Lag Time to Deployment. On the basis of a historical scrap rate of approximately 6 percent, we estimate that the U.S. vehicle fleet would require approximately 16 years to fully turn over. Thus, even if EV sales climbed from virtually 0 percent to 10 percent of all new-car sales from 2010 through 2020, only 3 percent of the total fleet would be electrified. Of course, were emerging markets to adopt EVs more aggressively, penetration levels would be higher, as their current installed base is much smaller. The Chinese government's recent bold announcements about subsidies and infrastructure investments to promote EV deployment signal, perhaps, the beginning of more rapid emerging-market adoption.

Public Charging-Station Infrastructure. EV adoption will need to be supported by robust deployment of public charging stations for customers away from their own charging stations and for those without access to private charging stations. An analysis of the standalone economics of public stations shows that achieving reasonable returns will require either the cost of power at these stations to be pegged significantly above average retail rates (which would have a negative impact on the TCO economics of EVs) or annual government subsidies on the order of $5 billion to $7 billion worldwide.[26]

Grid Infrastructure. EVs will pose a challenge for utilities, as supporting the demand for rapid recharging of large battery packs will require large-scale infrastructure investments. The Level 2 chargers currently on the market—which, depending on battery size, require around four to five hours to fully recharge a battery—will necessitate that utilities upgrade local transformers should consumer adoption be clustered, as is expected. Level 3 charging stations, which will aim to recharge batteries in 15 minutes, will be even more problematic. Recharging the Nissan Leaf's 24-kilowatt-hour battery pack, for example, would require a draw of approximately 96 kilowatts—many times the draw of an average home. The deployment of Level 3 charging stations in residential settings isn't expected soon, but preparing local grids to handle these massive demand fluctuations would require upgrades to local substations, switches, and other grid infrastructure. Furthermore, these rapid charges can cause batteries to heat up significantly, which may degrade battery performance over time.

Advantaged-Disadvantaged Cycle. As EV adoption grows, demand for gasoline will fall, exerting downward pressure on gasoline prices. This, in turn, will create less favorable TCO economics and—if economics are the dominant driver—will reduce incentives to switch from ICE vehicles to EVs without additional regulation.

Raw-Material Constraints. Constraints on raw materials—such as lithium used in lithium-ion batteries and rare-earth metals used as magnets in electric motors—are often cited as potential roadblocks to long-term EV deployment. For example, while ample lithium exists to supply the needs of EV batteries, the potential for rapid market growth could cause temporary supply disruptions. A recent analogy would be the short-term shortages in polysilicon that impacted solar PV manufacturers through 2007 and early 2008. During the shortage, manufacturers that hadn't contracted for a secure supply of polysilicon were forced to procure it on the open market at very high spot rates. Similar periods of rapid growth or temporary supply disruptions—a potential concern given that four countries account for 90 percent of global lithium reserves and China alone accounts for the vast majority of rare-earth metal production—could negatively impact both EV manufacturers and battery manufacturers.[27]

Reaching Penetration Levels That Disrupt the Status Quo. Disruptive penetration of EVs will require significant declines in battery costs or a significant increase in the cost to operate an ICE vehicle in order to create an economic tradeoff that is compelling to consumers. It will also require business model innovation and partnerships—for example, between local utilities that deploy the charging stations required to fuel the vehicles and the OEMs themselves. Finally, given the time required to turn over the vehicle fleet, reaching levels of significant penetration will require a very fast ramp-up in EV sales. Considering all of these factors together, we find that the prospects for disruptive penetration of EVs by the end of the decade remain low.

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[26] This figure represents the projected cost of subsidizing 75 percent of the up-front capital cost of charging stations deployed in 2020 in North America, Europe, Japan, and China.

[27] It is estimated that Argentina, Bolivia, Chile, and China account for more than 90 percent of global lithium reserves and more than 60 percent of the current lithium supply. China is estimated to account for 90 percent of total global production of rare-earth metals.

Power Generation

Many alternative-energy approaches are being considered for power generation—for example, developing diverse renewable sources ranging from wind to waves and reducing the carbon intensity of coal-fired power generation. We consider four alternative-energy technologies: concentrated solar power (CSP), solar photovoltaic (PV), onshore and offshore wind, and clean coal through carbon capture and sequestration (CCS).

Concentrated Solar Power: Accelerating Adoption

A well-known and often-cited fact is that solar energy is an abundant power source—the generation potential of global solar resources over land is more than 100 times the total global demand for electricity. CSP is an attractive means of harnessing that energy. Unlike other forms of intermittent renewable energy, such as distributed solar PV and wind, CSP can be paired with thermal storage relatively cost-effectively. Or it can be combined into a hybrid solar–natural gas configuration to overcome the challenge of intermittency. With enough thermal storage or hybridization, CSP has the potential to serve as an effective baseload power source and to address a much bigger portion of the total electricity market than other alternative-energy power-generation sources. Although still small in the context of global power-generation capacity, installed CSP capacity is expected to rise eightfold from 2009 (at approximately 1 gigawatt) through 2015 (to more than 8 gigawatts).

Achieving Cost Competitiveness and Moving Past Subsidy-Driven Growth. For CSP to reach its potential, its costs must fall significantly. Currently, CSP deployments rely heavily on cost subsidies, as CSP's levelized cost of energy (LCOE) is $0.20 or more per kilowatt-hour, depending on site conditions, compared with less than $0.10 for conventional generation.[28] But several CSP companies, using different variations of the technology, are projecting that relatively soon, costs will go down significantly. If these companies' large-scale demonstration projects support their claims, more cost-competitive CSP could well become a reality. Thus, it is possible that, in the space of a few years, CSP adoption will be determined more by its potential to overcome a host of practical barriers than by its cost.

Our analysis suggests that CSP's LCOE could fall to $0.11 to $0.16 per kilowatt-hour by 2015 and to less than $0.10 per kilowatt-hour by 2020.[29] These cost reductions are expected to result from the cumulative effects of progress on four fronts. (See Exhibit 4.)

- *Scale Effects.* As the various CSP technologies mature, larger projects will translate into improved economies of scale. While the exact scale economies of various newer CSP technologies will vary, our detailed analysis of the scale effects for parabolic-trough technology, CSP's historical installed base, is indicative: moving from 50-megawatt parabolic-trough plants to 200-mega-

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[28] LCOE is the total annual discounted capital and operating costs for the life of the project divided by the annual discounted energy production. LCOEs for fossil-fuel power generation currently range from approximately $0.06 to $0.08 per kilowatt-hour, depending on the underlying prices for fuels such as coal and natural gas and the specific generation technology, excluding any carbon price.

[29] Some companies expect to achieve even lower costs—sooner. If these companies deliver, our estimates—which represent a balanced consideration of all costs involved, as well as the fact that these systems are not yet fully deployed—could prove conservative.

watt ones reduces per-unit capital costs by approximately 15 percent.

- *Learning Curve Effects.* History has shown that CSP costs fall by approximately 15 percent for every doubling of deployed capacity as a result of experience effects.[30]

- *Plant Convoy Effects.* Executing multiple identical projects in the same area can drive a 5 to 15 percent reduction in capital costs. For example, a CSP developer would need a single set of permits and a single engineering design to serve multiple projects in a single area. The company might also be able to set up a single "works" area for on-site assembly.

- *Improvements in Technology.* Advances in technology are projected to drive a reduction of up to 20 percent in capital costs across various technologies. For example, the continued development of central-receiver technologies—which offer more efficient power generation because of higher potential temperatures, more efficient thermal storage, and lower site requirements—could lead to steeper cost-reduction trajectories compared with those of parabolic-trough technology.[31]

Furthermore, CSP companies are actively value-engineering their systems to drive down costs, examining the potential of options ranging from optimizing heliostat size for lowest-cost production and installation to creating nontoothed gear boxes for the tracking mechanism to reduce maintenance costs and breakage.

These companies are reinventing their supply chains, using more standardized components, and leveraging advanced tracking software as they seek relentlessly to drive down costs. Finally, advances in technologies such as molten-salt storage will contribute to improvements in overall plant efficiency and the lowering of CSP generation costs.

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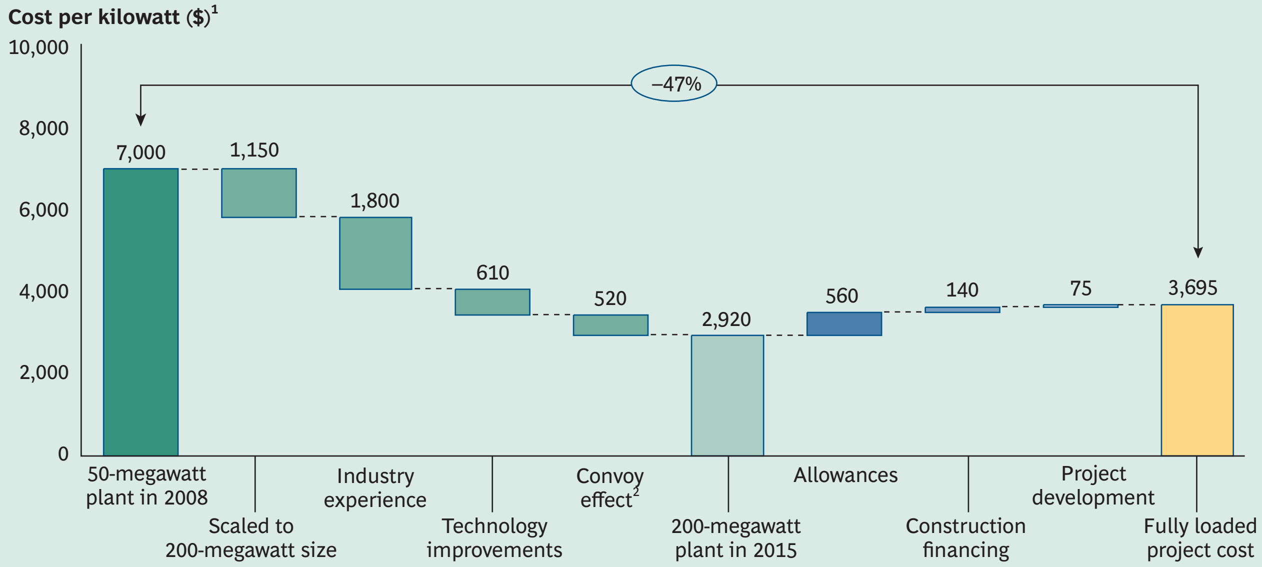
[30] National Renewable Energy Laboratory, *The Potential for Low Cost Concentrating Solar Power Systems,* 1999.

[31] Capital cost reductions for central-receiver technologies are projected to be as high as 20 percent.

Exhibit 4. The Cost of Concentrated Solar Power Could Fall Significantly, Driven Largely by Scale, Experience, and Newer Technologies

Newer technologies (for example, central-receiver designs that achieve higher temperatures) will help drive CSP's LCOE to $0.10 or less per kilowatt-hour by 2020



Sources: Industry expert interviews; National Renewable Energy Laboratory; BCG analysis.
Note: All estimates are based on plants with 7.5 hours of thermal storage; LCOE = levelized cost of energy.
[1] Data shown for parabolic-trough technologies.
[2] "Convoy effect" describes the impact of synergies across multiple projects executed at the same site (for example, facility sharing and one-time permitting requirements) and with the same technical specifications (for example, one-time engineering design).

Technology advances are inherently less predictable than scale, learning-curve, or plant convoy effects, which can be projected with some confidence on the basis of historical experience. Armed with that caveat, we conservatively estimate that pure-technology improvements will contribute to reducing CSP's 2020 LCOE by $0.01 to $0.02 per kilowatt-hour. Indeed many newer CSP entrants claim various specific technological improvements that, if validated at scale, will represent more substantial potential for cost reduction than we have assumed here.

Barriers to adoption will prove surmountable as CSP costs drop.

Overcoming Structural Challenges to Rapid Adoption Once Cost Competitive. Once CSP is a cost-competitive option, it will still have to overcome several barriers to achieve widespread deployment. The most critical are land and water requirements, transmission availability, permitting delays, and financing.

- *Land and Water Requirements.* A 100-megawatt CSP plant with storage requires approximately 3.8 to 4.7 square kilometers of land—roughly two to three times what is required for a nuclear plant—primarily to support its field of solar collectors, as well as approximately 1,000 gigaliters of water per year for cooling and mirror cleaning. However, the ideal conditions for CSP sites are often found in remote, arid, and previously undeveloped (or protected) areas. These conflicting requirements can strain local systems and generate resistance. The CSP industry is working to address these concerns by developing technologies that require smaller footprints, focusing site selection efforts on nonvirgin land, and using dry-cooling technologies to minimize water usage. Furthermore, many power-generation options face similar barriers, and several studies have concluded that CSP is the second-most attractive generation source (after wind) from an overall environmental perspective.[32]

- *Transmission Availability.* The lack of transmission capability from the most attractive CSP sites (for example, the deserts in the Southwest of the United States) to demand centers (for example, Los Angeles) is a major barrier to the deployment of the technology. For example, in California alone, approximately 8 gigawatts of planned CSP capacity (approximately eight times total worldwide deployed capacity) await connection to the grid.[33] In total, to reach the renewable-energy target put forth by the Obama administration in 2009, the United States is estimated to require approximately 11,000 miles of additional transmission capacity before 2020.[34]

- *Permitting Delays.* Permitting delays plague CSP development. This will remain a barrier to adoption unless governments worldwide intervene. It is encouraging that there are efforts under way to streamline the permitting process and designate development zones to facilitate faster rollout. California, for example, has commissioned several studies that have led to definitive recommendations on how to overcome regulatory barriers. India, as part of its National Solar Mission, is designating massive tracts of land as "solar parks," clearing regulatory and other barriers to development. Furthermore, the U.S. Bureau of Land Management has designated 700,000 acres of public land for solar plants, with environmental studies under way.

- *Financing.* More than 75 percent of the total lifetime cost of building and operating a CSP plant is incurred in the initial capital outlay. Large-scale plants are projected to cost upwards of $750 million, and securing financing has proved to be a barrier, particularly when the transmission and permitting issues have not been solved. In the short term, guaranteed loans from government agencies have aimed to bridge this gap. Unless project financing is available, large-scale adoption will not occur, and that, in turn, will slow down the cost decline trajectory.

The barriers are all quite real and problematic and are not easily overcome. However, as the cost of CSP falls and its benefits, compared with other generation options, become more compelling, the barriers could prove surmountable.

Reaching Penetration Levels That Disrupt the Status Quo. If CSP's structural barriers can be overcome and

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[32] Mark Z. Jacobson, "Review of Solutions to Global Warming, Air Pollution, and Energy Security," *Energy & Environmental Science*, 2009.

[33] Based on the California ISO Controlled Grid Generation Queue.

[34] This estimate includes the transmission capacity necessary to support all renewable-energy sources (for example, wind, solar, and geothermal).

the technology becomes cost competitive as expected, CSP could become a disruptive contributor to the power generation mix from 2020 through 2025. A CSP plant with 7.5 hours of thermal storage is already operating commercially; plants with storage of 12 to 17 hours are expected to be deployed over the next few years. The first hybrid CSP–natural gas plants are coming online now, and increasing numbers of these plants are expected to be deployed from 2015 through 2020.[35] Purely theoretically, CSP could meet more than 90 percent of U.S. electricity requirements, given the abundance of sunshine.[36] We are not suggesting that CSP will ever approach anywhere near this level, but we note it as a reminder of the technology's truly disruptive potential over the long term.

PV players continue to scale up operations and achieve ever-lower costs.

Solar Photovoltaic Power: Accelerating Adoption

Solar PV has grown rapidly over the past five years: annual installed capacity rose from 1.1 gigawatts in 2004 to more than 7.3 gigawatts in 2009, a 46 percent annual increase. Aggressive subsidies have been essential to this growth, as PV costs are otherwise prohibitive. PV's current LCOE is estimated at approximately $0.22 to $0.26 per kilowatt-hour under average conditions. Expectations of continued subsidies in many regions are fueling aggressive growth projections: it is expected that approximately 120 to 140 gigawatts of total capacity will be installed worldwide by 2015 compared with the roughly 20 gigawatts of total capacity installed as of 2009.[37]

PV has two major applications: individual or small groups of PV panels can be used for distributed solar generation, while larger groups of panels can be used to create utility-scale projects, often referred to as "solar farms."[38] Distributed PV makes up approximately two-thirds of the total installed base and is expected to continue to do so for the near term. The underlying economics of the two applications are not dramatically different, although solar farms can produce electricity a bit more cheaply. However, the barriers to adoption are different.

Achieving Cost Competitiveness and Moving Past Subsidy-Driven Growth. Even without radical technical breakthroughs, PV costs will decline to reach an LCOE of approximately $0.11 to $0.13 per kilowatt-hour by 2015.[39] We project that by 2020, PV LCOEs could approach $0.09 to $0.10 or less per kilowatt-hour, especially in sunny regions.[40] These cost reductions will be driven by four major levers:

◇ *Increases in PV Conversion Efficiency.*[41] Today, conversion efficiencies are between 19 and 20 percent for best-in-class commercially available crystalline silicon (c-Si) PV modules. We expect conversion efficiencies to increase to as much as 25 percent.

◇ *Increases in Production Scale and Experience Curve Effects.* PV players across the value chain continue to scale up operations and achieve ever-lower costs. For example, one industry leader plans to increase cell production by 250 percent from 2009 through 2012. BCG's experience suggests that per-unit PV costs can be reduced by up to 20 percent for each doubling of operational capacity.

◇ *Continued Migration of Operations to Low-Cost Countries.* PV players continue to improve the efficiency of their supply chains by capitalizing on low labor and energy costs in many low-cost countries. BCG's experience suggests that pursuing a low-cost-country strategy can reduce costs by 10 to 25 percent, depending on the step in the value chain.

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35. Florida Power & Light, a U.S. utility, recently opened a 75-megawatt CSP–natural gas hybrid project at its Indiantown facility.

36. David Mills and Rob Morgan, "Solar Thermal Power as the Plausible Basis of Grid Supply," Ausra Working Paper, 2008.

37. *Solar Storm: Navigating Through the Turbulence to Reap Value in Solar Energy,* BCG White Paper, October 2009.

38. Our definition of distributed solar generation includes off-grid, residential, and small commercial-scale projects.

39. This includes site development costs estimated to range between $0.30 and $0.60 per watt for utility-scale PV.

40. We have not explicitly differentiated here between crystalline silicon (c-Si) and thin-film (TF) PV costs. Although we believe that the cost of TF PV will have a slight advantage in the short term, the differences are well within the tolerance of our estimates. In addition, while several PV technologies—such as organic PV and dye-sensitized cells—have long-term "breakthrough" potential that could fundamentally change the rank order of technology attractiveness, these technologies do not yet exist at scale, and we do not expect deployment before 2020.

41. PV conversion efficiency refers to the ratio of the energy input to output of a PV module.

- *Gains in Operational and Process Efficiencies.* Refinements in technology and processes continue to drive industry cost reductions. For example, building an integrated polysilicon-and-wafer factory can yield energy savings of up to 20 percent. Further cost declines will be driven by reducing resource consumption in production processes—for example, using less silicon, glass, lamination, and back-sheet material per panel, and less electricity and other consumables, such as slurry and process chemicals.

Cost-effective storage is a critical enabler of widespread adoption of solar PV.

The combination of increased scale, continued migration of manufacturing to low-cost countries, and continued gains in operational and process efficiencies is already creating a hypercompetitive supply chain, making an advantaged cost position a critical success driver. In fact, the competitive intensity of the solar market has contributed to recent steep declines in PV prices as suppliers have competed for market share, increasing the cost attractiveness of PV relative to other solar technologies. Overall, we expect that, from 2012 through 2015, there will be a divergence of PV's competitiveness in various markets. PV could reach residential grid parity in lead markets with high current prices (for example, California and Spain) or in markets in which time-of-day pricing pays a premium for power delivered at peak times. (Solar production generally coincides with peak energy demand.) In markets with lower electricity prices (for example, China and India), PV will continue to require significant subsidies to be viable. We expect the picture to change by 2020, when with an LCOE of $0.10 to $0.11 or less per kilowatt-hour, PV will be much closer to grid parity in a wider range of markets.

Overcoming Structural Challenges to Rapid Adoption Once Cost Competitive. Once PV reaches cost competitiveness, utility-scale solar farms will face many of the same barriers that stand between CSP and scale-up and adoption: large land requirements, limited transmission availability, permitting delays, and difficulty securing financing—all of which we have already discussed at length. These barriers threaten to slow adoption of PV for utility-scale applications.

Distributed PV avoids many of these challenges, as it does not require large tracts of land, new transmission capacity, or multimillion-dollar capital outlays. However, for it to have a large cumulative impact, it does require action by millions of individual consumers and companies. Reports of communities with aesthetic reasons for pushing back on homeowners' plans to install rooftop solar panels are common, and individual home installations often require up-front capital of $15,000 or more.[42] These hurdles could slow the residential deployment of distributed PV.

Reaching Penetration Levels That Disrupt the Status Quo. Lacking cost-effective storage, solar PV produces power that must be used immediately, creating challenges to its large-scale incorporation into the mainstream power grid. Although the limit varies widely by region, major issues for grid operators arise when the total share of the mix represented by intermittent sources rises above 20 to 25 percent of the total "on-grid" energy mix.[43]

One example of this problem occurred in Texas in February 2008 with another intermittent energy source—wind. During a period of rapidly increasing electricity demand, wind generation output fell from 2,000 megawatts to 360 megawatts over the course of 3.5 hours (two hours sooner and faster than had been forecast). Lacking sufficient generation resources to fill the resulting gap, the Electric Reliability Council of Texas, the grid operator, implemented emergency demand-response measures, shutting down many industrial and commercial customers. Solar radiation can be predicted both days ahead and with higher certainty than wind, and the geographic distribution of PV panels can help smooth interruptions, but overcoming this ceiling will ultimately require pairing PV with cost-effective, large-scale storage technologies and—or alternatively—developing a more flexible grid system to enable better, more dynamic response.

Several potential storage solutions exist.[44] Batteries are arguably the most broadly applicable solution at present,

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[42] Solarbuzz, a solar-energy research and consulting firm, estimates that it would cost from $16,000 to $20,000 to satisfy around 25 percent of the energy needs of an average home in Sacramento, California.

[43] Denmark is already pushing this. With approximately 20 percent of its total electricity generated by wind since 2008, the country has not experienced significant disruption. This situation, according to Greenpeace International in its *Renewables 24/7* report (February 2010), is unique: Denmark benefits from a nearby abundant and flexible hydropower resource.

[44] See *Electricity Storage: Making Large-Scale Adoption of Wind and Solar Energies a Reality,* BCG White Paper, March 2010.

as the other solutions are viable only under specific conditions. Yet batteries are no panacea.

Although many battery technologies are currently being pursued, none of them appears capable of offering both high efficiency and low cost. (Ultimately, we expect that costs for storing solar-PV-generated power will add from $0.04 to $0.06 to the overall cost per kilowatt-hour in 2015; by 2020, we expect this cost to fall to $0.03 to $0.04.)

Efforts are also under way to enable a more flexible grid system comprising various upgrades that in aggregate are often referred to as a "smart grid." (See the sidebar below.) Although efforts to create a smart grid are advancing rapidly, we do not believe that advanced grid balancing, pricing, and demand-response mechanisms will be fully developed worldwide by 2020.

Despite these challenges, solar PV's explosive growth prospects and ability to claim up to 20 to 25 percent of the total generation mix (if no other intermittent source is present) make it a potential disrupter of the status quo.

Onshore Wind Power: Steady Adoption

Wind is an abundant power source: the global potential for wind electricity generation exceeds total global demand for electricity by a factor of five. Wind is also the most mature of the various alternative-energy sectors, with approximately 140 gigawatts of capacity installed worldwide as of 2009 and an additional 300 gigawatts projected to be installed by 2015. Onshore wind accounts for 99 percent of the total wind capacity deployed to date.

Smart Grid

A Key Enabler for Alternative Energy

A "smart grid" is a collection of equipment, infrastructure, and information technologies designed to optimize the production, transmission, and usage of electricity. Business cases for smart-grid deployment typically combine benefits in the areas of utility cost reduction, generation optimization, and intelligent demand-response management. From the perspective of alternative-energy deployment, it is apparent that two of the most important enabling capabilities of smart grids are improved ability to integrate distributed generation and the ability to implement demand-response programs to improve the management of intermittent generation sources. Both of these are crucial for expanded deployment of wind and solar PV technologies.

To date, deployment of even the basic building blocks of smart-grid technologies—such as advanced metering infrastructure (AMI), or "smart meters"—has been uneven. The U.S. Federal Energy Regulatory Commission's 2008 report showed that AMI adoption in the United States has reached approximately 16 percent for cooperative utilities but less than 5 percent for other utility players.[1] Meanwhile, AMI penetration of European markets is estimated to be approximately 15 percent in total, but Sweden reached 100 percent penetration in July 2009, the first country to do so.

These differences in adoption can be explained in part by examining the major barriers blocking rollout. We believe that the following four barriers are having the greatest impact:

- Questions about the attractiveness of the business case to stakeholders
- Regulatory hurdles
- Implementation challenges
- Concerns about customers' willingness to adopt and sufficiently utilize smart meters

Recouping large up-front smart-grid investments requires pulling multiple value levers simultaneously, and the business cases vary significantly in the extent of their benefits. Our experience shows that although smart-grid technologies can lower a utility's overall cost to serve, returns on individual projects are highly market specific. For example, utilities that have already achieved labor cost savings through prior installations of drive-by or one-way meters lack access to a significant portion of the potential cost savings that smart grids afford.

Regulatory barriers also hinder smart-grid deployment. These barriers range from rate recovery to data privacy

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[1] U.S. Federal Energy Regulatory Commission, *Assessment of Demand Response and Advanced Metering*, 2008.

Various forms of subsidies, including production tax credits in the United States and feed-in tariffs in Europe, have been instrumental in the development of the onshore wind industry. Increasingly, however, onshore wind deployment is being driven by its improving standalone economics compared with those of other renewable technologies.

Achieving Cost Competitiveness and Moving Past Subsidy-Driven Growth. Onshore wind generation costs have declined substantially over the years—today, prime wind sites can deliver an LCOE of $0.09 or $0.10 per kilowatt-hour.[45] Given the relative maturity of the technology, cost declines for onshore wind going forward will be incremental in nature and driven primarily by learning curve effects: we expect an approximately 15 percent reduction by 2015, which would drive onshore wind power's LCOE to $0.07 to $0.09 per kilowatt-hour for prime sites and roughly $0.10 per kilowatt-hour for less attractive sites. Onshore wind is well on its way to producing power at rates competitive with traditional energy sources and is rapidly moving beyond subsidy-driven growth.[46]

Overcoming Structural Challenges to Rapid Adoption Once Cost Competitive. Onshore wind is close to moving into a growth phase characterized by greater economic viability. Nevertheless, its adoption will be slowed by several barriers, including transmission limitations and permitting delays. In the United States at the end of 2009,

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[45] These figures are based on a 32 percent capacity factor (which is defined as the ratio of a site's actual productivity to its potential maximum).

[46] This estimate does not account for any additional "balancing" costs that are the result of wind adoption.

and security regulations, data management and usage guidelines, technical standards setting, and rules for the integration of distributed generation and microgrids.[2] Failure to overcome these hurdles threatens to greatly slow smart-grid adoption, and little evidence exists that regulatory bodies are already approaching these challenges with cohesive direction.

Implementation of smart-grid technologies is difficult and can cut deep into utilities' operations and organization. Seemingly simple matters—such as managing data—can be a challenge. BCG's analysis shows that implementing AMI can increase data management requirements by nearly 3,000 times those of traditional meters. Furthermore, complex back-end IT systems must be integrated with new software to ensure smooth operations of functions such as real-time pricing, billing, and customer service.

Concerns about customers' willingness to adopt smart meters and engage sufficiently to realize the meters' potential constitute a fourth barrier to deployment. While smart-grid pilot programs, such as the recent Pacific Northwest GridWise Demonstration Project, have shown positive customer responses at a high level, BCG's recent proprietary customer research points to a much more nuanced picture.[3] It is clear from BCG's research that although most customers are willing to listen to the case for smart meters, it will be a challenge to get customers to buy in and become engaged in the process. For example, 67 percent of the customers we polled believed that smart meters and smart-home tools would help them do a better job of managing their power usage. Simultaneously, 74 percent said that they were concerned about the privacy of their power-usage data, and 70 percent believed that utilities would raise rates as a result of smart-meter deployment.

But large-scale deployment of smart-grid technologies will eventually materialize. And when it does, it will create a powerful tool for lowering energy costs, advancing the deployment of renewable generation sources, and reducing total energy demand. Various industry observers have estimated that demand-side management techniques facilitated through smart-grid technologies could reduce total energy consumption by up to 25 percent, which would not only fully offset the expected growth in energy demand in developed markets but would also satisfy emissions reduction targets for many years. Furthermore, fully developed smart-grid technologies would allow the deployment of greater percentages of intermittent sources, such as wind and solar PV.

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[2] Rate recovery is the mechanism utilities use to recoup investments in generation and other assets. In the context of a smart grid, which promises to reduce overall energy consumption, rate recovery is a particularly thorny issue: utilities are asked to make investments in infrastructure that will serve to lower their overall revenues.

[3] "Capturing the Value of Smart Meters," BCG Working Paper, April 2010.

for example, there were onshore wind projects representing approximately 300 gigawatts of capacity—roughly 11 times existing wind capacity—that were idle because the companies had requested but not yet received permission for a connection to the grid.

Reaching Penetration Levels That Disrupt the Status Quo. There will still be common barriers to large-scale adoption of onshore wind—even if the technology becomes cost competitive. But we believe onshore wind will continue to see steady adoption and play an important role in the renewable and overall power-generation mix. Onshore wind has the potential to reach a ceiling penetration (assuming no storage) of 20 to 25 percent of total generation in some countries (assuming no other intermittent sources in the mix)—a degree of penetration that will still disrupt the status quo.

CCS is critical for the reduction of carbon emissions, but it faces many challenges.

Offshore Wind Power: Slow Adoption

Offshore wind is a different story: it is nascent. Its economics are challenging. Today, its LCOE is $0.15 or $0.16 per kilowatt-hour. Driving this is a host of factors, including higher maintenance costs due to the remote locations of the sites and higher capital costs.

We expect that for the most favorable locations, offshore wind's costs will drop to $0.12 or $0.13 per kilowatt-hour in 2020. However, its slow progress to cost competitiveness means that offshore wind will not likely exit the subsidy-driven phase by 2020.

Nevertheless, offshore wind's share of overall wind deployment will increase significantly in the years ahead. Offshore wind will be focused in regions and countries that are committed to aggressive alternative-energy targets, have limited other alternatives, and have the willingness and capacity to incur large subsidies to promote it.

A prominent example is the United Kingdom, which plans to deploy 13 to 20 gigawatts of offshore wind capacity by 2020.[47] Although this is certainly a meaningful level of deployment, the continued need for heavy subsidies and the limitations on scale of and scope for deployment prevent offshore wind from being classified as disruptive.

Clean Coal Through Carbon Capture and Sequestration: Very Slow Adoption

The relatively low cost of coal-fired power and the abundance of coal make coal the mainstay of power generation in many countries. And the world's installed base of long-life coal power plants will only rise—and likely rise dramatically—over the next decade, driven in particular by rapid growth in China, India, and other rapidly growing economies. This, however, will likely be accompanied by rising concerns over coal's carbon footprint: coal-fired generation is currently responsible for approximately 20 percent of the world's greenhouse-gas emissions. It is difficult to see how aggressive carbon-reduction targets can be met without dramatically reducing carbon emissions from coal plants.

CCS is considered one of the more promising approaches to meeting the challenge, especially for the large installed base of coal plants. CCS refers to the suite of technologies that make it possible to separate, collect, and store in perpetuity the CO_2 produced by coal-fired plants and other stationary sources. The collected CO_2 can be stored, for example, in depleted oil fields, in saline aquifers, or deep in the ocean. If CCS were to be successfully developed and deployed, it would be a game changer in terms of reducing carbon emissions from power generation. However, while the technology behind each component of CCS exists and is understood, many significant barriers stand in CCS's path to becoming a credible alternative over the next decade or two. These include large-scale feasibility, costs, and policy and public relations.

- *Large-Scale Feasibility.* It has yet to be demonstrated that large-scale CCS is viable. The sheer volumes of emissions (even from a single typical coal plant) are daunting, as are the challenges of integrating the transportation, storage, and monitoring of the captured CO_2. There have been attempts to launch "commercial" CCS plants, but these have failed as a result of flawed

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[47] All current offshore wind capacity is located in the European Union. Total deployment in the European Union by 2020 is estimated to be 40 to 55 gigawatts. See European Wind Energy Association, *Pure Power: Wind Energy Scenarios up to 2030,* 2008.

business cases: there simply is no viable business model to justify the up-front investments and uncertainties—technical, commercial, and legal.

It is clear that material government support will be required to achieve the immediate priority: actually building and operating a portfolio of large-scale integrated CCS demonstration projects. A number of governmental and intergovernmental initiatives are aiming to address this priority but are unlikely to achieve it until later in this decade. (Examples of such initiatives include Australia's Global Carbon Capture and Storage Institute and the CCS projects planned as part of the European Technology Platform for Zero Emission Fossil Fuel Power Plants program.) Unless these plants are actually built and operated, large-scale CCS will remain a theoretical possibility despite the fact that some of its component technologies are well known.

- *Costs.* CCS adds costs to and lowers the efficiency of coal-fired power plants, with total cost estimates varying depending on the assumptions used. BCG's detailed CCS cost model estimates that fully integrated CCS would cost roughly \$50 to \$60 per ton of CO_2 captured.[48] On the basis of detailed assumptions and analyses of scale and experience curve effects, we expect that CCS will require at least \$500 billion in combined subsidies and carbon price or tax offsets to support its development to 2030 and help it move down the learning curve.[49] This presents a significant funding challenge for governments, but if they are successful, we estimate that by 2030, CCS could be economically viable with a carbon price of \$40 per ton. Hence, CCS will not be economically viable on a standalone basis for a long time and will require subsidies and policy support well beyond 2020.

  Using some of the captured CO_2 for enhanced oil recovery (EOR) can certainly boost the technology's economics. In 2007, around 40 million tons of CO_2 were used for EOR worldwide, and this figure could grow to more than 500 million tons by 2030. However, these 500 million tons are equal to the emissions of fewer than 100 large coal-fired power plants.[50] This is a meaningful amount, to be sure, but it is only a small fraction of the 4 gigatons of carbon that we estimate could be captured under an aggressive adoption scenario.

- *Policy and Public Relations.* One of the critical enablers of CCS is a meaningful price on carbon emissions. As of this writing, the prospects for that do not seem to have advanced materially in many countries. But CCS faces other policy barriers as well, such as the lack of a suitable legal framework for addressing issues such as long-term liability for underground storage. Finally, there is emerging public resistance to CCS installations.

These barriers will also decrease the attractiveness of CCS relative to other low-carbon baseload power sources, such as nuclear or, later, CSP. Nuclear energy, for example, will likely generate roughly one-eighth the lifetime CO_2 emissions of CCS-equipped coal-driven energy.[51] Furthermore, the cost of nuclear energy is significantly lower.[52] Regardless, if reducing carbon emissions becomes a high priority globally, CCS is one of the few available solutions for reducing emissions at existing coal plants. However, overcoming CCS's challenges will clearly take a long time. We do not expect significant deployment until the late 2020s at the earliest.

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[48] *Carbon Capture and Storage: A Solution to the Problem of Carbon Emissions,* BCG Focus, June 2008. Although this may translate to an LCOE of \$0.10 to \$0.12 per kilowatt-hour, if large-scale CCS can be proved to be technically viable in the 2020s at the earliest, then alternative baseload technologies (such as CSP) may already have established themselves as lower-cost alternatives, relegating CCS to a role of retrofitting existing coal-fired plants as carbon prices are introduced.

[49] Our earlier estimate, calculated in anticipation of a carbon price of at least \$25 per ton starting in 2010, was for the subsidy portion to be \$100 billion. Given the poor outlook for carbon prices, however, most of the \$500 billion will likely need to come from subsidies.

[50] This estimate assumes a 1,000-megawatt coal-fired plant that produces 6,000 gigawatt-hours of electricity per year and the capture of CO_2 at a rate of 1,010 tons per gigawatt-hour.

[51] Paul J. Meier, "Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis," Fusion Technology Institute, University of Wisconsin, August 2002.

[52] Nuclear energy's LCOE is estimated at \$0.084 per kilowatt-hour versus approximately \$0.12 per kilowatt-hour for CCS-equipped coal (for the first at-scale plants). See Massachusetts Institute of Technology, *The Future of Nuclear Power Study,* the 2009 update to a 2003 report.

Implications for Stakeholders

As noted, several alternative-energy technologies are poised to make their presence felt in the global energy landscape in the coming decade. Yet as we have discussed, even promising alternative-energy industries face barriers and uncertainties. Large infrastructure investments—in, for instance, new capacity and transmission—will certainly be required. However, when adoption becomes constrained more by matters such as the availability of capital to build infrastructure than by the technologies' economic viability or technical feasibility, things can change fast. Even in the relatively slow-moving energy space, there are cautionary examples of how quickly fundamental assumptions can be overturned. It took about a decade for France to expand its nuclear generation from 25 percent to 75 percent of its electricity-generation portfolio. Until just a few years ago, North America was expected to be short of natural gas, yet within the span of a few years, technical advances in drilling for shale gas have created a new reality of plentiful natural gas. In Brazil, FFVs' share of total light-duty-vehicle sales climbed roughly 70 percent in little more than five years.

Simply put, there are many risks and uncertainties, but there are also opportunities. So what might the acceleration of some alternative-energy sectors mean for different stakeholders?

Oil and Gas Sector Incumbents

Accelerated adoption of advanced biofuels over the next five to ten years, even if just to meet existing mandates, will increasingly lead to the substitution of conventional fuels. This will add to the severe strain that fuel markets are already under because of demand declines that result from gains in engine fuel efficiency and other factors. Future cyclical upswings in demand for conventional fuels will be dampened or offset in markets where biofuels are viable alternatives. As the cost of advanced biofuels falls, there will be further substitution pressure on hydrocarbon fuels; this will be exacerbated if carbon legislation becomes a reality. The growth of EVs will exert more modest pressure on conventional fuels, but even modest EV substitution will have seriously adverse impacts on the economics of oil refining when combined with the effects of biofuels' substitution and efficiency gains.

On a global level, oil demand will be robust for the foreseeable future as a result of the enormous energy needs of China, India, and other emerging economies. However, there will be large regional differences. In high-growth developing markets, alternative energy will simply help fill overall energy demand alongside conventional sources. But in many developed markets where growth in the overall demand for oil will be modest or even anemic, the emergence of alternative energy will put enormous substitution pressures on conventional fuels. In these markets, conventional oil-refining and marketing businesses will face increasingly serious challenges. Although some players have made modest efforts at transforming themselves into full-spectrum "fuels companies," the urgency for this will rise in the coming years. Key questions these players should ask include the following:

- Are we in reactive mode, responding defensively and narrowly to near-term developments—or, worse, simply ignoring the alternative-energy space?
- If we are being reactive, are we just waiting for alternative-energy sectors to develop further before we act?

- Is our stance grounded in careful analysis and understanding of cost trajectories? Does it consider scale, experience, and other effects? Or are we hiding behind the notion that advanced biofuels, electric propulsion, and other alternative-energy technologies are experiments whose effects can be safely ignored for another decade?

- Are robust overall energy-demand projections keeping us complacent? Are we ignoring the fact that disproportionate growth rates in developing markets are masking slow growth in other regions?

Much of the innovation in alternative energy is being driven by start-ups or smaller companies.

- Do we have a cohesive defensive plan (for instance, against the potential entry of large, well-capitalized non-oil players into the advanced biofuels space)?

- Do we have a proactive plan to participate in and profit from the creation of new value from vast new alternative-fuels businesses? Are we making moves to secure access to critical elements of the value chain, such as upstream feedstocks for advanced biofuels?

Power Sector Incumbents

Direct cannibalization will be more of an issue for oil and gas companies than for incumbent utilities and power producers, as cost-competitive renewable power simply gets added as yet another generation source in these incumbents' portfolios. For instance, many utilities were quick to acquire or otherwise gain access to wind assets and integrate them into their asset portfolio. Utilities will likely respond similarly when CSP and solar PV become more relevant or mandated.

The larger issue for utilities will be the major portfolio, operational, organizational, and other challenges that will arise as renewable power and smart grids evolve from being just a sideshow to being a material part of the power landscape. Questions players should ask themselves include the following:

- Do we have a clear understanding of the cost and development trajectories for alternative energy—one that factors in technology development, experience curve, and scale effects? Do our plans adequately take this understanding into account?

- Is our alternative-energy strategy purely reactive or defensive, or does it also look at new growth opportunities that might arise through more aggressive participation in the shaping of alternative energy's development?

- Is our portfolio of alternative-energy activities and investments optimal given the likely costs and development trajectories of various alternative-energy sectors? If not, how should it be optimized?

- How can we mitigate the problem of stranded conventional-generation assets in a world with ever-greater renewable-generation capacities?

- Have our business models adequately considered and addressed the realities of a world in which distributed generation is more prevalent and consumers are also producers?

Emerging Alternative-Energy Pure-Play Companies

Much of the innovation in alternative energy is being driven by technology-centric start-ups or small to midsize companies. These companies—and their backers—are sometimes prone to believing that they will be the new energy giants of the future, displacing incumbents. This is simplistic thinking: the energy sector is vast, capital intensive, and complex, with significant challenges in translating technology promise into large-scale deployment. Questions players should ask themselves include the following:

- How can we work effectively with incumbents?

- What should our participation strategy be in parts of the value chain beyond technology?

- What skills and capabilities do we need to build to support that strategy?

- How can our enterprises become efficient, productive, and competitive?

- How can we contribute to addressing and overcoming barriers to deployment?
- What are realistic aspirations for our technology?

Industrial Suppliers

Opportunities from the increased prevalence of alternative energy will represent a major growth vector for a wide array of suppliers, ranging from component suppliers that apply their high-volume manufacturing expertise to drive down costs to IT companies that help migrate utilities' legacy computer systems to handle the vast quantities of data from smart meters. The investments required to support the rise of alternative energy are likely to create tremendous opportunities for industrial conglomerates that focus on infrastructure development. The key challenges will be to identify the most promising technologies, markets, and segments of the value chain on which to focus effort and resources.

Governments

So far, governments have focused on the policy enablers and subsidies that have catalyzed the growth of various alternative-energy technologies. However, alternative energy's future will be equally, if not more, dependent on the removal of roadblocks to its adoption. Many of these roadblocks relate to infrastructure and policy. Key questions that governments will have to answer include the following:

- How can we appropriately sequence and time regulatory support to most effectively drive each technology to become cost competitive without subsidies?
- When developing regulations, how can we balance the often-differing interests of alternative- and conventional-energy producers?
- How can we help the private sector overcome specific deployment challenges—including transmission and siting—through effective policies and incentives?
- How can we effectively pinpoint these policies and incentives?
- How can we speed approval processes for infrastructure projects?
- How can we leverage the growth of alternative energy to drive economic and job growth?
- As alternative-energy capacity grows, how can we design incentive structures for the necessary conventional backup capacity?
- How can we design trade policies, similar to those in place for oil and gas, that are harmonized to facilitate easier global matching of advanced biofuels supply and demand?

Alternative energy will profoundly impact the energy landscape. The future is closer than commonly assumed, and companies must actively revisit their alternative-energy strategies. Should you play defense, offense, or both? The answer depends on a host of variables unique to your situation. But dismissing alternative energy's prospects because of, for example, the current uncertainties of climate legislation is unwise and potentially costly.

For Further Reading

The Boston Consulting Group has published other reports and articles on alternative energy that may be of interest to senior executives. Recent examples include:

East Wind: Prospects for Equipment Manufacturers in China's Burgeoning Wind-Power Sector
BCG White Paper, August 2010

Electricity Storage: Making Large-Scale Adoption of Wind and Solar Energies a Reality
BCG White Paper, March 2010

Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020
A Focus by The Boston Consulting Group, January 2010

Solar Storm: Navigating Through the Turbulence to Reap Value in Solar Energy
BCG White Paper, October 2009

The Comeback of the Electric Car? How Real, How Soon, and What Must Happen Next
A Focus by The Boston Consulting Group, January 2009

Note to the Reader

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