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How to decarbonize global power systems

Decarbonization is becoming a higher priority. Here is how it can be done—and how much it might cost.

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The power sector is undergoing a global transformation. Over the past decade, the costs of renewables have dropped substantially—solar power by as much as 80 percent and wind power by about 40 percent—making them economically competitive with conventional fuels, such as coal and natural gas, in the vast majority of global markets. As a result, renewables are growing fast: they accounted for the majority of new power-generation capacity in 2018. In most markets, they are now the least expensive option to add marginal capacity. In addition, renewables make up an essential element of any country's plan to cut greenhouse-gas (GHG) emissions.

It is not possible to control when the sun shines or the wind blows, however. Therefore, 24/7 matching of the supply of wind and solar power to demand cannot occur the way that baseload-generating plants fueled by coal, natural gas, or nuclear power can. That creates a conundrum. Utilities, municipalities, states, and nations want low-cost, reliable electricity. Many have also set goals to decarbonize[1] their power systems. How can they do both?

Flexibility—the ability to manage the intermittency of nondispatchable power, such as wind and solar power—is crucial to integrating significant levels of clean power. There are different ways to ensure the real-time matching of supply and demand.[2] For example, gas and coal plants can adjust production up or down to smooth out fluctuations in the output of wind and solar power. Transmission lines can balance production across geographies. Well-designed incentives can encourage users to modify their consumption via demand-side management programs. Battery storage can act on the power system as both a generator when discharging and a consumption point (or "load") when charging. These approaches all exist and have been well documented. Even so, few utilities or governments have yet compiled a detailed, quantitative pathway to decarbonizing the power sector substantially.

No two markets are identical. Even so, some principles apply widely, depending on the desired level of decarbonization. And in every decarbonization scenario, managing the intermittency of wind and solar power will be crucial. In this article, we describe, in general terms, how integrated power systems—across bulk-generation, transmission-and-distribution, and direct-customer offerings—can achieve up to 100 percent decarbonization by 2040[3] and the approximate costs.[4] Then we consider possible pathways in four types of markets.[5] Finally, we suggest how technological breakthroughs could affect these pathways.

On the basis of our research, we conclude that getting to 50 to 60 percent decarbonization is not that difficult technically and is often the most economic option. Getting from there to 90 percent decarbonization is generally technically feasible but sometimes costs more. And getting to 100 percent is likely to be difficult, both technically and economically.

Reaching 50 to 60 percent decarbonization of the power system by 2040

In most markets, reaching 50 to 60 percent decarbonization can be done with little or no investment beyond that determined by purely rational economic behavior. The costs of solar and

[1] We measure decarbonization as the reduction (in percent) in greenhouse-gas (GHG) emissions for a given power system. Therefore, 80 percent decarbonization means 80 percent fewer GHG emissions in 2040 than in 2020; in 100 percent decarbonization, the power sector has zero emissions.

[2] Evan Polymeneas, Humayun Tai, and Amy Wagner, "Less carbon means more flexibility: Recognizing the rise of new resources in the electricity mix," October 2018, McKinsey.com.

[3] The model includes the bulk-electricity-generation, distributed-electricity-generation, electric-transmission, and electric-distribution systems (down to the feeder level). It also includes necessary interlinkages, including ties to the natural-gas network for power-to-gas-to-power technologies and adoption of electric vehicles and other behind-the-meter devices to provide flexible load, insofar as they provide support for decarbonizing the power sector. Finally, the model makes optimization trade-offs across the network, such as comparing the costs of a new-build transmission line, a distributed battery-storage system, and the operation of an existing bulk-power asset. This analysis does not explore decarbonization outside of the power sector. For example, it does not include decarbonizing the transportation or agriculture sectors.

[4] We focus on decarbonization because the goal of most renewables-focused policies is to reduce greenhouse-gas emissions, and most markets will require expanding the use of intermittent generation sources, such as solar and wind power, to do so.

[5] Both the principles for achieving full decarbonization and the pathways for the four markets are modeled at the system level and, as such, are general pathways. Some dynamics (such as voltage and frequency regulation and ensuring that there are sufficient local capacity reserves) must be managed based on a specific market's characteristics and at a more localized level (such as a settlement point or specific zone within a market).

Wind and solar power tend to be complementary, with wind blowing more strongly at night and in the winter, when solar energy is weaker.

wind power and storage—three important elements in all deep-decarbonization scenarios—have fallen so far and so fast that decarbonizing is often the lowest-cost option.

The daily cycle of the sun fits well with midrange (four- to eight-hour) storage. The energy stored during the day can be released at night, ensuring a steady supply of power—thus, "solar-plus storage" (the same cannot be said of "wind-plus storage," because wind is not as predictable). In fact, wind and solar power tend to be complementary, with wind blowing more strongly at night and in the winter, when solar energy is weaker. Markets that have both solar and wind resources are therefore better positioned to manage intermittency.

Achieving this level of decarbonization generally would not materially affect the performance of the power system. Almost all the power created would be used; we estimate curtailment[6] of 2 to 5 percent. The utilization level—meaning the percentage of time a plant produces power—of individual fossil-fuel plants would also not be significantly affected, staying at 50 to 60 percent. Some of these assets would be retired, though, displaced as cheaper renewables come on line. Little to no new transmission would be needed. In short, the power system would not need to change much to get to 50 to 60 percent decarbonization.

Reaching 80 to 90 percent decarbonization of the power system by 2040

Getting to 80 to 90 percent decarbonization will generally be more expensive, more complicated,[7] and require more market-specific actions. Although no new technologies are required, storage would have to be used for longer periods, and demand might need to be managed more tightly, including through active management of building heating and cooling and industrial-load shifting. Some markets may need new transmission interconnections to pool renewable assets and to share baseload resources across a larger geographic area.

At this level of decarbonization, the system would look noticeably different from how it looks now. We estimate curtailment of 7 to 10 percent because there is so much renewable power being produced to meet demand during lower-production periods. As renewables become more prominent, fossil-fuel plants are utilized less (20 to 35 percent), but many are kept available as backup to cover periods when renewables cannot meet demand.

At the 80 to 90 percent level, the costs of decarbonization vary widely. In markets with above-average costs of power, there might be a modest decline (1 to 2 percent a year) in total system costs. Other, lower-cost markets might see increases.

Reaching 100 percent decarbonization of the power system by 2040

The path to 100 percent decarbonization gets even more complex, and the lowest-cost options will vary, depending on the market. Most geographies will need to rely on newer technologies to match supply and demand when wind- and solar-power production are depressed. While reaching this level is technically feasible, it could cost up to 25 percent more than the lowest-cost option.[8] The path to

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[6] Curtailment, defined as the purposeful reduction in the output to the grid of a generator from what it could otherwise produce, is a concept that is particularly applicable to renewables because they cannot be controlled like thermal plants.
[7] Except in markets with high levels of clean baseload generation—chiefly, hydroelectric or nuclear power.
[8] Based on the average marginal cost of power in a power system with a carbon-reduction goal versus optimizing for lowest total system cost.

complete decarbonization of the power sector is fundamentally about filling longer-duration gaps. Accordingly, the cost to decarbonize the last 10 percent of a power system could be significant.

Here are some existing technologies that could help markets close the gap and build a 100 percent decarbonized power system:

— *Biofuels.* Biofuels, such as landfill gas and biomethane, are net-zero-carbon renewables. But they are expensive, and their supply is limited, so they can only serve as part of the solution, in most cases.

— *Carbon capture, use, and storage (CCUS).* CCUS refers to capturing the GHG emissions produced by burning fossil fuels and then either using the CO_2 for other processes, such as enhanced oil recovery, or storing it somewhere safe, such as in deep-rock formations. CCUS has been proven to work but is expensive. Reducing its cost will require finding and making technological improvements and achieving scale efficiencies. Moreover, CCUS cannot capture every carbon molecule, so other technologies will still be needed to get to 100 percent decarbonization. CCUS will likely work best in highly interconnected markets, where space for renewables is at a premium, clean power has value across a larger geography, and CCUS plants can be run at or near full utilization.

— *Bioenergy carbon capture and storage (BECCS).* BECCS is a technology in which carbon-neutral biomass, such as wood pellets and agricultural waste, is burned for fuel, with capture or storage of the resulting CO_2 emissions. The net result is negative emissions—meaning that the GHGs are removed from the atmosphere. It is not clear to what extent biomass can be scaled up, and the technology itself is relatively new. One advantage is that retired coal plants can be converted into BECCS plants, lowering capital costs and taking advantage of existing interconnections.

— *Power to gas to power (P2G2P).* P2G2P technology involves using excess electricity to produce hydrogen that can be stored in the gas network and later converted into power again. The "clean gas" created through P2G2P technology enables storage of extremely long duration—weeks or even months. But it is also expensive and inefficient. Ten megawatt-hours of generated power in the beginning makes about three megawatt-hours of usable power by the time it is reconverted back to electricity for consumption. If there is demand for clean gas outside the power sector, however, the flexibility provided by P2G2P technology could go a long way toward integrating intermittent renewables.

— *Direct air capture (DAC).* DAC separates CO_2 from the air. It is another negative-emission technology that could be used to eliminate the last few percentage points of carbon-intensive power. The technology has been demonstrated but tremendous amounts of energy are needed to capture, separate, and then sequester the CO_2. And doing so is very expensive. Therefore, our findings generally suggest it is not part of the solution for 100 percent decarbonization.

Compared with the scenario for 80 to 90 percent decarbonization, fossil-fuel-plant utilization would need to fall sharply (down to 4 to 6 percent) to decarbonize the power sector entirely. Each market would also need to net its carbon emissions, likely via biofuels, P2G2P technology, or by finding additional offsets. Curtailment would be about the same.

Decarbonization pathways in four types of power markets

Given differences in climate, natural resources, and infrastructure, different markets will need to take different pathways to decarbonize their power systems (exhibit). We have analyzed four types of markets. We selected these markets because they capture most of the globally relevant salient features, including transmission potential, quality of clean resources (both intermittent solar and wind energy and dispatchable hydro and nuclear energy), the starting point of a market's carbon intensity, and the potential for the distributed network to provide flexibility.

'Islanded' markets

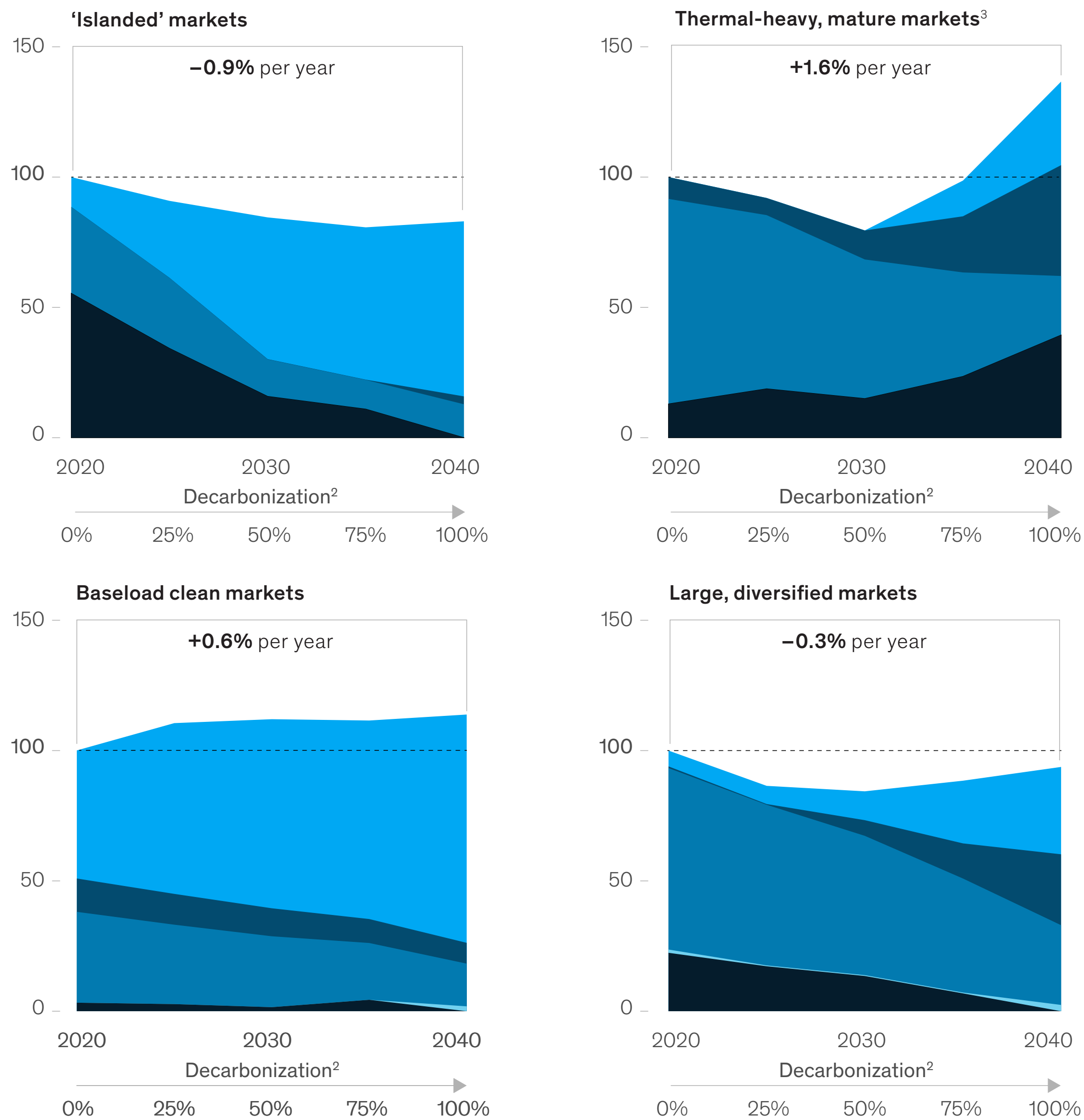
"Islanded" markets, as the name implies, refer to islands, such as Hawaii, as well as to places that

Exhibit

The pathway and cost of decarbonization will vary, depending on the market.

Total cost of power, by technology type, indexed, real (2020 = 100)

- **Intermittent capacity:** wind, solar, run-of-river hydro
- **Clean dispatchable capacity:** reservoir hydro, nuclear, CCUS,[1] battery, pumped hydro storage
- **Fossil-fuel capacity:** coal, natural gas, oil
- **Clean fuel:** biogas, biomass, uranium
- **Fossil fuel:** coal, natural gas, oil



[1] Carbon capture, use, and storage.
[2] Net total power-sector CO_2-emission reduction relative to starting point.
[3] To achieve 100% decarbonization, fossil fuels continue to play a role via operation of gas plants outfitted with carbon capture, use, and storage (CCUS). The balance of uncaptured emissions from CCUS (~10%) are abated through bioenergy carbon capture and storage and direct air capture.

Source: McKinsey analysis

are unusually remote or isolated. These markets are expensive because they usually must import fuel and lack interconnections. But many islanded markets also get a lot of sun. Because of the falling costs of solar power and the high prices of conventional fuels, most islanded markets do not need incentives or targets to decarbonize. In fact, we estimate that they can get up to 82 percent decarbonization just by transitioning to the lowest-cost power mix available.

Pathway to 90 percent. Ninety percent decarbonization can be attained in islanded markets mostly through a combination of solar-plus storage and wind. Relying so much on intermittent sources, however, would lead to a fairly high level of curtailment (10 percent) and to underutilized fossil plants (9 percent), which would function mostly as stopgaps when renewable generation falls short. Given the relative prices of wind, solar, and fuel imports, this pathway likely represents a substantial decline in costs over the period to 2040.

Pathway from 90 to 100 percent. Unlocking the final 10 percent of decarbonization in islanded markets requires finding carbon-free, dispatchable generation to manage periods of low sun or wind. We believe the best solution for this market archetype is P2G2P. Despite a high marginal cost, P2G2P technology is the cost-effective option for providing dispatchable generation in instances when it is infrequently required. Because the technology can use excess solar or wind power to generate clean fuel, curtailment could drop to 6 percent and power-plant utilization to 4 percent. We estimate that moving from 90 percent to 100 percent decarbonization would increase total system costs 3 to 5 percent by 2040.

Thermal-heavy, mature markets

Thermal-heavy, mature markets typically have large populations, good interconnections, and significant fossil-fuel assets. Their power systems are reliable and accustomed to managing significant load. Germany and the PJM Interconnection, the largest regional transmission organization in the United States,[9] are two examples of such markets.

Pathway to 90 percent. Reaching the level of 90 percent decarbonization can likely occur in thermal-heavy, mature markets by building more wind capacity, complemented by significant storage. Curtailment rates should be low (1 percent), while thermal utilization of the remaining plants will likely fall to 20 to 25 percent. The downside, however, is the cost of the transition. Because these markets have substantial existing thermal infrastructure, unwinding the asset base means they are also likely to incur the highest cost of decarbonization of the four market types.

Pathway from 90 to 100 percent. Reaching the level of 100 percent decarbonization in heavy-thermal, mature markets probably means investing in CCUS,[10] which is an effective technology when it can run continuously, or nearly so. But the associated capital costs are high. In markets with insufficient physical space to support enough renewable power, CCUS technology may be able to provide a large fraction of baseload power needs. In this approach, thermal-plant utilization would hold steady, around 48 percent, and curtailment would be negligible. But because CCUS plants are so expensive to build, moving from 90 percent to 100 percent decarbonization could increase total system costs 12 to 16 percent by 2040.

Baseload clean markets

Baseload clean markets are those that already have significant zero-carbon baseload power—such as France, with its vast nuclear assets, and Brazil and the Nordic region, with their hydroelectric resources. This gives them a structural advantage. Given their foundation of dispatchable, clean power, they can choose additional generation from lower-cost resources. As a result, these markets are likely to be able to pursue significant decarbonization at little or no cost.

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9 The PJM Interconnection serves all or part of Delaware; Illinois; Indiana; Kentucky; Maryland; Michigan; New Jersey; North Carolina; Ohio; Pennsylvania; Tennessee; Virginia; Washington, DC; and West Virginia.

10 The CO_2 capture rate from CCUS gas plants is assumed to be 90 percent; full decarbonization is achieved in this archetype by blending a fraction of carbon-neutral fuel, such as biomethane, with natural gas as the input to CCUS plants.

Pathway to 90 percent. Given the availability of clean, dispatchable power, progress toward decarbonization should be relatively inexpensive in baseload clean markets. This archetype builds the most cost-effective source of decarbonized generation—in this case, wind—to reach 90 percent decarbonization. Because of the system's inherent flexibility, curtailment would be only about 1 percent, and thermal utilization would be 12 percent. The cost of power would rise less than 1 percent over the period to 2040 as wind power replaces some existing thermal capacity.

Pathway from 90 to 100 percent. Unlocking the final 10 percent of decarbonization can be done in baseload clean markets by investing in negative-emission technologies as offsets[11] to a small amount of peaking gas capacity that is dispatched when wind production is low and baseload resources are not enough to supply peak demand. DAC is likely to be the lowest-cost option because it is most effective in markets where it is needed only rarely. Curtailment would remain at around 1 percent, while thermal utilization would fall to 3 percent. We estimate that moving from 90 percent to 100 percent decarbonization would increase total system costs 10 to 12 percent by 2040.

Large, diversified markets

"Large, diversified markets" refers to places like California, Mexico, and parts of eastern Australia. Such large markets cover extensive territory and have good potential for renewables—typically, a mix of wind, solar, and, sometimes, run-of-river hydroelectric power. On the other hand, these markets often do not have much clean baseload power.

Pathway to 90 percent. The key technology for 90 percent decarbonization in large, diversified markets is likely to be solar-plus storage, complemented by gas power to help manage intermittency. Thermal utilization would fall to 13 percent, and curtailment would be 14 percent. Our modeling suggests that many of these markets could achieve 90 percent decarbonization by 2040 at a net decline in total system costs, as the costs of solar and storage continue to fall.

Pathway from 90 to 100 percent. Achieving 100 percent decarbonization in large, diversified markets will require overbuilding solar-plus storage, a technology that becomes increasingly inefficient as more power is lost through storage cycling and curtailment. Even when there are high-quality solar resources, the need for consistent day-to-day production challenges the system during occasional low-production periods. P2G2P technology could be the best option for replacing fossil fuels in this type of market. Although it is expensive, it works well when peaking capacity is not needed often. Thermal utilization would fall to 6 percent to cover multiday periods with below-expected solar production; curtailment would increase to 16 percent. We estimate that moving from 90 percent to 100 percent decarbonization would increase total system costs 10 to 12 percent by 2040.

What could change the pathways?

Power-system operators need to think decades ahead. That is never an easy task, and it is even more difficult now, given the fast pace of technological advances and business-model innovations. The pathways we have described, then, are not meant to be narrowly prescriptive. Adaptability and a willingness to change direction will be important in achieving high decarbonization at the lowest possible cost.

If high-cost resources, including those that play little or no role in our scenarios, come into the money and are scaled up, that could change these pathways. In some cases, a cost reduction that puts a higher-cost technology in play could also displace traditional sources of generation. Here is our analysis of how some of these technologies could affect the costs and operations of power systems that seek to achieve full decarbonization by 2040:

[11] An offset is a source of negative emissions that allows the remainder of the system to produce some amount of emissions. The result is that the total emissions of the system are zero when summing positive and negative sources.

— *Nuclear.* If new nuclear plants could be built 20 to 40 percent less expensively, that could translate into 20 percent lower total system costs. At that price, nuclear power could supplant investment in both thermal and renewable sources of generation. We see a clear tipping point at a new-build capital cost of $4,000 to $5,000 per kilowatt compared with $6,000 to $7,000 per kilowatt today.[12] At that price, nuclear power begins to outcompete the combination of storage and renewables otherwise needed to reach 100 percent decarbonization.

— *Transmission.* Improved siting, land acquisition, and permitting processes could cut the cost of siting interregional transmission by as much as 40 percent. That could translate into 5 percent lower total system costs.

— *P2G2P.* Improving round-trip efficiency—meaning how much energy is generated up front compared with how much is available for consumption after the conversion cycles—is the most important factor with P2G2P technology. If this improved to 60 percent, from today's average of 30 percent, system costs could fall 5 percent.

— *Electric vehicles (EVs).* Envision a market in which vehicle-to-grid-enabled EVs account for a third of light-duty vehicles on the road. This level of penetration would displace a meaningful fraction of the stationary battery storage that would otherwise be built. Perhaps surprisingly, though, total system costs would only decline about 5 percent because displacing battery storage does not do much to solve the puzzle of achieving the transition from 90 percent to 100 percent decarbonization. The solutions required to reach full decarbonization are of a longer duration in nature than EVs can provide. While EVs are beneficial in overnight balancing, they generally fail to address multiday reliability resources.

— *CCUS.* The potential of CCUS is considerable because it can extend the use of existing thermal-power infrastructure, provide baseload power, and substitute for some generation from renewables. A 60 percent reduction in the cost of CCUS—to $1,050 per kilowatt—could cut 2040 total system costs by 10 percent.

— *BECCS.* The biggest single factor in the use of BECCS is the availability and cost of the biomass-input fuel. If this cost could be cut by 40 percent, BECCS could be commercialized and scaled up. At this price, the negative emissions from BECCS allow unabated-gas plants to run when renewable production is low and still achieve net-zero power-sector emissions, resulting in a total-system-cost reduction of 9 percent.

— *DAC.* DAC technology is nascent and could come down in cost to $1,200 per kilowatt by 2050. That cost needs to go down sharply for DAC to scale up. We estimate that if DAC were 60 percent cheaper, its deployment could reduce total system costs by 3 percent.

Executing a strategy for deep decarbonization

A variety of stakeholders will need to work together to make the decarbonization transition happen.

Utilities and system planners must develop more sophisticated ways of incorporating projected energy flows and consumption patterns into their scenarios. They need to understand how a future energy system could work with the natural-gas network; the potential of behind-the-meter resources, such as distributed energy; the full potential of more complicated resources, such as storage; and the ability to trade off different types of assets, such as transmission, hydrogen, P2G2P technology, and CCUS. In addition, they need to figure out the delicate balance between the investments needed to serve their customers now and the longer-term risk of leaving expensive assets idle—or of massive, last-minute spending to reach decarbonization targets in 2040.

[12] The National Renewable Energy Laboratory estimates 2020 capital expenditures at $6,600 per kilowatt (atb.nrel.gov).

For *regulators*, navigating this territory means creating market signals and compensation structures that are effective and transparent. This is particularly important given that power systems will be increasingly complicated, with marginal assets dispatching at nearly zero marginal cost and the value of "firmness"—or reliable capacity—growing in significance.

The priority for *developers and investor*s is to think through the implications of deep decarbonization as they plan and build future capacity. They will need to evaluate an increasingly broad range of technologies and infrastructure offerings—from stand-alone solar and wind power to hybrid renewables to transmission to multiple storage types to CCUS and BECCS to P2G2P technology. At the same time, the contracts under which developers operate are likely to be of shorter duration as these markets become more competitive, which will further complicate underwriting.

The road to deep decarbonization will be complicated, and there will be both winners and losers along the way. If decarbonization is done well, however, the benefits could be momentous. Customers will find their costs optimized, companies will create new value from decarbonization, and society will benefit from cleaner air and lower emissions.

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