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Foreword

Looking back at the range of insights published by McKinsey's Electric Power & Natural Gas Practice in 2022, one thing remains exceedingly clear: the energy transition is already well under way. In the global response to limit greenhouse-gas (GHG) emissions, renewable power from solar, wind, hydrogen, and batteries is taking an ever-increasing share of generation capacity.

Although much progress has been made to achieve the goal of net-zero carbon emissions by 2050, a number of challenges still remain, including significant energy supply–demand mismatches and complex electric-grid upgrades and retrofits, as well as the need for increased operational effectiveness and improved supply chains of key technologies.

This compendium collects 12 articles published in the past year that best reflect the findings most important to industry leaders and readers of McKinsey.com alike, including the following:

— *Power purchase agreements (PPAs) for 24/7 clean energy can help balance supply and demand for renewable power.* As part of the RE100 global corporate renewable-energy initiative, more than 300 companies across 175 markets have pledged to use 100 percent renewable electricity—and 24/7 clean PPAs could help them go even further.

— *Global decarbonization will require a massive build-out of wind and solar farms.* We estimate that by 2026, global renewable-electricity capacity will rise more than 80 percent from 2020 levels (to more than 5,022 gigawatts). Of this growth, two-thirds will come from wind and solar, an increase of 150 percent (3,404 gigawatts). By 2035, renewables will generate 60 percent of the world's electricity.

— *Specific technical expertise and experience are crucial elements of success for renewable energy.* In fact, our estimates show that the global installed capacity of solar and onshore and offshore wind projects will have quadrupled from 2021 to 2030. This huge surge in new wind and solar installations will be particularly difficult to staff with qualified development and construction employees as well as operations and maintenance workers.

— *Hydrogen's momentum continues to grow.* Hydrogen has a critical role to play in enabling a decarbonized electric grid and providing a substitute for fossil fuels in the industry, transportation, and building sectors. A strong push for hydrogen—with increased regulations around faster uptake and revised production routes—could double the value pool in 2040 from $5 billion to $10 billion or more.

We hope this compendium offers new insights that can help electric power and natural gas players, as well as those in the broader energy industry, remain competitive as the energy transition continues apace.

Corporate opportunities

A devilish duality: How CEOs can square resilience with net-zero promises

Amid turbulence on the path to net zero, leaders will have to be much nimbler to balance resilience with an energy future that is secure, affordable, and clean. Five actions can help.

by Anna Moore, Daniel Pacthod, Bob Sternfels, and Humayun Tai

What a difference a year makes. In November 2021, business leaders showed up in force in Glasgow at the UN Climate Change Conference (COP26), pledging to take on the challenge of reaching net-zero greenhouse-gas-emission goals by 2050. While no one believed that the path to net zero would suddenly become easy, commitments made to target nearly 90 percent of CO_2 emissions for reduction signaled that the private sector was truly engaged. Then major new headwinds began swirling: surging inflation, war in Europe, energy insecurity, and a potential global recession. Still, governments pressed ahead, passing major climate legislation packages in Europe and the United States. More than 3,000 companies have made commitments on net-zero pathways.

At the time of COP26, McKinsey released a perspective on the requirements needed to secure a net-zero carbon emission transition.[1] It was clear, given the challenges to deploying capital at scale, managing economic dislocations, and scaling up supply chains and infrastructure, that the path would not be linear and would include slowdowns and backstepping. Ultimately, sustainable systems are more value creating than traditional ones. But countries and companies must balance trade-offs among net-zero commitments, affordability for citizens, and security of energy and materials supply.

As disruptions have intensified, the moment confronts CEOs—an organization's ultimate integrator—with a devilish duality. As net zero has become an organizing principle for business, executives are on the spot to lay out credibly how they will deliver a transition to net zero while building and reinforcing resilience against the certain volatility of ongoing economic and political shocks. The zigs and zags of present conditions will tempt some leaders with exclusive choices—doubling down on fossil fuels, for example, at the expense of new and emerging renewable technologies. Leaders will face multiple calls on their attention, as well as concerns about how quickly to drive a sustainability agenda forward.

We believe that the right response to such challenges has always been a matter of "and," not "or"—that is, maintaining focus on the long term while adjusting in the face of present conditions rather than opting for one or the other. A resilient stance, being prepared to withstand shocks and poised to accelerate into a changed reality, permits companies to weather not just the current moment but also the future storms that are likely to come their way in a world of rising risks.

The task is neither simple nor easy.[2] Yet as leaders prepare to gather in Egypt for the 2022 UN Climate Change Conference (COP27), there is also good news: today's reality is that sustainability, economic competitiveness, affordability, and national security dovetail as never before. To make the most of the situation, CEOs can shape strategy around resilience now to tap value-creating businesses tomorrow as the world continues to head toward net zero in the long run. In this article, we present five core actions to help meet the dual imperatives at the heart of a new sustainability strategy.

Stormy weather

The path to net zero was always going to be fraught with complexities. Recently, several "weather fronts" have emerged, posing significant challenges to leaders across both the private and public sectors.

Energy availability and security

The Russian invasion of Ukraine and the resulting energy crisis in Europe are reminders that, fundamentally, disruption in energy markets can wreak havoc on the global economy. In response, countries are boosting the use of fossil fuels, including coal and gas, and extending the life of conventional energy infrastructure, which is under growing pressure.

Physical risks are proliferating. Europe saw a record-breaking heat wave this summer. Floods devastated Pakistan this autumn, and tropical

[1] "Solving the net-zero equation: Nine requirements for a more orderly transition," McKinsey, October 27, 2021.
[2] "The net-zero transition: What it would cost, what it could bring," joint report from McKinsey, McKinsey Global Institute, and McKinsey Sustainability, January 2022.

storms raged across Japan, the Koreas, and China. In the United States, Texas saw an unprecedented grid failure in 2021, with a near miss in California this year. There are important choices to be made, some of which entail trade-offs between climate mitigation and climate adaptation—for example, rebuilding versus relocating and investing in cooling versus keeping energy consumption down—all of which occur within a limited envelope of infrastructure funding.

Affordability

Prices are rising across the globe, driven by the energy crisis in Europe, the growing food crisis resulting from the invasion of Ukraine, and a recovery from the COVID-19 pandemic that has been faster than expected, and, though welcome, has put pressure on supply chains. The outlook is ominously recessionary.

There is a growing perception that net zero comes at the expense of affordability, with a zero-sum trade-off. The universal problems of supply chain and talent shortages complicate the equation, particularly as deployment for the new assets and infrastructure needed for the net-zero transition picks up. This, in turn, could result in price spikes for the key inputs needed for the net-zero transition. Companies also face growing challenges in securing the parts, labor, and specialized skills they need to execute on net-zero commitments. From heat pumps to recycled textiles and insulation installers to carbon management data scientists, companies are struggling to match supply to customer demand.

Governance and regulation

A key tenet of any orderly transition to meeting net-zero goals is demonstrating ongoing governance and cooperation among public- and private-sector institutions, meeting commitments, and maintaining public support for progress toward cutting greenhouse gases. The war in Ukraine has already reduced the potential for such cooperation. Also, the United States is seeing growing backlash against standardized environmental, social, and governance (ESG) reporting requirements and skepticism of ESG funds that some criticize as punishing fossil-fuel producers and hurting local economies. The outlook for aligned standards, requirements, and public support is becoming murkier.

Shaping a resilient sustainability strategy

There is an increasingly popular view that leaders will need to navigate a zero-sum trade-off between addressing climate action headwinds and sticking to their commitments for achieving an orderly net-zero transition. However, while the path to net zero will not be a straight line, and some regions will step back commitments for the short term, the long-term trajectory remains intact.

More important, these discontinuities also create opportunities—and imperatives. We believe that the potential is great to shape a resilient sustainability strategy that creates a virtuous cycle of managing short-term shocks; bolstering prospects for an affordable, clean, and secure energy future; and improving the long-term competitiveness and value creation of companies. In part, this is because competitors may be tempted to pause during this period of turbulence. That creates a chance for those who stay the course to gain strategic distance:

— *Energy independence via accelerated use of renewables and clean power and capture of the full potential of energy efficiency and distributed electricity.* Diversifying the energy supply with renewables, green hydrogen, and green power promotes national energy security and economic competitiveness. In Europe, the invasion of Ukraine and the effort to develop a future free of dependence on Russian gas has prompted Europe to raise its commitment to renewables (alongside imported natural gas in the medium term and possibly nuclear power in the longer term). Of course, energy market resiliency must be built in tandem—for example, by rewarding the firming of capacity in power markets as the share of intermittent power generation grows. Even prior to the invasion of Ukraine, industrial policy across the larger European economies was focusing on clean-energy tech as a source of national competitiveness. Examples include European clean-tech export policies, support for rare-earth minerals needed for new climate tech, and national funding to drive local new-energy industrial growth (such as the US Infrastructure Investment and Jobs Act). Companies that operate in this space or serve those in it have clear long-term growth prospects.

— *New value from existing systems.* It is becoming increasingly apparent that it may be possible to repurpose existing methods of carbon-intensive production with additional enabling technologies to future proof them for a sustainable future. Numerous examples—such as retrofitting existing industrial production facilities for carbon capture, use, and storage (CCUS); using hydrogen blends in methane carriers; and employing direct air capture (DAC)—are emerging to lower carbon intensity and transform existing systems into cleaner alternatives. Owners and operators of this infrastructure that invest in future proofing through CCUS, DAC, or other tech stand to make significant gains. Repurposing rather than stranding these assets will not just enable affordability and system resiliency but also provide incumbents with greater confidence that decarbonizing their legacy assets is feasible.

— *Sustainable materials transition.* The energy transition requires a materials transition. Projected electric-vehicle demand, for example, will raise demand for cobalt, copper, lithium, nickel, and rare-earth minerals, putting further upward pressure on pricing across these commodity classes. Commitments to decarbonize automotive, consumer goods, packaging, and other sectors are also already driving supply–demand shortages in aluminum, plastics, and steel. We expect, for example, a 50 to 60 percent shortage of same-cycled plastics compared with demand in 2030, driving significant green premiums. If supply eventually meets demand, early movers will most stand to gain. With the current commodity cycle at a peak, cash can be reinvested in nascent materials opportunities that will be in clear demand in the longer term.

— *New sources of capital.* Investors and incumbents have started a new wave of capital deployment toward net zero, including investments in new materials, new climate tech, and more adaptive supply chains. These investments are increasingly following a "private equity plus" model, with heavily involved investors helping build new green challengers from the outset. Countries and regions with hard-to-abate sectors are also increasingly important sources of

Investors and incumbents have started a new wave of capital deployment toward net zero—including investments in new materials, new climate technologies, and more adaptive supply chains.

climate tech and transition capital as they seek to decarbonize while preserving economic growth. These ventures are in their early stages as voluntary and policy-driven demand materializes and grows. But they demonstrate that while there is some ESG-related backlash, a broader set of clean investments are continuing to grow.

— *Voluntary carbon market (VCM) development.* A critical pillar of enabling net zero and financing asset decarbonization is the ability to value carbon with liquidity. VCM will be critical. Although the situation is unsettled now, we see expanded dialogue and more concrete actions toward establishing VCM at the country and private-financing levels. For example, several Southeast Asian governments are shaping national voluntary carbon exchanges, and company commitments to voluntary carbon have grown.

— *Reshaped value chains and reindustrialized nations.* In some developed economies, game-changing policies are supporting new net-zero value chain plays. The US Inflation Reduction Act commits $370 billion in climate spending, targeting the creation of new sustainable industries across the country and accelerating clean tech, such as green hydrogen. Another US legislative measure, the Bipartisan Infrastructure Law, is poised to prompt reindustrialization, replacing value chains based on internal-combustion engines with electric- and battery-based alternatives. In the European Union, the Fit for 55 and REPowerEU packages will create new winners across industries and reshape value chains in a way that brings affordability to the fore. New forms of public–private partnerships will therefore also need to take shape. Instilling more control within regions and individual countries will enable them to protect against price shocks for citizens.

Done well, pursuing these opportunities should create a virtuous cycle for economies among affordability, decarbonization, energy security, job creation, and resilience. Renewable energy is one obvious example with the potential to promote energy security, create high-quality jobs, and reduce emissions in tandem. New sources of capital and VCM could make sustainable investments more affordable, bringing them to market sooner, and successful delivery of these projects would in turn boost returns and attract further capital. Sustainable materials could facilitate the energy transition while creating new value from existing systems and infrastructure. And so on. These examples illustrate the power and possibility of the "and"—a flywheel-like effect that enables meeting security, socioeconomic, and sustainability goals in parallel.

Across these opportunities, incumbents are positioned to succeed more often than not. Every incumbent player, especially in hard-to-abate sectors, has two sets of opportunities: decarbonizing while extending fossil-fuel-based core business (potentially earning green premiums as a result, as early movers in sustainable materials already are) and building new sustainable businesses. Incumbents can use existing cash flows and strong balance sheets to fund new sustainable businesses that lay the foundation for future growth. They can afford to invest for the long haul and place bets across multiple new clean technologies—another advantage when the end point is clear but the precise path to get there is not.

Resilience today and value tomorrow: Five actions for CEOs

The pressure to demonstrate real progress on and create true value through sustainability is growing. The world has, however, entered an era that is increasingly challenging for CEOs and business leaders to navigate. There is a new strategic paradigm—one with reasonable certainty of where the world needs to be in the medium and long term and tremendous volatility in terms of how and when it will get there.

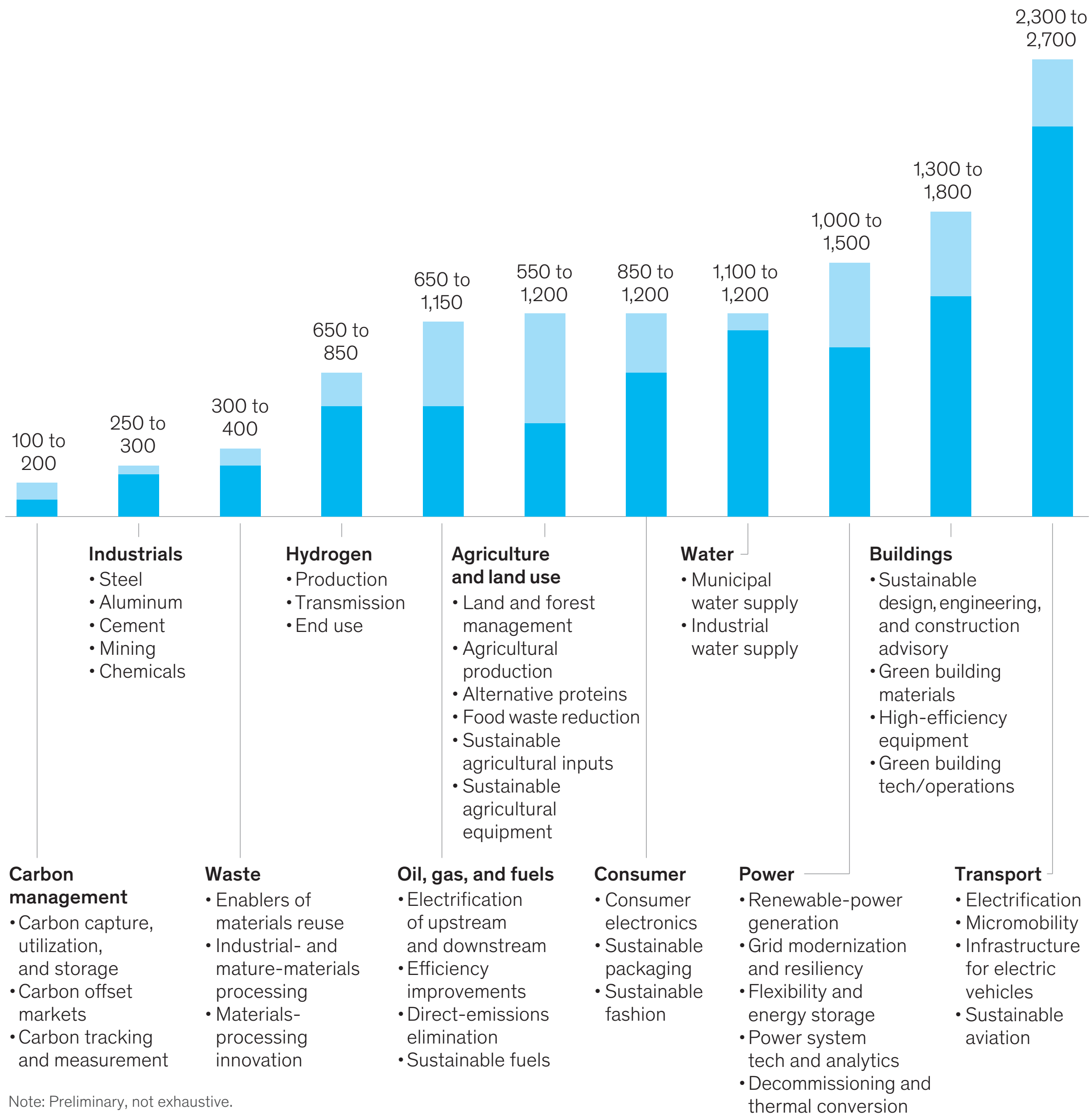
Leaders must build resilience to today's shocks to build tomorrow's champions. Some approaches will be easier than others and offer a good starting point.

Accelerate capital deployment with a private-equity mindset
Leading with resilience while navigating toward net zero means participating early in the materials transition and green-business-building wave to secure exposure to promising innovations (exhibit). Earlier-cycle investments have higher risk but also higher returns because they benefit from early policy funding, greater willingness for counterparties to participate (for example, through sustainable aviation fuel contracts, which guarantee demand from airlines that allows investment in supply), new talent, and the opportunity to gain first-mover advantage in nascent and emerging value chains.

Exhibit

Eleven high-potential value pools could be worth more than $12 trillion of yearly revenues by 2030 as the net-zero transition advances.

Addressable market size in 2030, selected categories, $ billion



Note: Preliminary, not exhaustive.

Two objectives should be paramount: extend and decarbonize the core business, and build new sustainable businesses in reshaped value chains.

In many industries, there will be multiple sustainability winners. For example, we expect both hydrogen-fueled and electric vehicles to be part of the 2050 ground transport system. This is another reason to consider an investor mindset—spreading bets across multiple potential investments earlier. Companies can further manage their transition risk by aggressively pursuing operational decarbonization measures that already pay for themselves (for example, through energy efficiency) while making longer-term investments in sustainable infrastructure and building new businesses. Pursuing energy efficiency and rapidly scaling distributed clean heating (for example, via heat pumps) will become a critical lever in Europe to manage the energy crisis.

Play offense through a sustainable value creation strategy

Two objectives should be paramount: to extend and decarbonize the core business and to build new sustainable businesses in reshaped value chains. This would represent an "*Apollo 11* moment" in many industries—a moon shot requiring not just incremental improvements but wholesale rethinking of how to build, operate, and maintain every sector of the economy. Leaders need to make quantum leaps to meet the moment, by getting smart on climate tech fast, engaging with the innovation ecosystem, and leveraging their engineering and business-building talent. Similarly, a focus on sustainability—and ESG measures, more broadly—is defensible, pragmatic, and needed. CEOs can articulate their approach to ESG topics proactively by focusing on resilience and value creation, not simply as part of "right to play" and risk mitigation.

Go beyond net zero

CEOs should also look to make their companies net nature positive. Actions include moving ahead in the game on biodiversity, demonstrating stewardship of shared water and air resources, ensuring a responsible supply chain, and contributing to a just transition, among other steps. Adaptation investments to address physical risks will also be critical. Companies able to weather the storm, literally, will have a material advantage.

In some instances, sustainability aims come into conflict—for example, lithium brine operations are less carbon intensive than hard-rock extraction but consume far more water. CEOs will need to weigh current trade-offs carefully and invest in innovation that meets multiple aims, "squaring the circle" in an increasingly complex ecosystem. The bar is rising on sustainability; companies need to have a plan on these and other factors.

Build the partnership and ecosystem muscle

CEOs should realize that the challenge of maintaining resiliency while driving toward net zero is too great to go it alone. New public–private partnerships will be needed because many of the emerging energy and materials value chains will require full ecosystem development. Consider, for example, clean-fuel consortiums, such as those developing around hydrogen hubs, and shared CCUS networks. There are also opportunities to partner with competitors on shared tech road maps to mitigate tech risk and to better direct innovation funding.

Aggressively reskill leadership teams, boards, and frontline workers

As companies embrace a sustainable future, they will need new skills. Sustainable fashion, for example, requires fully rethinking design, manufacturing, procurement, marketing, and waste management processes while also better tracking carbon emissions and circularity. Talent across the organizations will need to reskill to meet these new demands. Companies need to identify the skills needed for their more sustainable business models and work toward acquiring them *and* building them internally.

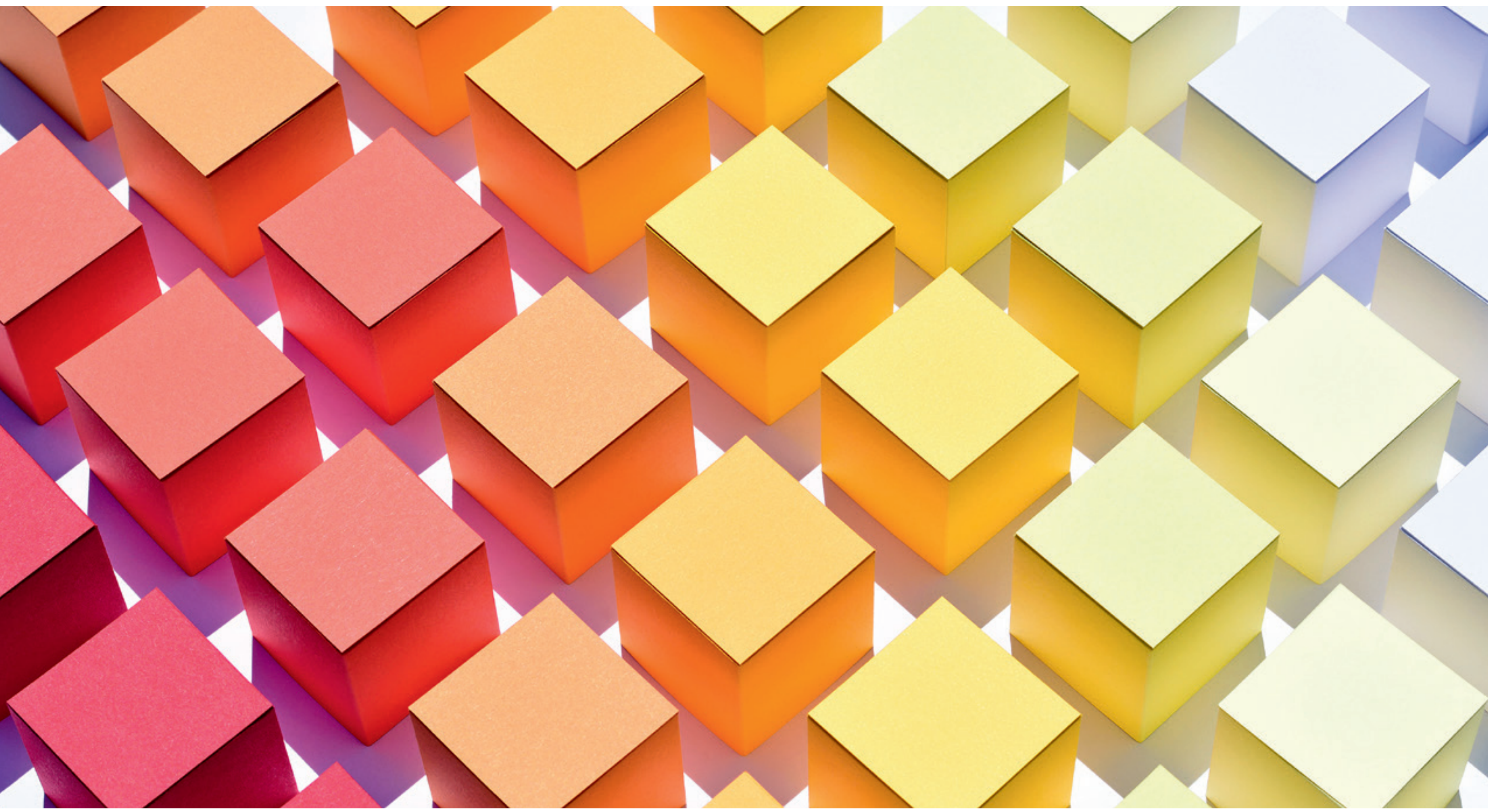
Navigating the current turbulent period for the net-zero agenda may require temporary responses that, in some cases, may look like setbacks. They need not be. CEOs who understand the virtues of strategic resilience know that addressing immediate hardship and building a sustainable future can—and should—be pursued at the same time. By maintaining vision, moving nimbly, playing offense, and embracing opportunity instead of recoiling from risk, leaders can improve the future of their businesses and the planet.

Anna Moore is a partner in McKinsey's London office, **Daniel Pacthod** and **Humayun Tai** are senior partners in the New York office, and **Bob Sternfels** is McKinsey's global managing partner and is based in the Bay Area office.

How can CFOs rebrand themselves as innovation allies?

They can take five actions to improve objective-setting, performance measurement, and cultural factors associated with successful innovation projects.

by Ankur Agrawal, Matt Banholzer, Eric Kutcher, and Scott Schwaitzberg



CFOs continue to have an innovation problem—or, rather, teams in their organizations think they do. Research shows that many business unit leaders view the CFO and the finance team as obstacles, not allies, to the innovation process.[1]

That perception isn't the reality, of course—but it's easy to see why it exists.

Boards, CEOs, and others on the senior-management team rely on the CFO to be an independent arbiter and guardian against overoptimism—or conservatism—in annual planning and budgeting discussions and in performance management meetings. During these conversations, CFOs must help the rest of the senior-management team assess proposals from business unit leaders. CFOs must also quantify the potential value from those proposals while accounting for the inevitable financial and strategic uncertainties associated with new products or services or with process or systems changes.

To become true collaborators and allies for innovation—not just seen as authority figures holding the purse strings—CFOs need to change their colleagues' (and in some cases their own) perceptions of their role in innovation. In our experience, a CFO can take five actions to flip the script: formally build innovation goals into the company's plans for growth, discover and validate untested assumptions about an innovation project, speed up the standard budgeting process, establish metrics specific to innovation projects, and upskill finance teams and empower them to help lead changes in the company's culture.

Making changes in these areas will take time and a commitment to developing an innovation mindset. But CFOs who make the effort may end up working more effectively with project teams and advancing corporate innovation in a way that dovetails with the company's overall strategic aspirations and promotes growth and resilience.

How the CFO can better support innovation

At base, the innovation process is about allocating resources toward initiatives that create value for a company and, ideally, change an industry. To innovate successfully, companies must identify the most promising projects and set clear goals for realizing them, regularly measure progress in reaching those goals, and change hearts and minds—internally and externally. The CFO can promote success by focusing on the following five steps associated with objective-setting, metrics, and culture change.

1. Build innovation goals into the company's plans for growth

The first step for a CFO looking to serve as an innovation ally is to formally build innovation goals into the company's plans for growth. Where and how does the company expect to find growth, and what role should innovation play in securing it? With input from the CEO and other members of the senior-management team, the CFO can help answer those questions and devise objectives that compel teams to move beyond the status quo and explore new ideas, not just incremental process improvements. At one global insurance company, for instance, business unit leaders felt that they could hit their performance targets by tweaking existing operations rather than exploring larger initiatives. In effect, they felt they didn't need to innovate to meet the company's growth goals. Despite interventions from the top team, innovation languished for years.

To counter that thinking, the CFO could have established a "green box"—an effort to quantify how much growth in revenue or earnings a company's innovations must provide in a given time frame.[2] With this information in hand, the CFO and

[1] McKinsey Global Survey, "Are today's CFOs ready for tomorrow's demands on finance?" December 9, 2016.
[2] Daniel Cohen, Brian Quinn, and Erik Roth, "The innovation commitment," *McKinsey Quarterly*, October 24, 2019.

The innovation process is about allocating resources toward initiatives that create value for a company and, ideally, change an industry.

other senior leaders could have established new innovation-centered objectives for the business units—objectives focused on closing the gap between their current performance and capabilities and the company's overarching growth aspirations. In this way, the CFO and the rest of the top team would also have communicated the fact that innovation was a priority for the finance function and the company as a whole.

2. Discover and validate untested assumptions about an innovation project

The CFO must acknowledge that standard planning and budgeting processes may not be suited to innovation. In most companies, business unit leaders present preapproved business cases to the CFO, and the two sides engage in back-and-forth about whether the proposal merits investment. In all likelihood, many of the assumptions underpinning the idea have already been tested—indeed, they are implicitly embedded in the company's current business models. The decision to set a certain price for a product, for instance, often results from tested assumptions about, say, the customers' willingness to pay for other products the company has launched or the perceived value from those products.

Innovation ideas, by contrast, are often built atop what may be untested assumptions. For instance, it's very possible that the targeted customers won't be willing to spend a significant amount of money on an unfamiliar product or a product with a different level of functionality. What, then, is the right approach to pricing?

The CFO and other leaders will need to discover and validate the untested assumptions associated with innovative ideas. The finance leader could start by asking business unit leaders how big an opportunity must be to justify moving forward. What are the most important assumptions we need to test? How can the finance function help business unit leaders get the data they need to prove the case and turn a good idea into a better one? To gain greater clarity about straightforward assumptions, CFOs may ask business unit leaders for literature scans, surveys, or other forms of research to bolster confidence in an investment decision. To gain greater clarity about trickier assumptions, they may ask for real-world information, such as data on experiments with minimally viable products, mock products, beta launches, or early partnerships.

For the CFO and finance team, the focus here should not be on costs but rather on creating a mechanism to explore the most promising ideas. They should, for instance, avoid using a hurdle rate that might encourage teams to engineer their numbers. Instead, they should surface and challenge the business unit leaders' assumptions and use them as the basis for important finance discussions.

3. Speed up the standard budget process

There is often a lag between budget and innovation cycles. A business unit might get approval for funding a project only to find, nine months into the annual budget cycle, that changes in technology or the market mean that more or different resources are needed. Innovation happens day to day and month to month—not once a year.

To be an innovation ally, the CFO must work with the rest of the senior-management team and the business units to change the pace and intensity of (and the dialogue around) resource decisions. For instance, the top leaders can institute monthly and quarterly reviews—or even more frequent discussions—as a catalyst for adjusting resources. Some businesses have even instituted stage-gate discussions for investments in new products, services, and other innovations. A business unit may receive a minimum spending base that covers costs associated with a product's first iteration. Additional funding would be contingent on increases in, say, demand or delivery rates. The business unit would have to meet predetermined thresholds set jointly by it and the finance team.

This stage-gate approach can help clarify expectations, enable the business unit to change course if needed, and ensure that resources are allocated continually rather than cyclically. It can also help strengthen a company's innovation pipeline: many innovations fail, so it is important for CFOs to take stock of projects frequently—and to help shift resources to the most promising initiatives and end unsuccessful ones.[3]

4. Establish metrics specific to innovation projects

A big source of tension between CFOs and business unit leaders is how to report and measure the performance of new initiatives. In proposing them, business unit leaders often build multiyear revenue projections too precise for the context. In other words, they don't account for the inevitable changes, in business drivers and assumptions, that occur when new products are launched. In the first year, customers may flock to a shiny new product—which would imply success—but what happens when demand drops off or attention shifts to a fast-following product?

To get past this disconnect, CFOs and business units can jointly establish metrics specific to innovation projects. These would include traditional business metrics, like the internal rate of return (IRR), net present value (NPV), and ROI. But they could also incorporate nontraditional metrics, such as customer loyalty or environmental, social, and governance (ESG) scores and the *ranges* of performance appropriate for certain types of projects or portfolios of projects. In addition, the CFO and the finance team can identify and use metrics that quantify the biggest sources of uncertainty from an innovation, the pace and efficiency of the innovation team's learning process, and the opportunity timeline, among other factors.

Equally important, CFOs and business unit leaders must engage in an ongoing dialogue about how innovation projects are faring rather than conduct only periodic reviews or focus only on struggling projects. As noted earlier, it's important to understand when and how to cut the cord on underperforming innovation projects—but it's just as critical to understand when and how to scale up the successes.

5. Upskill and empower the finance team

In our experience, members of the finance team who have spent time in business units tend to understand the uncertainties of and become better advocates for innovation. For this reason, the CFO may want to facilitate employee rotations that can give members of the finance team greater exposure to the business units and the day-to-day decisions facing their leaders and innovation teams. In this way, members of the finance team can build important relationships and better understand the

[3] J. André de Barros Teixeira, Tim Koller, and Dan Lovallo, "Bias busters: Knowing when to kill a project," *McKinsey Quarterly*, July 18, 2019.

assumptions underpinning innovation projects. The rotation program can also be an important professional-development tool for the company. At a large consumer company, such a rotation was the stepping-stone for a financial-planning and analysis (FP&A) analyst who participated in and then led an innovation project that eventually turned into a new product line with a multimillion-dollar P&L.

Most important, the CFO should empower members of the finance team so that they receive ideas in the early stages. The CFO can have only a limited impact with a set of already polished financial plans. The potential for successful innovation is far greater if the CFO receives draft plans with the assumptions clearly articulated—and that won't happen by accident.

CFOs need to make it safe to innovate. The CFO can help to maintain a nonjudgmental tone in innovation-related conversations. Rather than flatly asking business unit leaders, "How did you come up with this number?," the CFO can reframe the question as a point of appreciative inquiry: "I see this assumes we can convert 10 percent of customers. I wonder how we might be able to validate the take rate?"

CFOs need to make innovation fun. One company used a competition-style format to source new ideas. The CFO asked teams to come to the leadership with product, service, or process ideas and make the case for funding. The company gave bonuses and recognition to teams that made submissions. That created excitement, which encouraged people who may have hesitated to push ideas through the application process to do so in hopes of getting selected to present them to the C-suite.

CFOs need to make innovation easy. Another company has built lots of reversible decisions—or "two-way doors"—into the innovation process, so that it is easier for teams to test and learn from new initiatives. These two-way doors can mean fewer sunk costs for innovation teams, faster go or no-go decisions, and, ideally, faster times to market.

The long-standing perception of CFOs as obstacles to innovation is stale—and mostly incorrect. CFOs who perpetuate the old mindsets and processes associated with innovation initiatives may put their organizations' long-term health and viability at risk. But those who work to become innovation allies stand to boost value creation substantially and to improve both the company culture and the bottom line.

Ankur Agrawal is a partner in McKinsey's New York office, where **Scott Schwaitzberg** is a solution associate partner. **Matt Banholzer** is a partner in the Chicago office. **Eric Kutcher** is a senior partner in the Bay Area office.

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Full-potential procurement: Lessons amid inflation and volatility

Procurement organizations are uniquely positioned to catalyze cross-functional actions that promote efficiency and resilience in rapidly evolving market conditions.

This article is a collaborative effort by Joe Basar, Casper Bek, Roman Belotserkovskiy, Ezra Greenberg, Marta Mussacaleca, Juan Sarmiento, and Jan Vandaele, representing views from McKinsey's Operations Practice.

Procurement leaders are facing one of the toughest market environments of their careers. A combination of macroeconomic factors—including COVID-19 shocks, trade policy shifts, workforce scarcity, energy transition, and even extreme weather events—have upended long-running trends that have benefited the global economy for several decades. The Russian invasion of Ukraine has caused the greatest humanitarian crisis in Europe since the Second World War and further disrupted long-standing economic relationships.

In the years before the pandemic, rising productivity and declining costs for many inputs—achieved through lean and just-in-time strategies and the globalization of supply chains, among other factors—had allowed many procurement organizations to operate successfully. But now the inflationary surge and frequent scarcity of critical supplies have made shortcomings of the traditional operating model increasingly visible and costly (see sidebar "A snapshot of procurement and macroeconomic sentiment"). These shortcomings include a lack of reliable long-term planning, growing concentration of supply, limited insight into supplier economics, lack of collaboration across functional teams, and a failure to adopt and scale proven technologies that could reduce transactional loads. And the war in Ukraine has brought to the fore a host of noneconomic factors that must now also be considered in sourcing decisions.

To operate in this new context, procurement organizations are facing fundamental changes to management practices, capabilities, and supplier ecosystems based on now-outdated assumptions. We are no longer in a world where assuming "an annual RFP will yield 3 percent price savings" is a viable operating model. After a year of continual and intensive action to adapt, many procurement organizations have deepened their understanding of their supply chains and deployed new levers. But more can be done.

A snapshot of procurement and macroeconomic sentiment

During the past 12 months, we asked procurement leaders about their primary concerns as they face the new context. Rising prices and supply shortages topped the list (exhibit).

McKinsey's ongoing survey of senior business leaders showed that inflation has joined supply chain disruption as one of the biggest perceived risks to growth, supplanting COVID-19 for the first time since the onset of the pandemic.

To help companies stay on top of developments, McKinsey is publishing periodic updates of global economics intelligence. The updates reveal a number of conditions and trends that demand a new level of procurement excellence. For example:

Higher input prices. The prices of essential materials, products, and services are shooting up at rates unseen in a decade or more. The London Metal Exchange Index of six key industrial metals has doubled since the middle of the pandemic, reaching a height last seen in 2011. In Europe natural-gas prices have jumped 60 percent since Russia started massing troops. Brent crude oil is consistently trading near $120 per barrel. Further, prices for key agricultural, mineral, and metal commodities rose 10 to 15 percent in the first week of the conflict; nickel prices doubled recently. Ukraine and Russia together produce about 30 percent of the world's wheat; spot market prices are up about 40 percent.

Consumer price inflation. The US consumer price index rose by 7.9 percent between February 2021 and February 2022. In the eurozone and the United Kingdom, the equivalent figures were 5.9 percent and 6.2 percent, respectively. That's adding to upward pressure on wages, which were already rising because of the disruptions caused by COVID-19. Private-sector wages in the United States have increased at a 6.7 percent annualized rate since December 2019.[1] In the leisure and hospitality sector, in which staff shortages have been particularly acute, wages have

[1] Private production and nonsupervisory workers, all industries, from December 2019 to February 2022.

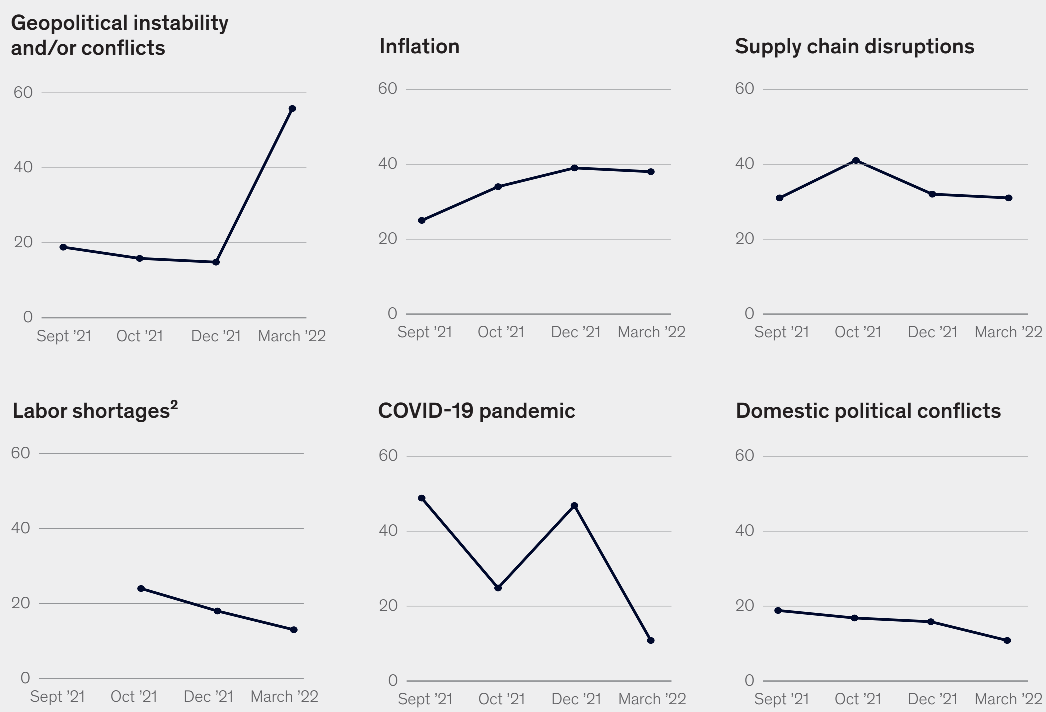
A snapshot of procurement and macroeconomic sentiment (continued)

been rising at a 7.2 percent annualized rate. Central banks around the world are acting to put the brakes on inflation. On March 16, 2022, the US Federal Reserve (Fed) raised its short-term rate by 25 basis points, the first hike since December 2018. In its statement, the Fed said that it "anticipates that ongoing increases in the target range will be appropriate." The Bank of England followed the next day with its third increase in four months.

Exhibit

Geopolitical instability emerges as a major concern for domestic growth, while COVID-19 pandemic concerns recede.

Potential risks to economic growth in respondents' countries, next 12 months,[1] % of respondents



[1]Out of 18 risks that were presented as answer choices in September, 19 risks that were presented in October, and 20 risks presented in December and March; Sept 2021, n = 958; Oct 2021, n = 902; Dec 2021, n = 955; March 2022, n = 785.
[2]Option starting in October 2021.

Procurement organizations have a unique opportunity to set more ambitious goals, define a broader role for their teams, attract new talent, build new capabilities, and deploy new systems.

Chief procurement officers (CPOs) can assess the organization's readiness to step up with a few incisive questions:

1. Have we quantified the potential impact of inflation, volatility, and supply chain disruptions at the commodity and supplier level?

2. Do we deeply understand our suppliers' industries and their dynamics? How are we sharing our insights with other functions to help protect revenues and margins?

3. Do we have a road map to protect margins and mitigate supply risk via pricing, technical, demand, inventory, process, design, financial, and commercial levers?

4. Do we have a proven playbook to recover and then control costs as inflationary pressures subside, volatility trends change, and supply chains are redesigned?

5. How are we embedding the learnings and improvements from this challenging period into our go-forward operating model? How can we incorporate noneconomic factors in our decision making?

A strategic road map for procurement

The lessons from the past year form a strategic road map for procurement, comprising three horizons and 12 major action themes (Exhibit 1). The road map is designed to drive a cross-functional response to market uncertainty—with procurement at the center—and to improve companies' operating models. The goal is to emerge from recent disruptions as a much more resilient and efficient company.

The road map starts with data-rich enablement. Companies can quantify how inflation and disruptions are affecting their spend and set up the cross-functional, data-enabled infrastructure to enable an informed response. They can then turn their attention to identifying a comprehensive set of responses that focus on securing supply and protecting margins through a cross-functional, advanced set of levers. Finally, organizations can embed the learnings and practices they develop by investing in new solutions, ways of working, talent, and capabilities to ensure sustained resilience and efficiency.

Enable immediate action

For any company, the first task is to quantify an independent perspective on the impact of inflation and volatility across the entire spend base. Tying budgets to external assessments—such as movements in Treasury bond prices or the consumer price index—may underestimate risk exposure and not be granular enough to prioritize the right response actions across categories.

Organizations can embed the learnings and practices they develop by investing in new solutions, ways of working, talent, and capabilities to ensure sustained resilience and efficiency.

Exhibit 1

Road map for a procurement win based on lessons learned in 2021.

Enable immediate action

Create transparency and right setup to implement immediate actions

1. Have you prioritized categories based on exposure?
2. Is a cross-functional inflation nerve center in action to quickly capture value?
3. Are you deploying a full set of levers to mitigate short-term challenges (eg, supply, demand, inventory)?

Take action to secure supply and mitigate price increases now and in the next months

Deploy advanced solutions to manage costs and set targets to enable resiliency

4. Have you identified a full suite of levers that mitigate risk via technical, demand, process, financial, and commercial levers?
5. How will you define longer-term value creation in the face of continued uncertainty?
6. Do you have effective cross-functional part-nerships in place to execute all levers?
7. Do you have effective strategic partnerships in place to assure supply and to stay relevant?
8. Do you have a way to accelerate alternatives (eg, new suppliers, new locations, new designs, new materials)?

Institutionalize to prepare for the new normal

Build capabilities, tools, and processes to manage future uncertainty

9. How will you improve the procurement operating model with the learnings from mitigating current challenges?
10. Which new systems and tools will you put in place to assure future resilience?
11. Do you have the right talent and capabilities in your team?
12. How will you redefine procurement governance and cross-functional collaboration to enable both agility and resiliency?

Transparency into spend and a view on input cost inflation by category and geography are critical. Gaining these insights requires an intimate understanding of the supply base and its economic drivers. Some leading companies are already increasing their use of indexing and should-costing to determine the areas of exposure and create fact bases for discussions with suppliers. Companies that cannot easily link their major categories to an index have experienced the biggest challenges, given the opacity of input-cost dynamics and their inability to use futures for category management. In these categories, the use of cleansheeting, embedded-cost analytics, synthetic indexing, and deeper supply market insights has proven powerful in discovering the true magnitude of exposure and creating robust fact bases.

Once companies quantify risk, they can mobilize cross-functional teams in “nerve centers,” whose sole focus is to protect margins across all levers. Some best practices have emerged for these nerve centers in high-exposure categories—such as executive empowerment for fast decision making, use of digital and advanced analyses for fast simulations, and integrated margin-management views. However, when not comprehensive enough, some of these short-term response efforts have failed to enable sufficient transparency and innovation to address the full scope of the problem. For example, a building-materials company set up a nerve center to manage the disruptions in its supply chain. But the nerve center focused exclusively on getting materials to warehouses. It did not explore opportunities to ship with alternate carriers, source from alternate regions, contract differently, challenge rates, or redesign products. As a result, the company became even more entrenched in its sourcing relationships with incumbent suppliers.

Take strategic action

To mitigate procurement risk, companies can apply a comprehensive set of commercial, technical, and cross-functional levers.

Commercial levers

Discovering new regions for sourcing—by either offshoring or nearshoring—has allowed companies to access suppliers with different cost structures and pressures. To master the art of regional diversification, procurement leaders balance the pricing improvements from new suppliers with the supply chain changes required to access them. For example, a home-durables manufacturer achieved substantial savings by sourcing from adjacent regions without reliance on global logistics. An electronics manufacturer responded to logistics challenges encountered in delivering products from Asia by expanding production to the United States and Mexico. And another major manufacturer addressed logistics challenges by sourcing its own fleet of aircraft to deliver products from Asia to end-user markets.

When we ask procurement leaders how they have handled cost pressures, they frequently cite supplier partnerships. However, partnerships have often focused on securing supply rather than capturing savings. For example, a packaging manufacturer focused on launching supplier collaboration efforts to ensure that it was the first customer serviced. But the parties did not develop new analytics or introduce new strategies. At the end of six months, the company’s external spend had risen much more than the prices of the underlying commodities.

Building strong supplier relationships not only helps a company obtain supply in an allocation environment but also positions it to benefit from future cost-saving opportunities. Some semiconductor buyers that have stuck with their supply partners during the good and bad times now benefit from preferred access to inventory from orders canceled by other customers.

Companies are building deep insights into supplier economics and embedding them into smarter contracting models. Facing across-the-board supplier cost escalations, an industrial manufacturer has now documented every escalation request in granular detail. It sought to better understand the exact cost drivers of each product or service, improve its internal cost models, and build better contracts indexed to the right commodities and input costs. When the commodity cycle turns, it will be well-equipped to use this information to renegotiate many of its supply contracts.

Smart contracting levers have allowed companies to use indices in a sophisticated way. Moreover, when combined with hedging and inventory optimization, contracting levers are powerful tools to manage margins for companies that invest in developing sophisticated insights about the dynamics of their supply markets. These leaders are tracking individual or synthetic indices that apply to the different drivers of cost for materials or services (such as raw materials, value-adding activities, fuels, logistics, and labor). And then they are adjusting prices dynamically, which offers relief as different elements of the total cost become less expensive: one manufacturer was able to mitigate 8 to 15 percent inflation across component categories by moving to a much more comprehensive and active index-based price adjustment.

Technical levers

With the right investments, procurement can take the lead in cross-functional discussions with its business partners to explore savings opportunities beyond commercial levers. To relieve the pressure on pricing, companies can seek to reduce total cost of ownership (TCO) through design and specification levers that also promote operational excellence. For example, a building-materials manufacturer faced with historically high costs for lumber and other inputs decided to look inward. It reduced total costs by redesigning products to enable the sourcing of more materials from lower-cost regions abroad, thus decreasing its dependence on high-cost suppliers in its own region. It also dramatically simplified its product portfolio—for example, by reducing the number of molding specifications by a factor of 20. These efforts are on track to deliver total cost reductions of 15 percent.

Another manufacturer responded to severe supply chain disruptions and historically high steel prices by pulling on design and demand levers—namely, insourcing—to almost double its EBITDA margin. The company had seen the input costs for its overseas manufacturing operations nearly double from 2020 to 2021. By redesigning its products so that it could eliminate labor-intensive production steps (such as welding), it was able to shift production to its home market. The company plans to ultimately move production to a nearshore location.

Rationalizing materials selection is a powerful—and permanent—way to structurally lower costs and gain more leverage over supply. By working with engineering in advanced design-to-value efforts, procurement leaders can discover new suppliers for a narrower set of higher-value materials. A durables manufacturer rationalized the number of raw materials used in its highest-volume product lines by applying design-to-value thinking. The rationalization allowed it to improve its cost base, provided access to less-constrained supply sources, and made it possible to redesign well-established products. Another example comes from the automotive sector, where manufacturers have simplified products (for instance, by removing wireless chargers or heated seats) to maintain production and sales while facing semiconductor shortages.

In addition, companies can upgrade their technologies to prevent themselves from becoming a buyer of legacy components. These are more difficult to source and more expensive because suppliers prioritize more profitable components and add a premium to legacy products. For example, companies with products still running on DDR3 memory pay more for semiconductors and have a harder time securing supply than those with products running on DDR4 memory.

Cross-functional levers

Companies in most industries were able to maintain their margins throughout much of 2021 by passing through cost increases. The need to manage input costs and uncertainty remains at the top of CPO and CFO agendas, especially in subsectors or product lines in which price pass-throughs are not possible (such as commoditized or regulated products or highly competitive markets). As a result, we continue to believe that resilience and structurally improved cost bases are a competitive imperative.

An automotive tier-one company addressed the risks in its semiconductor supply through a road map and procurement strategy that included two key levers. The first is an early-warning system that enables consistent long-term capacity contracting and reservations. The second is creating reservation and ordering flexibility in contracts through standard specifications. The R&D team built flexibility into the specifications, which allowed procurement to reserve semiconductors at the technology level (for example, field programmable–type semiconductors) and then order at the chip level with detailed specifications.

Every one of the companies described in this section faced circumstances unique to a specific context. However, all of their most effective responses combined a strong bias to action, a deep understanding of supply market dynamics, agile innovation, and rapid investment in new ways of working.

Spotlight on services

Services, a significant share of spend in many industries, offer a unique challenge in the current context. Strong demand, coupled with the Great Attrition, have created acute labor shortages and pushed labor rates higher, particularly in US service sectors (Exhibit 2). This has given rise to a sellers' market. However, tackling the set of levers we discuss above for materials, especially in supplier partnerships, has delivered a real impact in services.

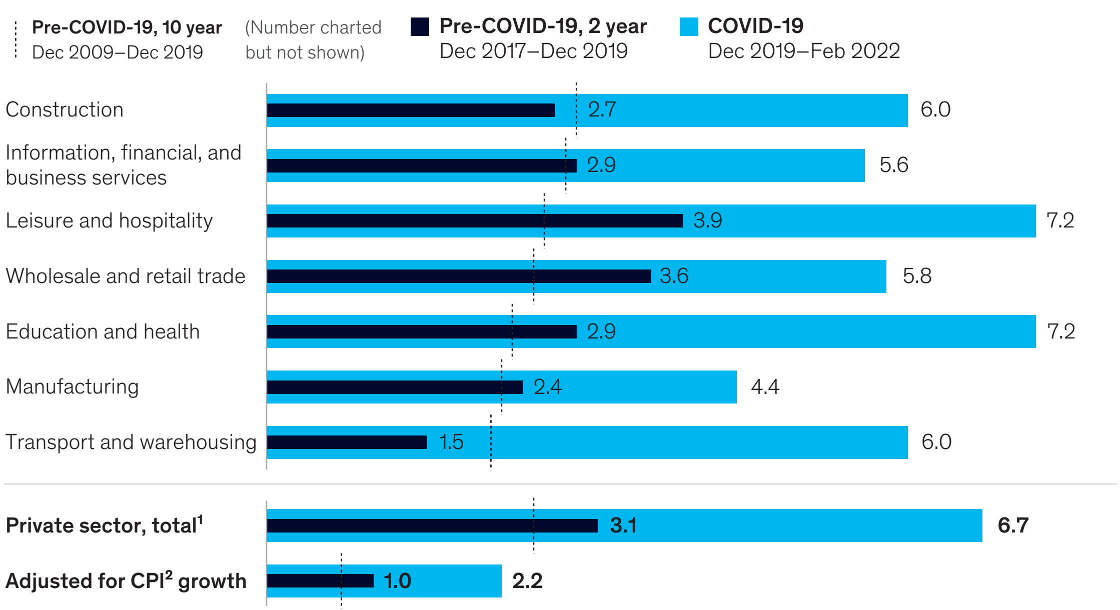
Commercial levers

To apply commercial levers in services, it is critical to gain a cleansheet understanding of labor rates. Procurement can use the insights to develop RFPs aimed at discovering new suppliers. A cleansheet view of rates also informs index-based adjustments to the category, ensuring that equitable adjustments are applied to the right portions of the total rate in a rising or falling market. Incumbent suppliers that have not faced a competitive

Exhibit 2

Postpandemic private-sector wages in the United States are rising—doubling prepandemic rates.

Average weekly earnings, compound annualized growth, %



[1]Private production and nonsupervisory workers, all industries; sector detail for mining, logging, utilities, and other services not shown.
[2]Consumer price index.
Source: BLS, McKinsey analysis

Revising the frequency, activities, and service level of contracted work is a best practice in almost any circumstance. But companies often miss opportunities because they outsource scope management to suppliers.

challenge are more likely to suggest price increases that are not commensurate with the index-based movements and their impact on the wage portion of should-costs.

Companies can use smart contracting to boost productivity and manage total costs, independent of rate trends. For example, an agricultural-equipment manufacturer launched an effort to improve contractor productivity after finding that a contractor's wrench time was less than half of the industry benchmark of 55 percent. The company created initiatives to mitigate the sources of loss originating from its own planning and introduced productivity terms into the contract, such as tying bonus multipliers to the contractor's productivity and operating outcomes. This effort is on track to deliver a 5 percent improvement in total costs and has deepened the partnership with the supplier, which is incentivized to continuously improve performance.

Additionally, companies can change how they pay contractors. Taking a page from law firms, they can require technical-services providers to bill in shorter increments, such as 15 minutes (or even less). This allows companies to manage paid time with much more precision and minimize rounding up of hours. A mining company that required its maintenance contractors to shorten billing increments was able to reduce spending by 5 to 8 percent, depending on the trade. To use this approach, a company needs to enhance its ability to efficiently track contractor time on-site (ideally using automation) and establish targets for job durations. These are no-regret investments that will unlock much-needed cost improvements.

Technical levers

Scope opportunities are critical to managing total costs. Revising the frequency, activities, and service level of contracted work is a best practice to adopt in almost any circumstance. However, companies often miss the opportunities because they outsource scope management to suppliers and end up overconsuming or gold-plating the work. A mining company gained control over equipment-component repair costs by managing the frequency and activities for each repair episode while reducing total labor costs. This lever alone resulted in a cost improvement of approximately 5 percent.

The insourcing of services is a powerful lever in the current market environment, especially when contractors are already embedded in a company's operations. If based on a carefully prepared business case, insourcing allows companies to reduce total labor costs while more closely managing utilization and productivity. For example, at the onset of the pandemic, an agricultural-inputs company reconsidered its facilities management strategy. With employees working from home and excess capacity in some groups, the company built the business case to insource facilities management. Insourcing helped reduce contracted spend and total labor costs by double-digit percentages. It also gave the company a flexible labor pool that it could redeploy more easily in response to changes to its physical footprint.

Institutionalize the new operating model

Current market challenges may continue. Most indicators suggest that commodity pricing pressure, labor shortages, supply chain congestion, and general volatility will persist over the coming 12 months, if not beyond. Procurement and business leaders must continue focusing on creating value, managing risk, and increasing resiliency in an uncertain context.

To win in this new normal, it will be up to procurement not only to swiftly mitigate immediate concerns but also to focus on building sustained, advanced capabilities that can be embedded in the operating model going forward (see sidebar "The CEO perspective: Five questions to ask your CPO"). Some companies have started setting up small agile teams focusing on advanced analytics and systems improvements to continue enabling a sophisticated, cross-functional approach to cost and margin management. One integrated chemical producer began a procurement transformation in late 2020 before inflation took off. As part of the journey, it set up a cross-functional transformation office that is now managing the producer's inflation response across all levers without missing a beat.

Indeed, institutionalizing a new operating model is the next frontier for procurement and business leaders. It requires identifying the processes, talent, ways of working, and solutions that will sustain resilience and efficiency for procurement organizations that adapt in the following ways:

- take a leading role in protecting enterprise margin and growth
- step into the center of cross-functional value creation to apply a broad range of levers that put "everything in play" based on TCO and life-cycle views of spend

The CEO perspective: Five questions to ask your CPO

CEOs can seek answers to several questions to assess procurement's inflation-fighting capabilities:

1. Have you developed a comprehensive perspective on exposure to the different input costs driving inflation? How are these costs impacting your near-term targets? What is the role of noneconomic factors in your decision making?
2. Do you have deep insight into supply market dynamics, risks, and economics? How are you sharing these insights with other functions to help protect revenues and margins?
3. Have you identified and enabled the full suite of value levers to mitigate supply and cost risk via pricing, technical, demand, process, design, financial, and commercial approaches?
4. Do you have a well-designed and practiced playbook to recover and then control costs as inflationary pressures subside and supply chains are redesigned?
5. How are you embedding the lessons learned into sustainable processes, systems, and organizational design choices to permanently upgrade the procurement operating model for the new environment?

— build deep expertise in supply market dynamics and supplier economics to become thought partners and innovation engines that optimize their operations through insight

— invest in proven technology and process automation to free up high-value talent for the most strategic activities

— if necessary, acquire talent who understand suppliers' markets and industries and are strong category managers, negotiators, and relationship builders

As procurement demonstrates its value to the enterprise, the stage will be set for procurement leaders to become full-fledged strategic partners to CEOs, CFOs, and COOs. They can expand from being the guardians of a portion of enterprise costs and use their deep expertise in supplier markets to help lead cross-functional teams focused on long-term, full-potential value creation and ultimate enterprise success.

Joe Basar is an associate partner in McKinsey's Cleveland office, **Casper Bek** is a consultant in the Seoul office, **Roman Belotserkovskiy** is a partner in the Austin office, **Ezra Greenberg** is a partner in the Stamford office, **Marta Mussacaleca** is a partner in the Toronto office, **Juan Sarmiento** is a consultant in the Houston office, and **Jan Vandaele** is an associate partner in the Brussels office.

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Building infrastructure

Decarbonizing the grid with 24/7 clean power purchase agreements

In the global struggle to curb greenhouse-gas emissions, renewable power is taking an ever-increasing share of generation capacity. Yet the rise of wind and solar power is creating new challenges in managing the system.

This article is a collaborative effort by Alix de Monts, Diego Hernandez Diaz, Florian Kühn, Martin Linder, Esperanza Mata, Jesse Noffsinger, Joscha Schabram, Benjamin Thaidigsmann, and Godart van Gendt, representing views from McKinsey's Advanced Electronics, Electric Power & Natural Gas, and Sustainability Practices.

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The electricity sector now occupies center stage in the global efforts to reduce greenhouse-gas (GHG) emissions. Renewable energy sources such as wind and solar power are providing an increasing share of power generation while at the same time presenting certain challenges to widespread use.

In particular, the inherent variability of wind and solar power creates a need to balance supply and demand, for example, by using fossil fuel power to fill gaps. The search is on for a solution that will further reduce the need for fossil fuels, increase the impact of emission reduction efforts, and improve risk management for electricity purchasers. One answer that is gaining currency is "24/7 clean" power purchase agreements (PPAs), which seek to match supply and demand for renewable power more precisely than the PPAs that have dominated the market up to now.[1]

Power purchase agreements for 24/7 clean energy are the subject of a new report[2] produced by the Long Duration Energy Storage (LDES) Council,[3] with insights and analysis provided by McKinsey. According to the report, such agreements offer a significant improvement from today's "pay as produced" PPAs, often coupled with reserve fossil fuel generation to fill the gap when the wind doesn't blow or the sun doesn't shine. The report estimates that these PPAs only achieve 40 to 70 percent decarbonization of an offtaker's actual electricity consumption, while exposing offtakers to market price risks stemming from renewables variability (for which a large portion of offtakers are not well equipped).

By contrast, 24/7 clean PPAs measure electricity consumption and greenhouse-gas emissions in much smaller time units—for example, by the hour—and provide a form of time-matched clean power by using hybrid energy sources, such as a combination of renewable power and energy storage. They are thus a potentially attractive option for corporate power buyers seeking sharp reductions in their Scope 2 carbon emissions (from purchased electricity, heat, and steam) and offer the longer-term prospect of full-scale grid decarbonization. As part of the RE100 global corporate renewable energy initiative, for example, more than 300 companies across 175 markets have pledged to use 100 percent renewable electricity—24/7 clean PPAs could help them go even further (Exhibit 1).

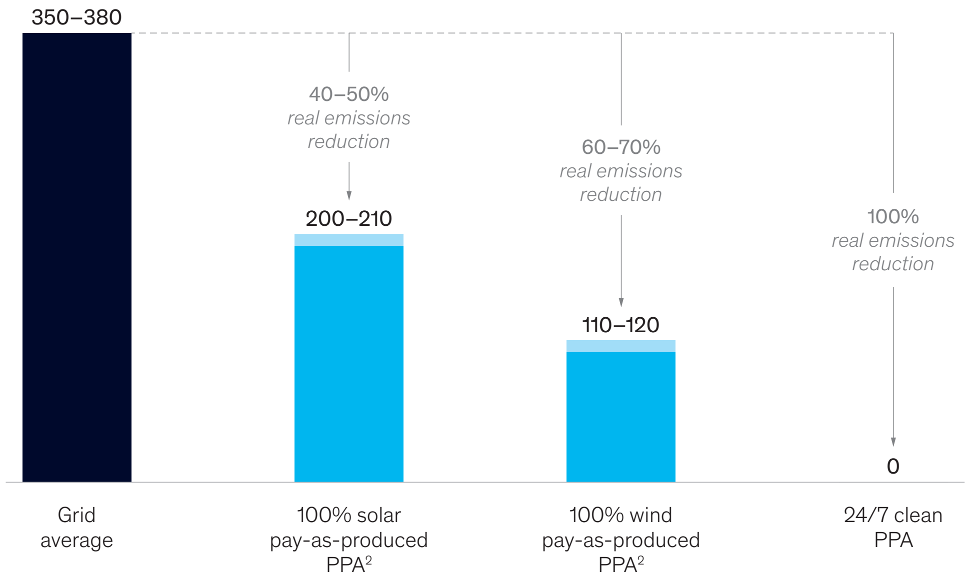
Power purchase agreements (PPAs) for 24/7 clean energy seek to match supply and demand for renewable power more precisely than the PPAs that have dominated the market up to now.

[1] Corporate renewable power purchase agreements (PPAs) are a key mechanism for deploying new renewable energy projects. From the standpoint of the energy seller, they ensure bankability of renewable generation; from the perspective of energy buyers, they enable corporates and major offtakers to meet their clean electricity targets and obligations.
[2] *A path towards full decarbonization with 24/7 clean Power Purchase Agreements*, LDES Council and McKinsey, May 2022.
[3] The LDES Council is a global, executive-led organization that strives to accelerate decarbonization of the energy system at the lowest cost to society by driving innovation and deployment of long-duration energy storage.

Exhibit 1

Standard power purchase agreements achieve 40–70 percent emissions reduction; 24/7 clean power purchase agreements can address the gap.

Emissions by power procurement option,[1]
grams of carbon dioxide equivalent per kilowatt-hour of electricity consumed



[1]Based on 2021 average grid emissions and renewable energy sources (RES) generation data for Germany and California. Emissions intensity of the grid and wind power purchase agreement (PPA): lower range applies to Germany (offshore wind) and upper range to California (onshore wind). Emissions intensity of solar PPA: lower range applies to California, upper range to Germany.
[2]100% indicates annual matching of consumed and generated power. Emissions calculated from offtaker perspective on hourly level (renewable energy directly consumed in hour of generation: no emissions; grid electricity consumed when renewable energy generation not sufficient: average grid emissions).
Source: *A path towards full grid decarbonization with 24/7 clean Power Purchase Agreements*, LDES Council and McKinsey, May 2022; McKinsey Power Model

According to the report, two factors are holding back wider adoption of 24/7 clean PPAs: relatively high costs and a lack of agreed-upon standards, but that both of these obstacles can be overcome with a concerted industry effort.

Regarding cost, achieving 100 percent actual decarbonization with today's storage technology is often perceived as prohibitively expensive, as the levelized cost of electricity from a wind, solar, and lithium-ion (Li-ion) hybrid system exceeds $200 per megawatt-hour (MWh) in most regions.

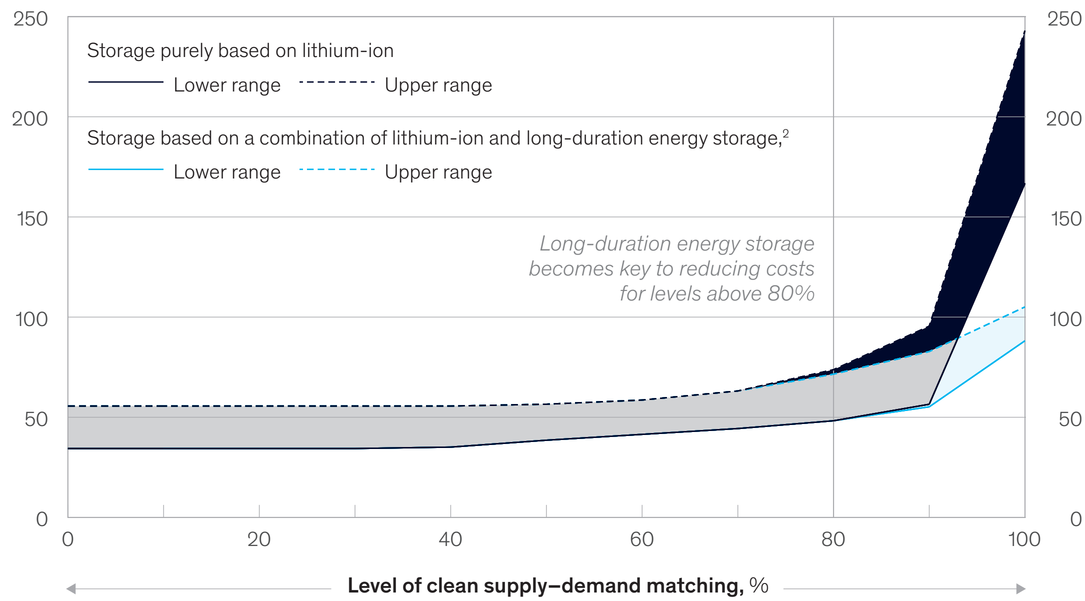
On the other hand, solutions based on novel energy storage technologies, such as long-duration energy storage (LDES), are expected to reduce the cost of fully firm renewable power to below $100 per MWh in the near future if deployment accelerates (Exhibit 2). Power purchase agreements for 24/7 clean energy are an essential nonregulatory tool to support this acceleration by enabling investments in clean, time-matched capacity that will drive down costs.

Action is needed to create agreed standards that can spur wider adoption. The report proposes development of a standardized quality assessment framework, allowing for different levels of ambition. This will establish a pathway to 24/7 clean PPAs with increasing levels of clean supply–demand matching (Exhibit 3).

Exhibit 2

Long-duration energy storage is key to reducing costs at high levels of clean supply–demand matching.

Levelized cost of electricity for onshore wind, solar, and storage hybrid system by level of clean supply–demand matching, 2025,[1] $ per megawatt-hour



[1]Based on modeling a baseload in locations with average (UK) and optimal (Australia) levelized cost of energy.
[2]Long-duration energy storage 8–24-hour and 24-hour-plus technologies.
Source: *A path towards full grid decarbonization with 24/7 clean Power Purchase Agreements*, LDES Council and McKinsey, May 2022; McKinsey Power Model

Exhibit 3

A standardized quality assessment framework is a pathway to 24/7 clean power purchase agreements with increasing levels of clean supply–demand matching.

Priority elements of the proposed clean power purchasing agreement (PPA) quality assessment framework

Minimum level of clean supply–demand matching, %		Renewables additionality	Flexible/dispatchable capacity additionality[3]
Entry-level	80	No requirement	Designated capacity cannot be older than 10 years
Silver	80	If renewables are part of the final system design, 100% of the capacity needs to be additional (including repowering)[2]	If flexibility/dispatchable capacity is required, 100% of the capacity needs to be additional (including upgrades and retrofits)[2]
Gold	90		
Platinum	>98[1]		

[1]Approaching 100% in standard weather years.
[2]To the extent that this results in a net capacity increase in the system, including overhaul of lithium-ion storage resulting in an increase in available capacity.
[3]Includes several dispatchable-generation technologies, eg, hydropower.
Source: *A path towards full grid decarbonization with 24/7 clean Power Purchase Agreements*, LDES Council and McKinsey, May 2022

“Entry level” 24/7 clean PPAs would have low entry barriers and would cost in the range of today’s average power market prices in many regions (around $70 per MWh). At the other end of the scale, “Platinum” PPAs represent the highest ambition level (approaching 100 percent clean supply–demand matching) and are designed for decarbonization leaders. The cost levels of those high-quality 24/7 clean PPAs are expected to decline by 30 to 40 percent over the next ten years as technology matures and scale increases, closing the gap to market prices.

The report’s key recommendation is that 24/7 clean PPAs would benefit from being officially certified by an independent organization based on up-front validation of contract terms, proposed sizing of the designated assets, and a process of continuous review. This would allow fine-tuning of the system to optimize CO_2 impact and cost, based on hourly tracking of demand and supply.

Further steps to boost wider corporate adoption of this type of contract could include incorporating 24/7 clean PPAs in carbon accounting standards; development of a transparent data ecosystem; and measures to lower barriers to entry for smaller and less sophisticated corporate players, including innovative business models that enable asset sharing and the involvement of intermediaries.

While there are many obstacles to overcome, this is an entirely feasible task, and the prize of effective power decarbonization is well worth the effort.

Alix de Monts is a consultant in McKinsey’s London office, **Diego Hernandez Diaz** is an associate partner in the Geneva office, **Florian Kühn** is a partner in the Oslo office, **Martin Linder** is a senior partner in the Munich office, **Esperanza Mata** is an analyst in the Madrid office, **Jesse Noffsinger** is an associate partner in the Seattle office, **Joscha Schabram** is an associate partner in the Zurich office, **Benjamin Thaidigsmann** is an associate partner in the Berlin office, and **Godart van Gendt** is an associate partner in the Amsterdam office.

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A new approach to advanced analytics in utility asset management

Studying how one North American transmission and distribution utility implemented advanced analytics in asset management can help other organizations embark on similar journeys.

This article is a collaborative effort by Anjan Asthana, Alfonso Encinas, Aditya Pande, Luis Fernando Rios Siliceo, Jesús Rodríguez González, Asong Suh, and Willem van Schalkwyk, representing views from McKinsey's Electric Power & Natural Gas Practice.

Asset management can account for a significant percentage of a transmission and distribution (T&D) company's operating expenses and capital expenditures, with optimized operations and investments key to generating savings. New technologies can enable companies to capture these efficiencies. In fact, a recent McKinsey article explained how T&D utilities can leverage advanced analytics in their asset management strategies to unlock 10 to 20 percent in savings while improving overall reliability and performance of their networks.[1]

This article builds on that thinking and takes a close look at a North American T&D utility, which we refer to as UtilityCo. In 2021, UtilityCo leveraged advanced analytics in asset management to unlock savings of 20 to 25 percent in operating expenses and 40 to 60 percent in capital expenditures, which could then flow as savings into the profit-and-loss (P&L) statement or be reinvested to deliver significant reliability improvement. These savings and increased investment capacity are particularly relevant given today's increasing constraints, including pressure from customers on affordability, inflation growth, supply chain bottlenecks, and the growing need for investments in the energy transition, such as renewable-energy solutions, electric-vehicle charging infrastructure, and cybersecurity. Based on the success of the initial model, UtilityCo developed a road map that scales the asset management risk–based approach to two-thirds of the capital portfolio over two years.

The following case study highlights the results of implementing advanced analytics at UtilityCo, including the approach taken, the lessons learned, and the best practices to adopt for others embarking on a similar journey. Although this article is presented as a stand-alone example, our experience shows that the results from applying advanced analytics to asset management are accelerated when deployed as part of a broader organizational transformation.

UtilityCo: An overview

UtilityCo faced a number of key challenges that are common in the industry. For example, the utility didn't take a risk-based approach when making asset replacement decisions or prioritizing preventive-maintenance activities, and it had decentralized asset management operations, with each operating company taking a distinct approach and methodology. In addition, although UtilityCo was able to collect valuable data, the data were underused and stored in multiple systems. Finally, UtilityCo relied on rules that oversimplified asset management decisions—for example, the "three strikes" rule, which called for replacing cables after they experienced three outages.

The results from advanced analytics

UtilityCo was able to effectively use advanced analytics in asset management in four ways. First, it optimized capital expenditures either by maintaining current risk and spending less—and letting the excess capital expenditures flow into the P&L or be reinvested to deliver more reliability—or by spending the same amount and achieving higher reliability through replacing the riskiest assets. Second, it lowered preventive-maintenance (PM) operating expenses by optimizing PM activities. When successful, this optimization can deliver similar or better reliability at lower cost. Third, it lowered corrective-maintenance (CM) operating expenses by lowering spending on CM after those riskiest assets had been replaced. And fourth, it replaced the riskiest assets to help achieve higher reliability (measured as lower SAIDI and SAIFI[2] performance) due to fewer failures.

Regarding capital expenditures for UtilityCo's transmission transformers, the company underwent a paradigm shift, collecting data about each dollar's impact on interrupted customer minutes. With this new perspective, UtilityCo determined it could reduce risk approximately two to three times over while spending the same amount, maintaining the same capital expenditures, and reducing customer

[1] Rui de Sousa, David González Fernández, Jesús Rodríguez González, and Humayun Tai, "Harnessing the power of advanced analytics in transmission and distribution asset management," McKinsey, April 9, 2018.
[2] System average interruption duration index and system average interruption frequency index.

interruptions. Alternatively, UtilityCo could maintain the same level of risk as determined by the current plan while spending 40 to 60 percent less, thus creating capital headroom for reinvestment, maintaining the same level of customer interruptions but reducing capital expenditures (Exhibit 1). Another option was to select a pathway that both reduced risk and required less spending.

On operating expenses, UtilityCo had the option of spending the same amount on PM—removing 1.5 to 2.0 times the level of risk from the system compared with the current baseline—or maintaining the same level of risk as determined by the current plan while spending 20 to 25 percent less on PM.

For the underground-cables asset class, UtilityCo was able to avoid up to 70 percent more outages as compared with the baseline by replacing its riskiest cables. The optimization model also gave UtilityCo the flexibility to achieve either higher reliability at current spending levels or P&L savings at current reliability.

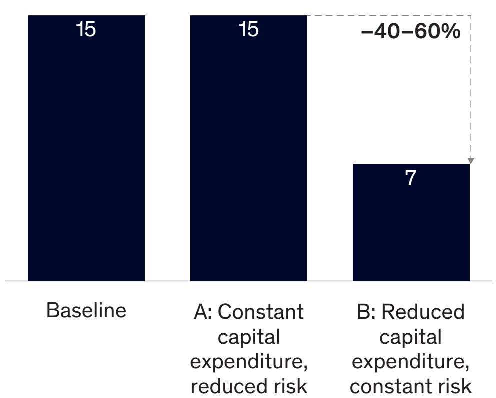
Finally, UtilityCo developed a visualization platform that displayed the results produced from advanced

Exhibit 1

The savings potential for UtilityCo's transmission transformers improved by 40 to 60 percent for capital expenditures and by 20 to 25 percent for operating expenditures.

Baseline and optimized capital expenditure spend, $ millions

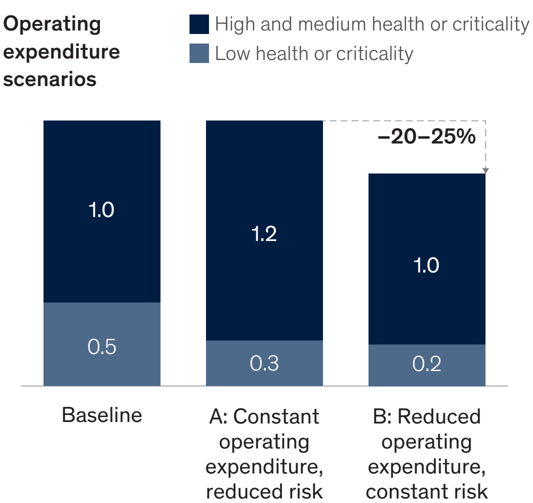
Capital expenditure scenarios



Options for unlocking value:
A: Reduce risk[1] by 2–3× compared to baseline while keeping capital expenditure spend constant
B: Alternatively, reduce capital expenditure by 40–60% while maintaining same risk reduction as in baseline

Baseline and optimized operating expenditure preventative maintenance (PM) spend, $ millions

Operating expenditure scenarios



Options for unlocking value:
A: Remove 1.5–2× more risk[1] compared to operating expenditure baseline while keeping operating expenditure spend constant
B: Alternatively, reduce operating expenditure by 20–25% while maintaining same risk reduction as in baseline

[1] Risk is a calculation of health score times criticality.
Source: McKinsey UtilityX analysis

analytics (see sidebar “Unlocking value as part of a broader transformation”). This dashboard allowed UtilityCo to visualize, prioritize, and implement new maintenance activities (Exhibit 2).

The approach

UtilityCo’s advanced analytics–led approach entailed leveraging both internal and external asset data to calculate a health score (the probability of failure) and criticality (the cost of failure) of a given asset. From there, it used the health score and criticality to estimate asset risk

Exhibit 2

A visualization platform allowed UtilityCo to visualize, prioritize, and implement new maintenance activities.

Unlocking value as part of a broader transformation

UtilityCo implemented the asset management advanced-analytics solution as part of a broader business transformation. While the broader transformation wasn’t essential to implement the advanced-analytics solution, it accelerated the adoption process. First, UtilityCo had already adopted a change mindset, so the implementation of a new asset management strategy was more manageable. Second, cross-functional teams were already working on various initiatives—for example, the IT and transmission and distribution (T&D) teams were focused on workforce management—and were thus able to build on these relationships to drive the advanced-analytics initiative. Finally, to successfully scale asset management to other assets and operating companies, UtilityCo needed to fill new technical roles, such as data scientists and engineers, and upgrade its IT infrastructure via cloud migration and machine-learning platforms, among other options. This was easier to do as part of the transformation because UtilityCo was already in the process of building a digital center of excellence, which was able to manage these new functions.

and prioritize asset replacement and maintenance activities based on risk (Exhibit 3).

Early on, UtilityCo had a clear plan to scale advanced analytics across all its assets and operating companies. It prioritized assets based on impact, including operating expenses and capital expenditures; time to impact; and feasibility, such as quantity and quality of data and the technical difficulty of building models. In addition, when sequencing distribution assets, UtilityCo followed the concept of "lead" versus "follower" (Exhibit 4). For example, it ensured that poles (lead) were modeled before cross arms (follower).

Health score: Estimating the probability of failure

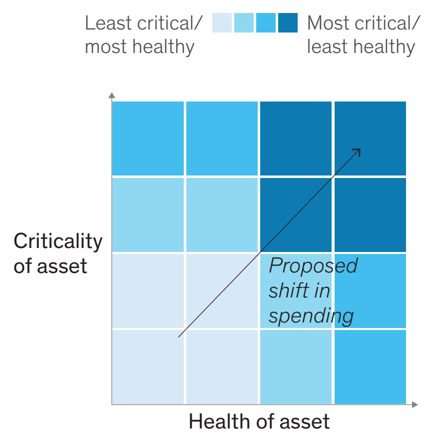
Depending on the asset, UtilityCo considered more than 100 variables to estimate the probability of failure. A machine-learning model was trained on internal data (such as the age of the asset, work orders, and failure history) as well as on external

Exhibit 3

UtilityCo's approach for leveraging advanced analytics was based on the probability and cost of failure as well as on building an optimization engine.

	Description	Outputs
1 **Compute probability of failure (health)**	Calculated the probability of failure for each asset based on the following: • historic outage data • structural data (eg, age and manufacturer) • environmental data (eg, soil temperature and water volume)	Probability of failure for each asset in the following year
2 **Define impact of failure (criticality)**	Calculated the cost of failure for each asset based on the following: • repair • service • safety • environmental impact	Cost of failure for each asset for the following year
3 **High-level clustering for the asset**	Grouped clusters of assets to optimize operational efficiency based on business rules: • eg, grouped assets for replacement at the protective-device level	Clusters of assets
4 **Optimize replacements and inspection**	Generated multiple scenarios to optimize the schedule for the inspection or replacement of assets based on certain constraints; eg, geography and age	Optimized list of assets to be replaced over the next year and prioritized project-management activities

Decision-making risked-based model

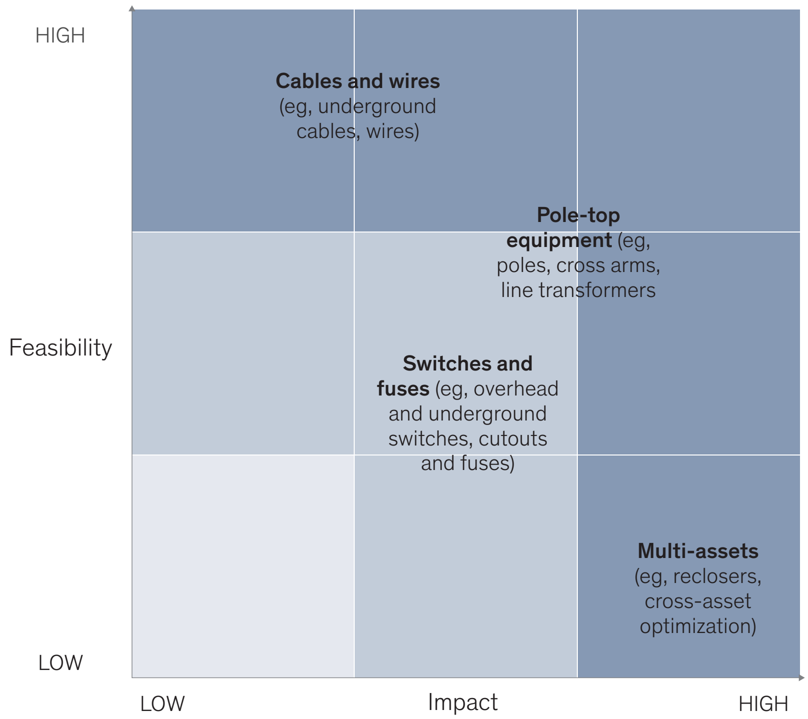


Maintenance optimization

Operating expenditures
↓
Capital expenditures
↓
Risk/reliability
↓
Long-term decision support

Exhibit 4

UtilityCo's sequence for distribution assets was based on impact and feasibility.



data (such as weather data, which stretched back a few years). A holdout data set[3] was used to test the model performance. For example, when looking at the transmission transformers asset class, the model was able to predict approximately 45 percent of failures in approximately 20 percent of the data (Exhibit 5).

To build the health model, UtilityCo aggregated data from several different systems, such as geographic information and outage-management systems. The utility then cleaned and unified the data in preparation for the machine-learning model and identified prediction targets. In some cases, the process was straightforward, such as labeling a transformer that had suffered an outage. In other cases, it was more difficult, such as when labeling a failed cable that was missing a serial or part number.

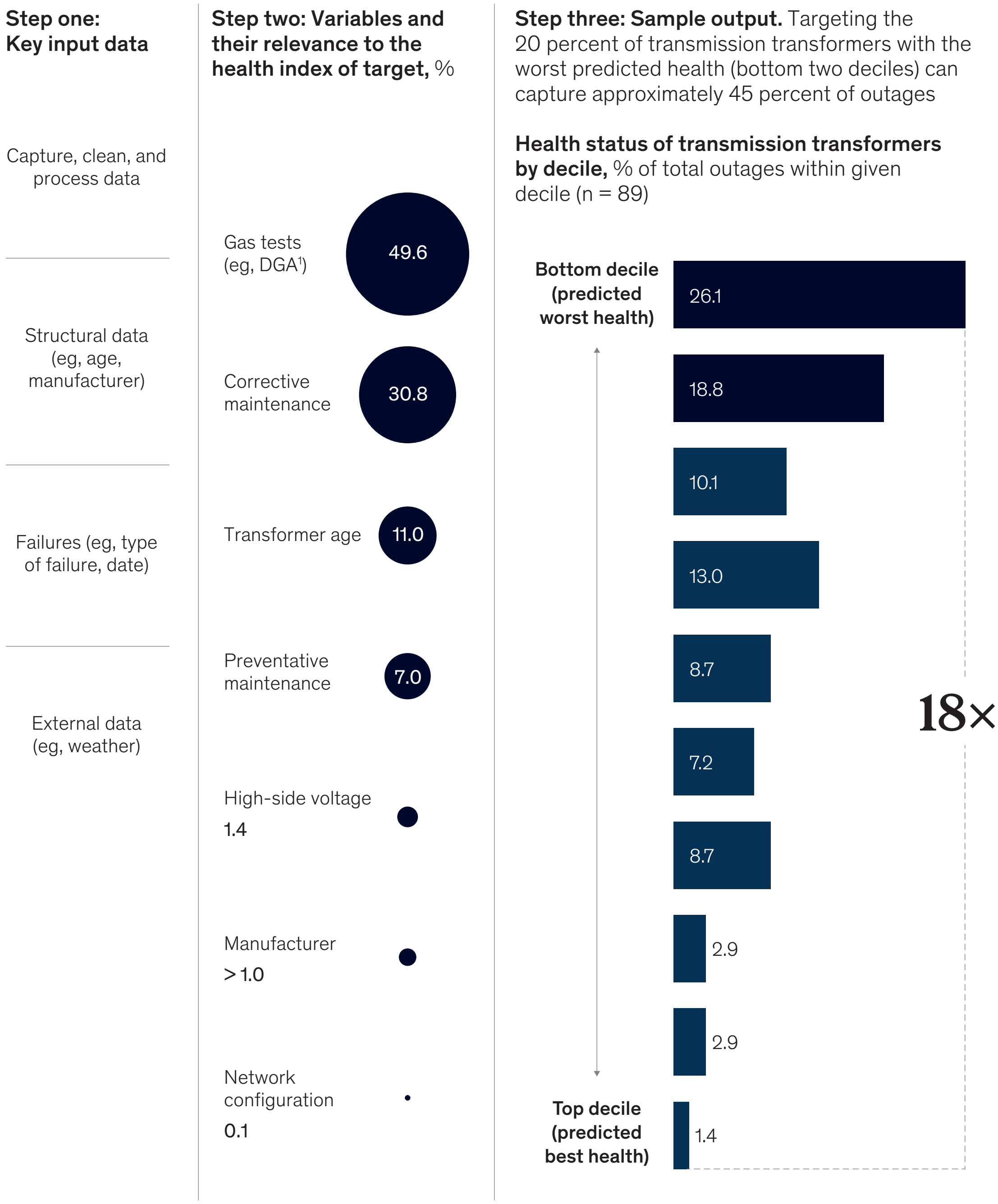
Next, the data were divided into a training set, which was used to train the machine-learning model, and a test set, which was used to help test the performance of the model after training (for example, testing how often the model correctly predicted asset failure). Because UtilityCo was interested in going beyond a standard machine-learning algorithm, it also incorporated a failure-mode analysis into the transmission-transformer models to support detailed assessments of probability of failure by component and to help with the prioritization of condition-based maintenance.

Finally, UtilityCo combined the outcomes from a previous engineering health model with the machine-learning model to calculate the probability of failure and improve performance.

[3] Holdout data, or test data, are historical, labeled data used for validating machine-learning models.

Exhibit 5

Estimating the probability of failure for transmission transformers relies on key input data, important variables, and sample output.



[1]Dissolved gas analysis.
Source: McKinsey UtilityX analysis

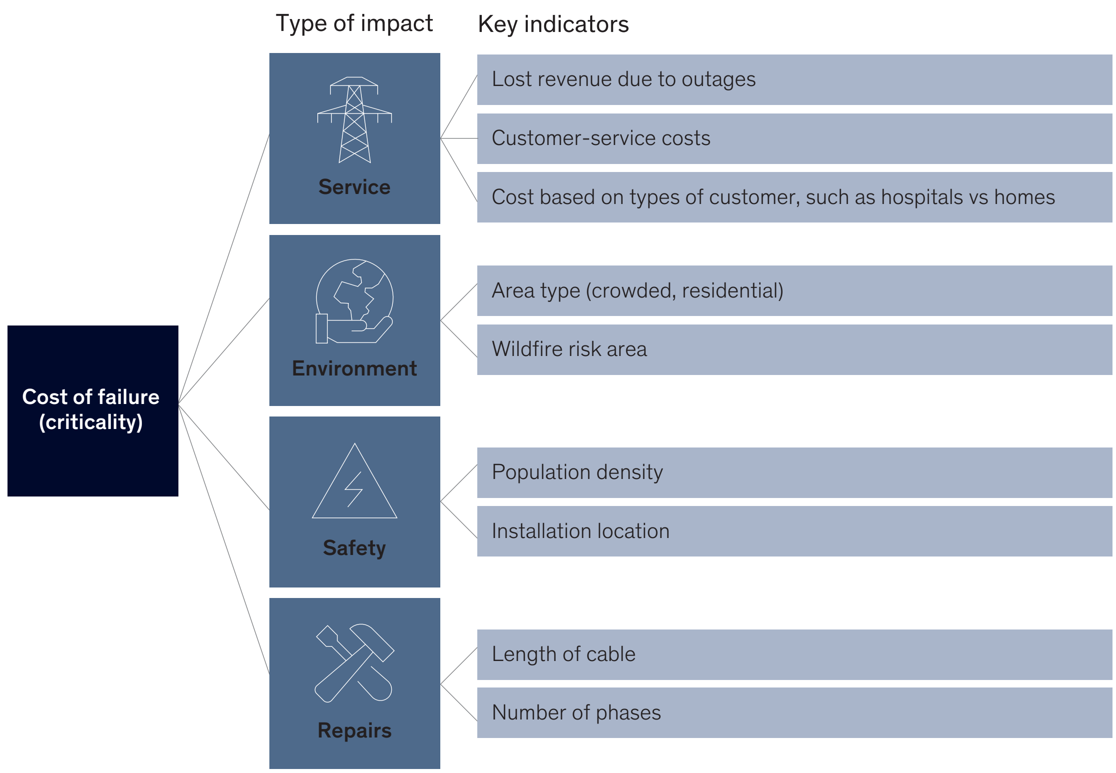
Criticality: Estimating the cost of failure
UtilityCo estimated the cost of failure across several dimensions, including repair, service, safety, and the environment (Exhibit 6). Repair costs are those related to bringing the asset back online after a failure, service costs are estimated based on lost revenue and other factors related to the "importance" of the customer (for example, a hospital is considered "more important" than a single household), and safety and environmental costs are dependent on location and asset type.

Depending on the asset, utilities will need to group the replacement of assets for operational efficiency. For example, UtilityCo found that grouping the replacement of underground cables and applying operational constraints made sense, but it wasn't necessary to cluster the replacement for transformers. Typically, simple business rules—such as clustering cables to be repaired based on the protective device they are connected to—can be used to cluster assets.

Building an optimization engine
UtilityCo used an optimization engine to prioritize asset replacement and PM activities based on the risk of the asset. To build the optimization engine, UtilityCo first estimated the risk of each asset by multiplying its health score by its criticality. Asset replacement was then prioritized based on the resulting risk score and the asset's replacement cost. For example, a high-risk transformer with a lower replacement cost was prioritized over the same type of transformer with a higher cost. To

Exhibit 6

Key dimensions are used in calculating the cost of failure for a typical asset.



UtilityCo built a digital center of excellence and leveraged it to manage the pipeline of talent and to develop processes and trainings to drive consistency across the organization.

optimize PM, a detailed failure-mode analysis was incorporated into the optimization engine to enable estimates of how much risk was removed by each PM activity. In addition, the optimization engine factored in the cost required to perform each of these activities and prioritized activities that reduced the most risk at given costs.

Lessons learned and the recipe for success

Implementing an advanced analytics–led asset management program resulted in several lessons learned, particularly with regard to getting started, data quality, talent and capabilities, change management, and implementation and governance.

First, the team faced internal resistance when getting started, including concerns about not having enough data, or the right data, to address regulatory considerations. The first key step to addressing this resistance was to implement a proof of concept, identifying assets that had good enough data to get started and developing a solution that was better than the current state. Success with the proof of concept gave UtilityCo the confidence to proceed with rolling out the solution across multiple assets and operating companies.

Another lesson involved data that were either siloed, scattered across several different systems, or incomplete or duplicated. For example, data from one asset class were missing installation dates. As a workaround, the manufacturing date was used instead. Developing data architecture and putting processes in place to capture and perform quality control checks on the right types of data were key to addressing this issue going forward.

Although the artificial-intelligence and machine-learning space is still emerging, it is growing quickly. The data scientists and engineers who are key to building solutions are scarce. Thus, UtilityCo built a digital center of excellence and leveraged it to manage the pipeline of talent and to develop processes and trainings to drive consistency across the organization.

During the advanced-analytics implementation, UtilityCo asset managers were asked to make changes to their management processes (see sidebar “Driving additional value from cross-asset optimization”). The key to addressing this issue was to engage the asset managers early on and bring them along as the solution was being developed.

Finally, incorporating advanced analytics into the processes for selecting assets for replacement and updating maintenance processes and policies based on model recommendation was an implementation and governance challenge. Engaging subject matter experts (SMEs) early and

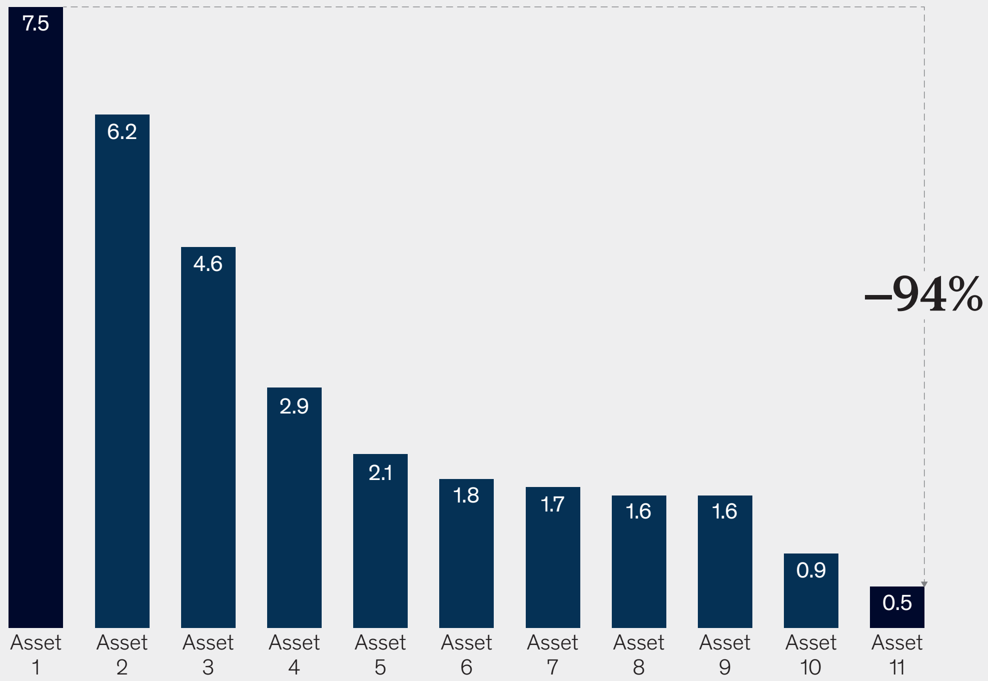
Driving additional value from cross-asset optimization

One of the key advantages of asset analytics is cross-asset optimization. Once UtilityCo implemented advanced analytics for multiple assets, it was able to take a risk-based approach that allowed replacement capital expenditures to be invested in the assets that reduced risk and increased reliability the most. Because risk measurement is the same across all assets, the risk-based approach makes it easier to decide where to invest the next million dollars of capital expenditures to achieve company-wide objectives. For example, with the objective of improving reliability, UtilityCo determined it was better off spending more on one asset over another based on estimated system average interruption duration index (SAIDI) improvement per million dollars spent, resulting in approximately 94 percent improvement to reliability (exhibit).

Exhibit

Everything being equal, investing replacement capital expenditures in asset 11 instead of asset 1 will lead to an improvement in reliability of approximately 94 percent.

Estimated SAIDI[1] improvement, $ millions/SAIDI-minute improved[2]



Note: Data sanitized by taking 90 percent of the original value.
[1]System average interruption duration index.
[2]Numbers have been rounded.
Source: McKinsey UtilityX analysis

running pilots to test new processes gave UtilityCo confidence in its models' abilities to meet its needs.

Several key ingredients contributed to the success of UtilityCo's asset management transformation:

- *Top-down leadership buy-in and push.* Because implementing such a solution usually involves changes in processes across different departments, entailing new technologies, UtilityCo discovered that leadership buy-in and push from the top was critical for advanced-analytics adoption. For example, the vice presidents of T&D and IT joined biweekly sprint reviews to take stock of progress, encourage the team, and communicate the importance of the effort.

- *Agile approach to working.* By setting one- to two-week sprints and working collaboratively to achieve the goals for each sprint, the team had time to cocreate, bring along team members, and course-correct as needed without falling behind. As part of this, a cross-functional team of business and IT was key to making the implementation successful. For example, in a joint meeting with IT and business, a subject matter expert was able to provide guidance on which corrective work orders should be included in the data used to calculate the probability of failure for a given transmission transformer.

- *Not letting perfection be the enemy of getting started.* It was more important for UtilityCo to get started with the data that were available and demonstrate some economic impact than to get everything perfect (or build a big data lake) before starting. For example, UtilityCo started with proof of concept for two assets to demonstrate the value before scaling to more assets.

- *Change management.* Asset managers typically have years of experience managing assets and follow specific procedures and policies. As a result, UtilityCo found it difficult to convince its managers to take recommendations from machine-learning models. For example, when it came to replacing underground cables, UtilityCo asset managers were accustomed to the three-strike rule—in which a cable is replaced after three failures within a 24-month period—and it was a difficult task to convince them to replace a cable that had a high probability of failure but no previous failures. One successful strategy was to involve the team from the beginning and bring them along in the process of building the models.

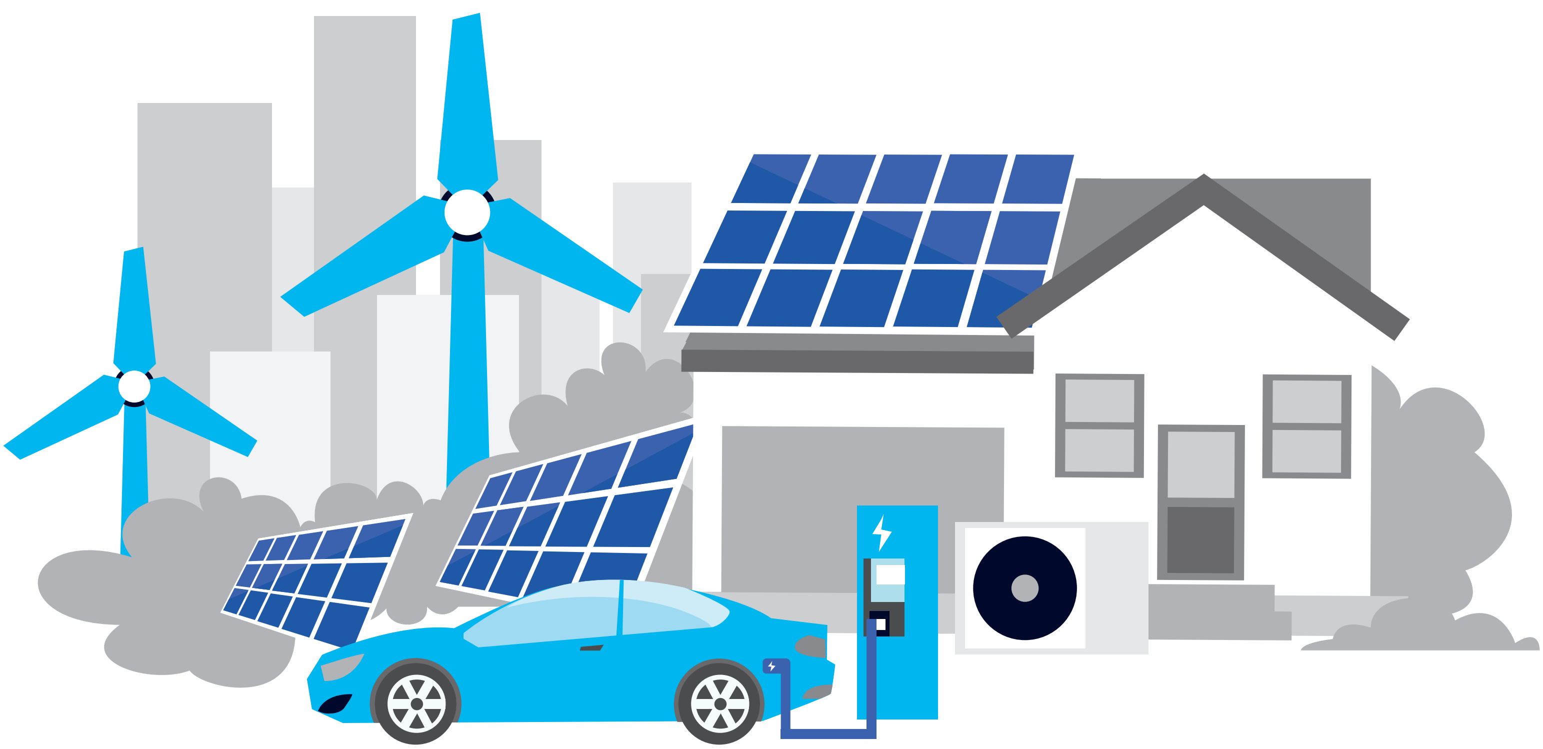
UtilityCo transformed its asset management strategy from a manual process that used very limited data to make asset replacement decisions and a preventative, one-size-fits-all maintenance approach into a strategy that leverages extensive data and advanced analytics to make replacement and repair decisions based on asset risk. In making this change, UtilityCo unlocked significant savings in capital expenditures and operating expenses while increasing reliability for customers and regulators.

Anjan Asthana is a senior partner in McKinsey's Miami office; **Alfonso Encinas** is a partner in the Washington, DC, office; **Aditya Pande** is a partner in the Bay Area office, where **Willem van Schalkwyk** is an associate partner; **Luis Fernando Rios Siliceo** is a consultant in the Monterrey office; **Jesús Rodríguez González** is a partner in the Madrid office; and **Asong Suh** is an alumnus of the Houston office.

Unlocking opportunities from industrial electrification

Electrification brings major value creation opportunities for industrial companies across the value chain—from integrators to raw-material suppliers—but also requires timely actions and investments.

This article is a collaborative effort by Harald Bauer, Luigi Gigliotti, Tamara Grünewald, Friederike Liebach, Bram Smeets, Christer Tryggestad, and Raffael Winter, representing views from McKinsey's Advanced Industries and Global Energy & Materials Practices.



Electrification is one of the key trends shaping the global energy transition. And due to recent geopolitical developments, favorable economics, and the demand for decarbonization, the pace of this trend is set to accelerate.

Surging demand brings opportunities along the electrification value chain. Demand is already increasing for key assets including wind and solar systems to supply green power, heat pumps to decarbonize the space and water heating of buildings, battery energy storage systems to respond to an increasingly intermittent grid, electrolyzers to produce green hydrogen, and electric-vehicle charging infrastructure to support a paradigm shift in the mobility industry. The growing demand for assets creates knock-on demand for a broad variety of key components and raw materials.

To capture these opportunities, companies along the value chain must understand and anticipate emerging developments and act quickly to increase production or adjust their portfolio mix. The key questions and actions required will vary by type of company—they will be different for utilities and developers, for OEMs, and for component manufacturers and raw-material providers. The companies that emerge as industry leaders will be those that take action now and back up their plans with judicious investment.

This article offers a quantitative perspective on the opportunities unlocked through electrification, including an assessment of value pools for critical enablers and components. Increased electrification also comes with many barriers—especially risks involving supply chain bottlenecks—but these will be the focus of a future article.[1]

Electrification is under way, and demand is surging across the value chain

Recent years have seen a strong uptick in electrification rates in specific sectors, especially passenger cars. Even on its current trajectory, without further acceleration of decarbonization targets, demand for electricity as a proportion of the global energy consumption mix is projected to rise rapidly in the coming years. McKinsey's Global energy perspective 2022 projects that electricity demand will more than triple, rising from about 83 million terajoules (TJ) in 2020 to more than 252 million TJ in 2050.[2]

Multiple factors are contributing to the rise of electrification. Foremost is the urgent need to replace fossil fuels and prevent climate change, an imperative that has prompted many countries to strive for net-zero emissions by 2050. Electrification is also driven by economics as technologies become cheaper and more competitive. Our analysis indicates that electric vehicles, for example, are already cost competitive (when including subsidies) in many European countries today on a per-kilometer basis, and increasing gas commodity prices have substantially improved the financial attractiveness of residential heat pumps over alternatives.[3] The war in Ukraine has also led to surging energy prices and complications in the oil and gas supply chains, which are further accelerating the electrification shift as countries attempt to reduce costs and become more self-reliant.

The anticipated and accelerating boom in electrification unlocks significant value creation opportunities across the electrification value chain, including in assets, components, and raw materials.

[1] A user-based perspective on barriers and potential unlocks for electrification can be found in *Unlocking beneficial electrification: The voice of end users*, Global Sustainable Energy Partnership (GSEP), April 2021.
[2] *Global energy perspective 2022*, McKinsey, April 26, 2022; "Further Acceleration" pathway.
[3] Electrification model from the McKinsey Center for Future Mobility (MCFM), May 2022.

Assets

Key assets across electrification sectors are already seeing an increase in demand, with further strong growth anticipated. The following are some of those assets:

— *Wind power systems.* These systems—both onshore and offshore—are key for renewable-energy generation and are thus already well established in key markets such as Europe. Growth rates continue to be high: investments in wind energy increased by more than 70 percent from 2019 to 2021 in Europe, reaching €41 billion.[4]

— *Solar photovoltaic (PV) systems.* These systems are already well established as a renewable-energy generation technology, with demand especially strong in regions with high solar radiance.

— *Heat pumps.* These enable the replacement of high-emissive gas and oil boilers in residential and commercial buildings with electricity-based, low-carbon alternatives. European annual heat pump sales reached 2.0 million units in 2021 (an increase of around 30 percent from 2019) and are expected to double by 2026, which would mean installing about 16.5 million additional units in the next five years.[5]

— *Battery energy storage systems (BESS).* These systems enable the storage of intermittent renewable-power generation and have important residential, commercial, industrial, and utility-scale applications due to the need for increased grid flexibility. Global battery production capacities increased sixfold between 2016 and 2020, and the latest announcements from battery manufacturers indicate that this trajectory is likely to continue.[6]

— *Electrolyzers.* Used in green-hydrogen production, these will be critical in decarbonizing industry processes. Three electrolyzer technologies are likely to become key: polymer electrolyte membrane (PEM), alkaline water electrolysis (AWE), and solid oxide electrolyzer cell (SOEC). In the past six months, the number of confirmed hydrogen-related projects to come online by 2030 has increased by more than 20, reaching more than 100.[7]

— *Electric-vehicle charging infrastructure (EVCI).* This infrastructure is a key enabler of increased mobility electrification and the move away from internal-combustion engines. A wide network will need to be established to allow for fast and convenient charging.

Of these key electrification assets, wind power may be the greatest source of revenue (Exhibit 1).[8] The time period of 2021 to 2030 could mean about $1.8 trillion in aggregate for OEMs from sales of hardware related to wind power. Solar PV provides the second-largest revenue pool, followed by residential and commercial heat pumps. The revenue pools from these assets would be even larger with the addition of revenues from software and service offerings.

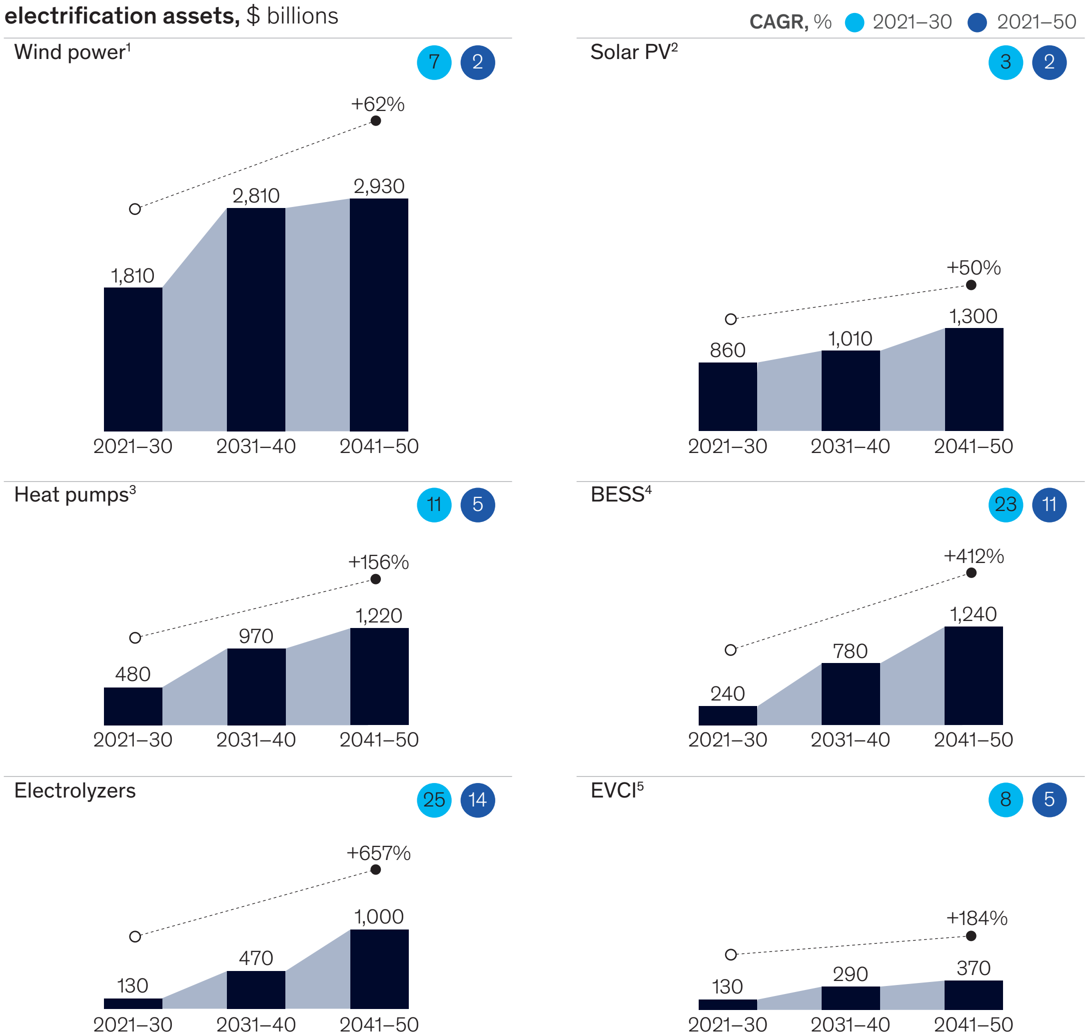
Technologies related to wind, solar PV, and heat pumps are already mature and have been widely adopted in many countries, especially in Europe. As a result, they offer significant revenue generation opportunities over the next decade, given that uptake is projected to grow significantly as a result of decarbonization efforts and further improvements in economics. BESS and electrolyzers are less mature, which means that they offer more opportunities for innovation and optimization, as well as greater growth potential if

[4] "Financing and investment trends 2021," WindEurope, May 4, 2022.
[5] Thomas Nowak, "European heat pump market," *REHVA European HVAC Journal*, August 2021, Volume 8, Number 4; "Press release #REPowerEU: 2x heat pump sales also requires a 'heat pump accelerator,'" European Heat Pump Association, March 9, 2022.
[6] McKinsey Battery Supply Tracker, June 2022.
[7] McKinsey Hydrogen Insights Project and Investment Tracker, May 2022.
[8] This figure includes only hardware-related revenues (that is, OEM sales) and does not include installation, EPC (engineering, procurement, and construction), or other services and software.

Exhibit 1

Wind and solar photovoltaics are the largest revenue pools, while electrolyzers and battery energy storage systems are the fastest growing.

Global cumulative revenues (OEM sales) for selected electrification assets, $ billions



Note: Figures are rounded.
[1]Turbine hardware, foundation, electrical infrastructure, and other balance-of-system (BOS) components. [2]Photovoltaic. Includes solar PV hardware only (includes modules, electrical BOS [eBOS], structural BOS [sBOS], inverters). [3]Residential and commercial heat pump hardware only. [4]Battery energy storage systems. Excludes engineering, procurement, and construction (EPC) and overhead costs. [5]Electric-vehicle charging infrastructure (DC and AC).
Source: McKinsey *Global energy perspective 2022* ("Further Acceleration" pathway)

adoption surges. Annual hardware revenue growth in these two categories is expected to exceed 20 percent globally from 2021 through 2030, far surpassing that of wind, solar PV, heat pumps, and EVCI.

Components

When breaking down the electrification assets into specific components, we see that most of the total value from each asset comes from a few key components (Exhibit 2), creating significant

Exhibit 2

Key components account for a significant share of total hardware revenue.

Global component-level cumulative revenues for selected electrification assets, 2021–30, $ billions

Note: Figures are rounded.
[1]Turbine hardware, foundation, electrical infrastructure, and other balance-of-system (BOS) components. [2]Photovoltaic. [3]Electrical balance of system. [4]Structural balance of system. [5]Residential and commercial heat pump hardware only. [6]Domestic hot water. [7]Battery energy storage systems. [8]Supervisory control and data acquisition. [9]Membrane electrode assembly. [10]Electric-vehicle charging infrastructure (DC and AC).
Source: McKinsey *Global energy perspective 2022* ("Further Acceleration" pathway)

opportunities for those involved in their manufacture and distribution. These components vary significantly by asset. With wind power assets, for instance, about a third of cumulative revenues from 2021 to 2030 are likely to come from blades (16 percent), towers (12 percent), and generators

(7 percent). By contrast, modules will constitute about half of revenues for solar PV components, while the control unit and compressor will account for 43 percent of heat pump component revenues.

Despite the diversity of components, electrification technologies often share some common characteristics, creating opportunities for companies to produce components with multiple applications. For instance, power electronics are essential for all electrification assets to perform up and down power conversion as well as rectification and AC-DC and DC-AC conversion, respectively. In the five years from 2020 to 2025, the market is expected to grow by 13 percent annually to more than $15 billion.[9]

The growing importance of power electronics is a major driver of semiconductor demand. For example, demand from industrial electronics, which accounts for about 10 percent of total semiconductor demand, is expected to increase by 9 percent annually between 2020 and 2025.[10]

Raw materials

Electrical equipment requires different types of raw materials in various combinations, which means that demand for raw materials is set to soar.[11] An increase in demand for assets therefore creates knock-on opportunities for miners, refiners, and other companies involved in the value chain of the corresponding raw materials.

For most electrification assets—including the six listed above—steel is essential. Steel demand for key electrification assets will grow more than 8 percent per annum by 2030, compared with an expected 1 percent for total steel demand.[12] While forecasts predict sufficient supply of steel, the demand for low-carbon-footprint (green) steel has increased due to decarbonization pressures. Green steel could be in short supply through 2030, with green premiums of $200 to $350 per metric ton through 2025 and possibly as much as $500 per metric ton through 2030.[13]

Demand for copper is also skyrocketing, partly because renewable-energy systems contain up to 12 times more copper than traditional energy systems such as fossil fuel power plants.[14] Driven by growing asset demand, the amount of copper needed to produce solar PV, for instance, is expected to double between 2020 and 2030. Any future mismatch between supply and demand could interfere with the production of many electrification assets.

Furthermore, many other raw materials are expected to see a large uptick in demand as electrification assets become popular. Rare earths such as neodymium and praseodymium are critical for wind power, for example. Polysilicon, gallium, Class 1 nickel, lithium, and cobalt will also be in high demand.

To ensure sufficient supplies, mining and refining capacity will have to increase worldwide—a step that will require significant and timely investment.

Setting a new course to capture value

The companies most intimately involved in developing and scaling electrification assets—and thus best positioned to capture the opportunity at hand—are utilities and developers, integrators and assemblers, component manufacturers, raw-material providers, and other industrials.

To seize the opportunities of rapid electrification, these companies must act quickly to ramp up production or adjust their portfolios (Exhibit 3). The actions required will vary by stakeholder.

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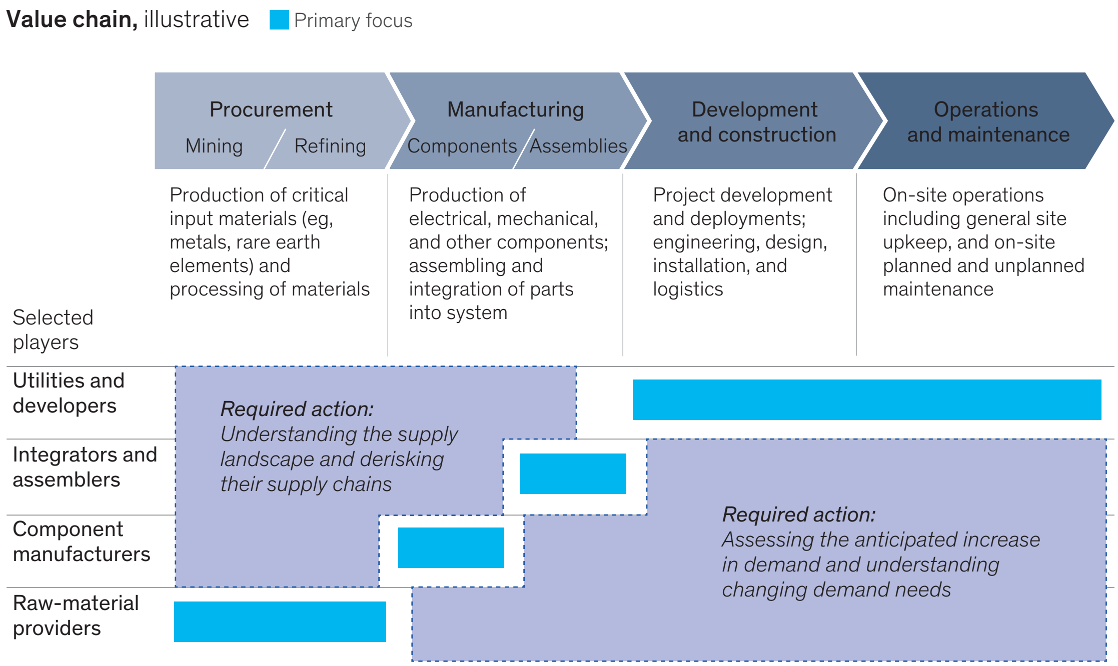
[9] McKinsey analysis; *Global energy perspective 2022*, April 26, 2022 (“Further Acceleration” pathway).
[10] Values based on 300 nanometer wafer-equivalent; “industrial electronics” also includes non-electrification-related technologies, such as automation and medical electronics; Omdia Q1 2022 semiconductor market analysis; World Fab Forecast SEMI, September 2021.
[11] “The raw-materials challenge: How the metals and mining sector will be at the core of enabling the energy transition,” McKinsey, January 10, 2022.
[12] Electrification assets include wind, solar PV, heat pumps, and BESS; McKinsey Metal Spans 2022 and McKinsey Basic Materials Insights; *Global energy perspective 2022*, April 26, 2022 (“Further Acceleration” pathway).
[13] McKinsey Green Materials Initiative (Q1 2022) and McKinsey Basic Materials Insights.
[14] “Copper: How much will the green transition impact demand?,” Fitch Solutions, June 24, 2021.

Exhibit 3

Actions required to capture the opportunity created by electrification vary by stakeholder along the end-to-end value chain.



Utilities and developers

Downstream players must understand the supply landscape and derisk their supply chains by, for example, securing long-term supply and forming partnerships or joint ventures with suppliers.

Major electric-vehicle companies, for instance, have been among the quickest to secure their supply of raw materials because they expect a strong surge in battery demand. They have moved quickly to form partnerships and develop long-term contracts with suppliers of cobalt, lithium, nickel, and other key raw materials. Furthermore, major companies along the automotive value chain are joining forces to make their supply chains more resilient.

Integrators and assemblers

Integrators and assemblers must prepare to capture the opportunities of increased future scale by expanding production capacities and adjusting their product portfolios and expertise to unlock high-value, high-growth technologies. Their options include investing resources and sustained management attention in organic growth, partnering, or pursuing inorganic growth by acquiring other companies to expand production capacity or import the expertise to fill critical capability gaps.

Component manufacturers and raw-material providers

Companies in the component and raw-material space must assess the anticipated increase in demand for their products and—like integrators and assemblers—must work to better understand the changing demand needs of their future customers. In many cases, the current go-to-market strategy may not be appropriate for the scale and variety of customers and partners they will need to interact with in the future.

Moreover, component manufacturers and raw-material providers should identify how their capabilities can be used or adapted to enable new technologies and should adapt their offerings and expand production capacity to meet future demand. Most major steel producers, for example, have already announced their intention to open low-CO_2 flat steel factories in Europe or to develop the new capabilities to respond to the increasing demand for low-carbon alternatives to existing products.

Rapid electrification will create new and growing value pools for companies across the value chain, from assets to components and raw materials. The companies that capture this opportunity will be those that can both anticipate key trends early on and pivot quickly to develop new capabilities or boost capacity. These investments will pay off in the years to come.

Harald Bauer is a senior partner in McKinsey's Frankfurt office, where **Friederike Liebach** is a consultant; **Luigi Gigliotti** is an associate partner in the Geneva office; **Tamara Grünewald** is an associate partner in the Zurich office; **Bram Smeets** is a partner in the Amsterdam office; **Christer Tryggestad** is a senior partner in the Oslo office; and **Raffael Winter** is a partner in the Düsseldorf office.

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Innovation and technology

Renewable-energy development in a net-zero world

Global decarbonization will require a massive build-out of wind and solar farms. But can developers find enough land, secure the supply chain, and recruit workers while maintaining profitability?

This article is a collaborative effort by Florian Heineke, Nadine Janecke, Holger Klärner, Florian Kühn, Humayun Tai, and Raffael Winter, representing views from McKinsey's Electric Power & Natural Gas Practice.

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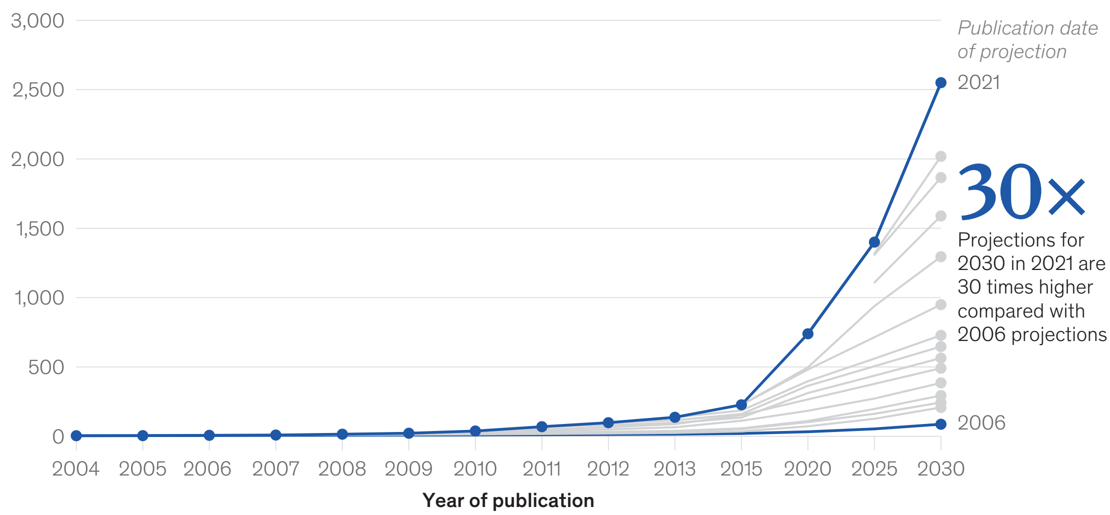
The rapid maturation of wind and solar power has been nothing short of astonishing. Not long ago, the development of new solar and wind farms was typically driven by small regional players, and the cost was significantly higher than that of a coal plant. Today, the cost of renewables has plummeted, and many solar and wind projects are undertaken by large multinational companies, which often also announce staggering development targets.

Over the past decade, the growth of renewable energy has consistently and dramatically outperformed nearly all expectations (Exhibit 1). Upward corrections of estimates have become something of a ritual.

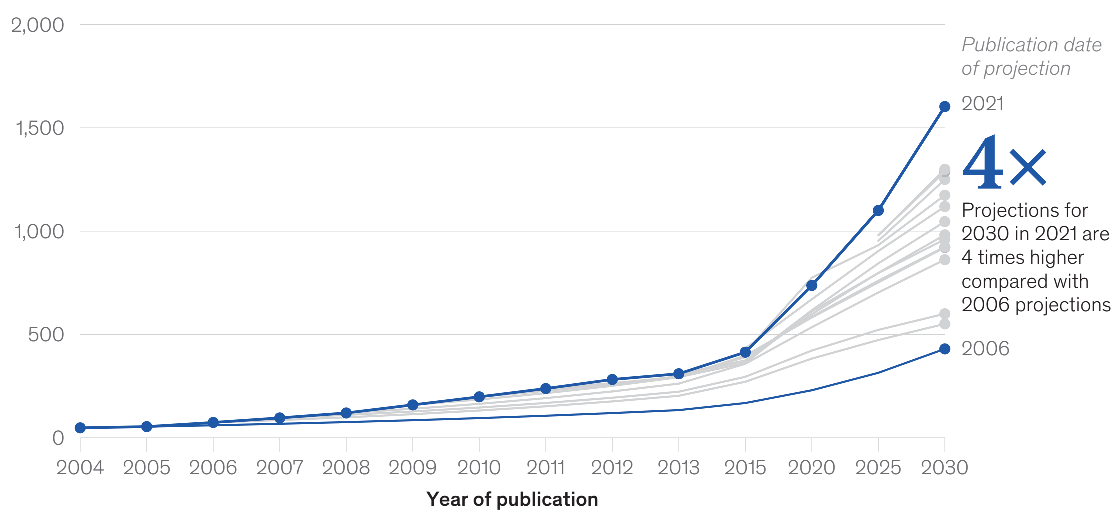
Exhibit 1

Today's projections for solar and wind power capacity in 2030 predict values much higher than those projected in 2006.

Global forecast of solar PV[1] capacity, GW



Global forecast of wind onshore and offshore capacity, GW



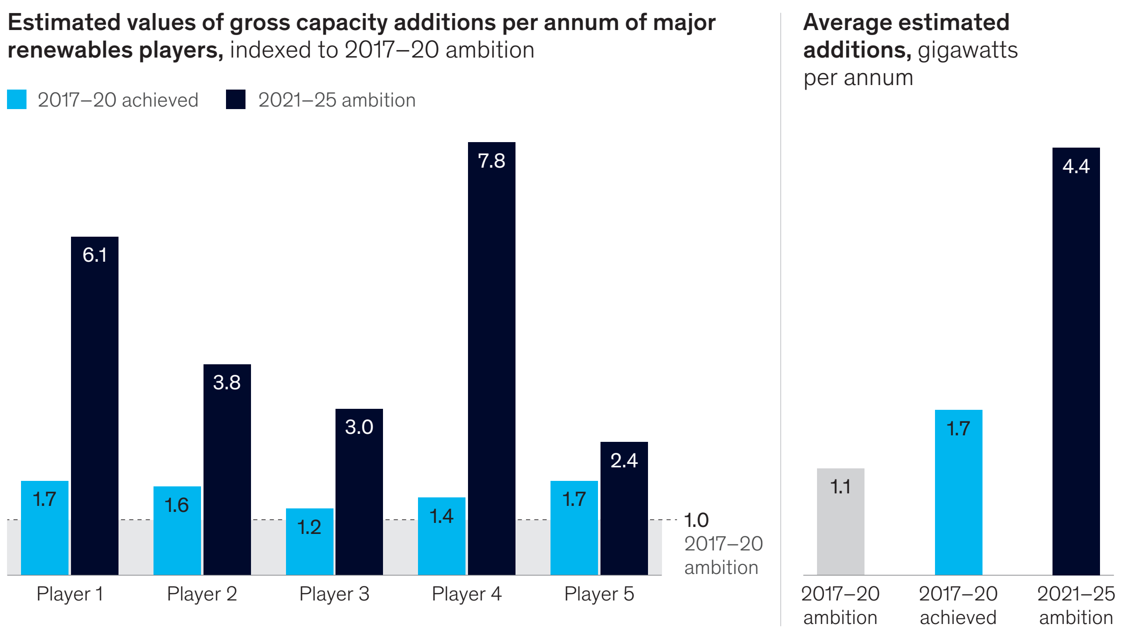
Note: Predictions start 2 years before publication date to show historic capacities as a base.
[1]Photovoltaics.
Source: IEA World Energy Outlook, New Policy Scenario and Stated Policy Scenario, updated September 2022

But this growth story is just getting started. As countries aim to reach ambitious decarbonization targets, renewable energy—led by wind and solar—is poised to become the backbone of the world's power supply. Along with capacity additions from major energy providers, new types of players are entering the market (Exhibit 2). Today's fast followers include major oil and gas companies, which aim to shift their business models to profit from the increased demand for renewables and the electrification of vehicles, and private-equity players and institutional investors that make renewable energy a central component of their investment strategy. Leaders in the shipping industry are investing in renewables to enable the production of hydrogen and ammonia as zero-emission fuel sources; steel manufacturers are eyeing green hydrogen to decarbonize their steel production, with renewables providing the green electricity for the process. Car manufacturing companies are also striking renewable-energy deals to help power their operations and manufacturing, as well as making investments in wind and solar projects.

McKinsey estimates that by 2026, global renewable-electricity capacity will rise more than 80 percent from 2020 levels (to more than 5,022 gigawatts).[1] Of this growth, two-thirds will come from wind and solar, an increase of 150 percent (3,404 gigawatts). By 2035, renewables will generate 60 percent of the world's electricity.[2] But even these projections might be too low. Three years ago, we looked at advances made by renewable energy and asked, "How much faster can they grow?"[3] The answer is: faster than you think they can.

Exhibit 2

Capacity additions have outperformed ambitions, with future plans scaling even higher.



Source: Company annual reports

[1] *Global Energy Perspective 2022*, McKinsey, April 2022.
[2] Ibid.
[3] "Rethinking the renewable strategy for an age of global competition," McKinsey, October 11, 2019.

Three core capabilities for wind and solar developers

This race to build additional solar and wind capacity increases the pressure on developers to execute efficiently and heightens competition for finite resources. Still, the three winning capabilities we identified three years ago as important for building or expanding a renewables business are even more critical now. They form the bedrock required to tackle upcoming challenges:

— *Value-chain excellence.* As competition intensifies and government support for renewables subsides, strong capabilities across the entire value chain are the required cost of admission. For instance, gaining access to scarce amounts of attractive land will require differentiation in project origination and development. As margins squeeze and operators' exposure to risk increases, ambitious companies will want to explore new, profitable offtake markets for their electricity, such as data centers or hydrogen electrolyzers for industrial production.

— *Economies of scale and skill.* Driven by the rapid scaling of the renewables industry, many players have built efficient operating models. However, finding employees with the necessary skills and capabilities, particularly in high-demand areas such as project development and engineering, is becoming a bottleneck for growth ambitions.

— *Agile operating model.* Agility and speed will be key in finding innovative ways to integrate partners and in establishing robust, high-performing supply chains. They will also enable businesses to shift resources quickly to the biggest value pools and respond to changes in the landscape, such as shifting regulations or price volatility.

Four challenges that will define the new era of renewable energy

Leveraging these capabilities as a strong foundation, successful renewables developers must navigate an increasingly complex and competitive landscape. Specifically, they will have to focus on and address four emerging challenges:

— *A scarcity of top-quality land.* Developers are in a constant scramble to identify new sites with increasing speed. Our analysis in Germany, a country aiming to nearly double its share of electricity coming from renewables by 2030, offers a glimpse into the constraints. Of the 51 percent of the country's land that is potentially suitable for onshore wind farms, regulatory, environmental, and technical constraints eliminate all but 9 percent.[4] Meeting capacity targets will mean adding wind turbines to 4 to 6 percent of the country, giving developers very little room for error.

— *A blue-collar and white-collar labor shortage.* Across economies, the "Great Attrition" is making it difficult for companies to find and keep employees. Since April 2021, 20 million to 25 million US workers have quit their jobs, and 40 percent of employees globally say they are at least somewhat likely to leave their current position in the next three to six months.[5] This environment presents a particularly acute challenge for industries such as renewable energy, where specific technical expertise and experience are crucial elements of success. For instance, our analysis suggests that between now and 2030, the global renewables industry will need an additional 1.1 million blue-collar workers to develop and construct wind and solar plants, and another 1.7 million to operate and maintain them.[6] This includes construction laborers, electricians, truck and semitrailer drivers, and operating engineers.

[4] McKinsey land use optimization model.

[5] Aaron De Smet, Bonnie Dowling, Bryan Hancock, and Bill Schaninger, "The Great Attrition is making hiring harder. Are you searching the right talent pools?," *McKinsey Quarterly*, July 13, 2022; Table 4. Quits levels and rates by industry and region, seasonally adjusted, US Bureau of Labor Statistics, updated October 4, 2022.

[6] *Renewable energy benefits: Leveraging local capacity for onshore wind*, International Renewable Energy Agency (IRENA), 2017; *Renewable energy benefits: Leveraging local capacity for offshore wind*, IRENA, 2018; *Renewable energy benefits: Leveraging local capacity for solar PV*, IRENA, 2017.

— *Supply chain pressures.* The soaring cost of steel, manufacturing disruptions caused by extended lockdowns in China, and transportation backlogs at ports are already making it difficult for wind and solar developers to complete projects in their pipeline on time and on budget. Some of these pressures will abate as others move to the forefront. For instance, many of the raw materials needed to manufacture solar panels and wind turbines are projected to be in short supply. This includes nickel, copper, and rare earth metals such as neodymium and praseodymium, which are indispensable for the creation of magnets used in wind turbine generators.

— *Pressure on profits and volatility of returns in the short term.* The increasing number of players moving into the renewable-development space, combined with reduced levels of government support and higher costs of materials, technology, and financing, is putting pressure on returns. At the same time, an all-time-high price volatility creates uncertainty and market risk.

Renewables developers will need to act decisively to prepare for these upcoming challenges. In a series of future articles, we provide detailed insights on each of these pressures and share potential ways players can take action.

Florian Heineke is a consultant in McKinsey's Frankfurt office; **Nadine Janecke** is an associate partner in the Hamburg office; **Holger Klärner** is a partner in the Berlin office; **Florian Kühn** is a partner in the Oslo office; **Humayun Tai** is a senior partner in the New York office; and **Raffael Winter** is a partner in the Düsseldorf office.

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Renewable-energy development in a net-zero world

Land, permits, and grids

Finding large tracts of land for solar and wind farms is getting harder. Developers will have to strengthen capabilities and enhance their operational effectiveness.

This article is a collaborative effort by Nadia Christakou, Florian Heineke, Nadine Janecke, Holger Klärner, Florian Kühn, Humayun Tai, and Raffael Winter, representing views from McKinsey's Electric Power & Natural Gas Practice.

Achieving the goal of net-zero carbon emissions by 2050 will require staggering increases in the amount of electricity coming from renewable sources. In just the next few years, McKinsey estimates that global renewable electricity capacity will almost triple between 2021 and 2030 to more than 8,800 gigawatts. Of this, the vast majority will come from onshore wind and solar.[1]

Additional solar panels and onshore wind turbines will need land—and a lot of it. Utility-scale solar and wind farms require at least ten times as much space per unit of power as coal- or natural gas–fired power plants, including the land used to produce and transport the fossil fuels.[2] Wind turbines are often placed half a mile apart, while large solar farms span thousands of acres.

The implications of this are daunting. Developers need to continuously identify new sites with increasing speed at a time when the availability of suitable, economically desirable land is getting tighter. Solar farms require flat, dry, sunny locations, while the best sites for onshore wind turbines are the tops of smooth, rounded hills, open plains, and mountain gaps that funnel and intensify wind. Many of the most attractive of these locations are already taken.

In this article, we explore several of the biggest constraints that wind and solar developers face in their search for clean-energy real estate. We also discuss how they can prepare for these intensifying land battles.

Regulatory and sustainability limits

To illustrate how little land is available for renewables development in some countries, we created a model for evaluating potential onshore wind development sites. In Germany, for instance, our analysis shows that of the 51 percent of the country's land potentially suitable for wind farms, only 9 percent remains after factoring in regulatory, environmental, and technical constraints (Exhibit 1). The biggest factor affecting land availability is regulation in some German states related to the distance between wind turbines and human settlements, followed by concerns about biodiversity and animal habitats. Despite recent discussions about loosening distance rules, these and other regulations will likely continue to be the primary constraint for wind development. This 9 percent of available land, which represents a low starting point for renewables developers, could be further reduced by cost considerations and public opposition. With Germany aiming to get 100 percent of its energy from renewable sources by 2035,[3] its capacity targets for onshore wind mean wind turbines must cover 4 to 6 percent of the country's land, giving developers very little room for error.

Similar regulatory constraints exist in other countries. For instance, in France, our land-use analysis shows that wind turbines are restricted from about half of France's total land area. This is because of flight paths, historic or protected sites, and radar exclusion zones—areas where wind turbines may interfere with military, civil, and commercial aviation radar systems.

In the United States, solar projects face a different constraint: increasingly contentious land-use protests. In 2021, 10 percent of planned solar capacity was canceled during the permitting stage, largely due to well-organized public opposition.[4] Reasons for this resistance include concerns about the aesthetics of solar farms, the loss of arable land, effects on wildlife habitats, concerns about harm to property values, and fears about health and safety. In China, provincial officials in Hebei also recently banned solar panels on arable land.[5]

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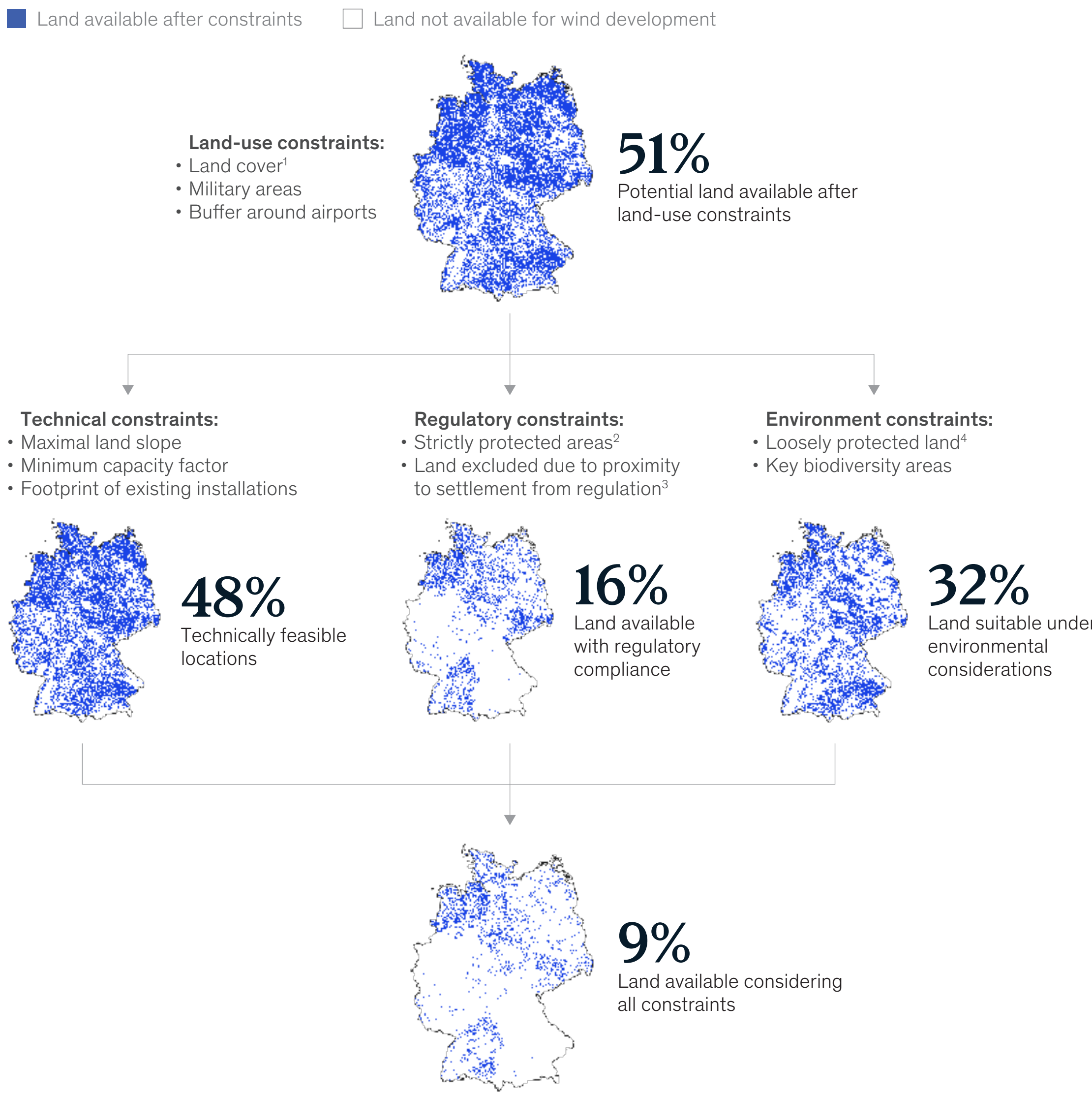
1 McKinsey's Energy Insights, Global Energy Perspective.
2 Samantha Gross, "Renewables, land use, and local opposition in the United States," Brookings, January 2020.
3 Markus Wacket and Zuzanna Szymanska, "Germany aims to get 100% of energy from renewable sources by 2035," Reuters, February 28, 2022.
4 Nichola Groom, "Special report: US solar expansion stalled by rural land-use protests," Reuters, April 7, 2022.
5 Yuan Ye, "China's solar projects raise land grabbing concerns," *Sixth Tone*, June 17, 2022.

Exhibit 1

Only 9 percent of Germany’s land is available for onshore wind development, considering various constraints.

Area theoretically suitable for wind turbines (150-meter height)



Disclaimer: Our land-use model has a national scope. Considering the necessary simplification, as well as the potential inaccuracies of the data at such a large scale, the results are not intended to represent precise local geographic contexts (such as land rights or planned land use) or recent local developments (political or otherwise). Although our analytics can provide useful directional guidance, drawing any local conclusions will require additional detailed, local studies.

[1]Land not available for solar and wind corresponds to all closed-forests land, urban areas, and bodies of water.
[2]Includes a 200-meter buffer around protected land with protection categories I–IV (strict nature reserve, wilderness area, national park, and natural monument or feature).
[3]Minimum proximity to settlements based on regional-level regulation.
[4]Includes protected land with categories V and VI (protected landscape or seascape and protected area with sustainable use of natural resources) or other.
Source: McKinsey land-use optimization model SpaceFit

Rising land prices

The areas suitable for wind and solar installations have attracted many interested parties, including small and medium-size renewables developers, large utilities, independent power producers, oil and gas majors, and financial players. In addition, other players, such as commercial and residential developers or agricultural companies, may be eyeing the same land. This wide range of interest has had the predictable effect of pushing land prices steadily upward over the past decade. Even though most wind and solar developments involve lease agreements, not land sales, ultimately these deals are driven by land prices. While countries such as France and Spain have experienced moderate price increases of 1 percent annually, land values in Germany and the United States soared nearly 10 percent annually between 2011 and 2020 (Exhibit 2). Furthermore, lease models can be complex: leasing rates can be tied to the surface area, installed capacity, energy generated, or even the revenue or profits generated by a project. This makes it difficult for developers to compare sites and evaluate their financial attractiveness early in the process.

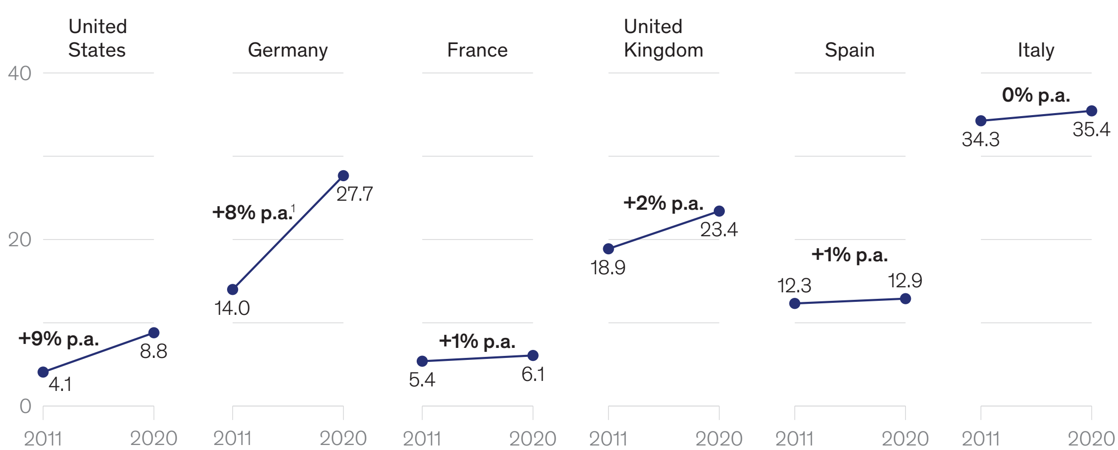
Long, unpredictable development timelines

Finding attractive locations for wind or solar installations often means a consideration not only of the land itself but also of the process and time required to receive the permits to develop it. Many factors in this process are outside of a developer's immediate control. Gaining the required permits, for instance, is usually a slow and decentralized process involving multiple governmental authorities and frequently shifting regulations. Although

Exhibit 2

In nine years, average land prices grew nearly 10 percent per year in Germany and the United States.

Average prices for nonresidential land, € thousands per hectare



[1]Per annum.
Source: Agricultural land prices by region, Eurostat, March 11, 2022; Average value of U.S. farm real estate per acre from 1970 to 2021, Statista, August 19, 2022; Olaf Zinke, "Land prices are on the rise: This is what farmers now have to pay," Agrarheute, October 28, 2021; US Department of Agriculture

regulators' standards for transparency and customer affordability continue to rise, these authorities often lack the staffing, capabilities, and tools to handle the permitting process efficiently. As a result, permitting can span up to ten years, from project start to permits granted. Onshore wind projects take the longest to gain approval, with developers in France and Italy experiencing the longest median duration: eight and seven years, respectively (Exhibit 3).

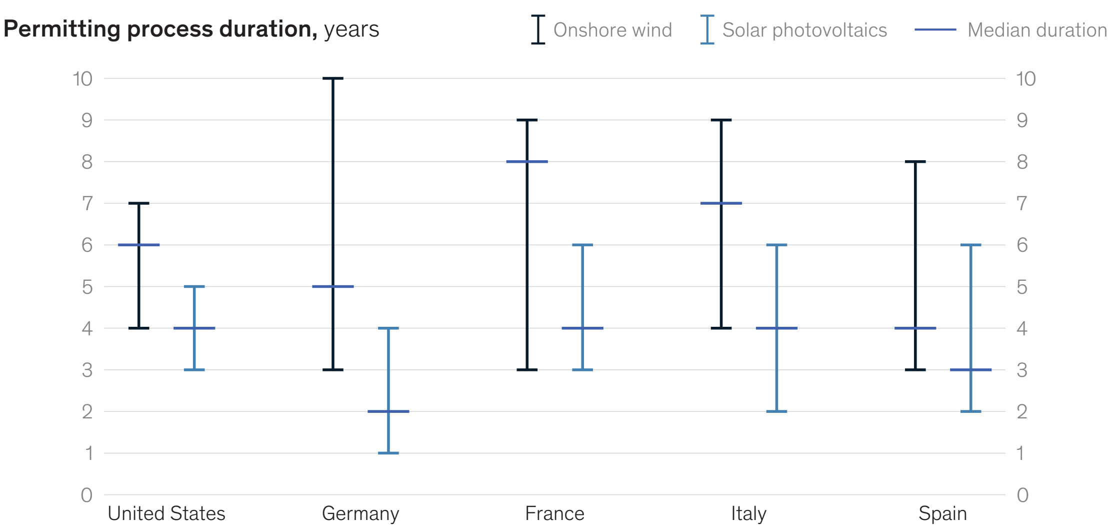
This development and permitting process is also subject to delays that result from public opposition. Even when resistance does not prevent new solar and wind projects, it can cause significant complications. Lawsuits, for example, can delay processes by several years and create unforeseen cost increases. In response, some developers have increased the level of stakeholder engagement they pursue. This can include a range of options, such as active outreach, public hearings, municipal consultations, collaborative decision making with key stakeholders, and even the possibility of giving residents equity or other forms of financial participation in the project.

Increased grid congestion

Utility-scale solar or wind installations need more than land. They also need a large-scale grid infrastructure that will transport clean energy to end users. In many countries, the land most available and suitable for wind and solar development is not located near the dense population, commercial, and industrial centers that need the most electricity. This is particularly true in the United States, where significant power imbalances exist. Densely populated states such as California, Massachusetts, and New York have considerable power deficits (of ten to 40 gigawatt hours), while rural states such

Exhibit 3

The permitting process (from project start to granted permit) for onshore wind projects can take years longer than the process for solar projects.



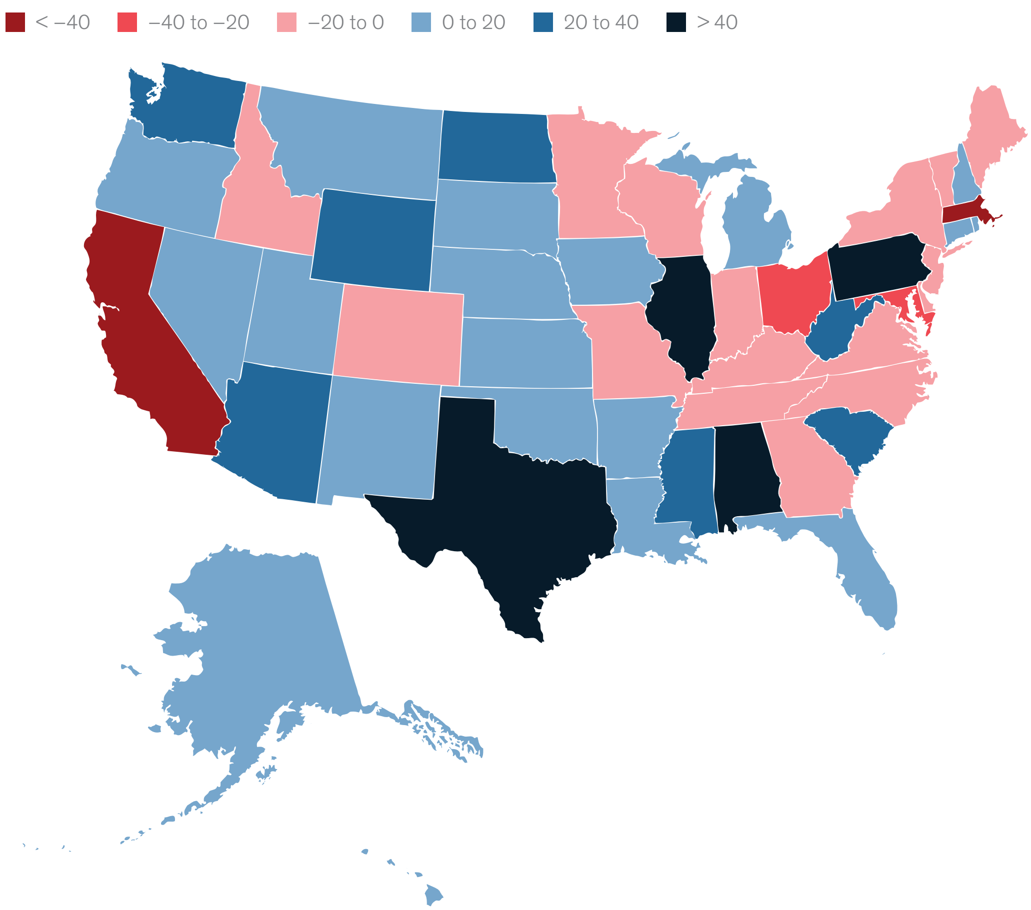
Source: Wind Europe; Fachagentur Windengerie an Land (Agency for Onshore Wind Energy) as North Dakota, Texas, and Wyoming have surpluses (of 30 to 40 gigawatt hours) (Exhibit 4). Building new transmission lines to connect rural areas to cities can also be a lengthy and expensive process, subject to its own set of challenges from landowners who don't want power lines they don't benefit from running along their property.

Beyond transmission, grid congestion also arises from a lack of systemwide flexible assets (such as battery storage systems or pumped stored hydroelectricity) that help manage the significantly higher level of variability inherent to wind and solar energy. Because the stability of the power grid depends on predictability and a balance of supply

Exhibit 4

There are significant power imbalances in the United States from region to region and even between neighboring states.

Electricity generation minus consumption, 2020, gigawatt hours



Source: US Energy Information Administration and demand, the US grid is not always able to immediately integrate all new wind and solar power. Renewable projects can wait for months[6] or even years to be connected to the grid. Projects occasionally have to be shut down, leading to lost investments and missed opportunity for developers, regulators, and society. Although this problem is particularly prevalent in the United States, countries such as Australia, Germany, and Italy face similar issues.[7] If investors and developers determine that unsolved congestion issues are creating unattractive market conditions, they may choose to exit the market. This presents a major risk to a country's renewables expansion targets and net-zero commitments.

Implications for developers

To remain competitive and ensure a smooth and successful development process, renewables players need to proactively address these challenges. We highlight five crucial steps developers may want to take:

Build strengths in early land origination. Finding suitable and financially attractive sites requires thorough and extensive site scouting and relationship building with local leaders, activists, and landowners. Such capabilities are distinctly different from those of project development, which focuses on the permitting processes, technical coordination, and structured public outreach. To ensure the optimal deployment of resources, larger developers may want to adjust their operating model to separate origination from project development. Incentivization mechanisms, such as equity stakes for individuals within an organization who successfully identify wind or solar sites, may also help to build the pipeline of new sites.

Create agile and lean processes across the organization. Succeeding in a challenging and highly competitive environment will mean moving quickly, efficiently, and strategically. For instance, to boost chances of finding suitable land, developers may want to identify as many sites as possible and then quickly narrow them down based upon on a clear, transparent, fast, and digitally enabled process. In addition, as community and stakeholder engagement becomes an increasingly important aspect of renewables development, companies will also need to develop the capability to do effective outreach.

Incorporate a bottom-line view for site identification. Ideal locations for wind and solar installations are those that will not only generate electricity at the lowest possible cost but also create value for shareholders. To make sure sites will become profitable later in their life cycle, site originators and project developers should complement their technical evaluations with an understanding of favorable market conditions, advantageous regulations, auctioning schemes, and grid modeling. These capabilities are often present in other parts of the organization, such as commercial, strategy, and regulatory affairs, or outside of the organization for pure developers. Building them up and leveraging them early in the site identification process can increase a project's future value and reduce the risk of unforeseen cost explosions.

Look to industrial players for additional land and new customer revenue. Industrial manufacturers such as aluminum, steel, cement, and chemical producers are faced with the formidable challenge of decarbonizing their energy-intensive operations. By building renewable-energy-generation assets on the sites of these producers, developers can help them replace fossil-based assets, reduce their dependency on power from the grid, and use clean energy to power their operations. For developers, this direct link to industry can present an attractive opportunity to diversify their revenue sources and bypass challenges related to land scarcity. To be successful, they need to develop new organizational

[6] Gracie Brown, Bernice Chan, Rory Clune, and Zak Cutler, "Upgrade the grid: Speed is of the essence in the energy transition," McKinsey, February 1, 2022.
[7] Christopher Hopson, "Grid congestion choking Australia's massive renewable energy pipeline: WoodMac," *Recharge*, May 1, 2020; Sophie Vorrath, "Grid problems now the biggest turnoff for renewable energy investment in Australia," *Renew Economy*, July 29, 2020; Jason Deign, "Germany's maxed-out grid is causing trouble across Europe," *Greentech Media*, March 31, 2020; "Focus on energy transition: Italy unveils grid development plan 2021," ReGlobal, October 13, 2021; Enza Tedesco, "Italian grid to struggle with fast green growth - experts," *Montel*, April 26, 2022.

capabilities and build strong ties with industry players. Once a customer relationship is established, this can be a basis for further upselling opportunities, such as in energy management services.

Strengthen communication and public advocacy. Throughout the development process, various external stakeholders influence the success or failure of projects. To improve the likelihood of a project's success, developers should enhance their ability to manage the flow of information. When creating new regulations or market frameworks, authorities need the perspective, project experience, and insights of developers. Renewables players should understand the value they can bring and establish strong channels of communication with authorities to ensure that perspectives are being exchanged and aligned regularly. To mitigate the risk of public opposition, developers should actively manage public opinion throughout the process and host forums for public participation early and often.

The renewables sector is at an exciting yet challenging crossroads. Now is the time for developers to use the market's momentum to get their organizations ready for an era of fierce competition for scarce land.

Nadia Christakou is an associate partner in McKinsey's Geneva office; **Florian Heineke** is a consultant in the Frankfurt office; **Nadine Janecke** is an associate partner in the Hamburg office; **Holger Klärner** is a partner in the Berlin office; **Florian Kühn** is a partner in the Oslo office; **Humayun Tai** is a senior partner in the New York office; and **Raffael Winter** is a partner in the Düsseldorf office.

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Renewable-energy development in a net-zero world

Overcoming talent gaps

The rapid growth of renewables depends on the industry finding enough employees with the right skills and experience.

This article is a collaborative effort by Paul Daume, Florian Heineke, Nadine Janecke, Holger Klärner, Jan Krause, and Raffael Winter, representing views from McKinsey's Electric Power & Natural Gas Practice.

Across economies, the Great Attrition is making it difficult for companies to find and retain employees. Since April 2021, 20 million to 25 million US workers have quit their jobs, and 40 percent of employees globally say they are at least somewhat likely to leave their current position in the next three to six months.[1] Companies have yet to get a handle on this problem. Many do not understand why their employees are leaving or know where they are going. Furthermore, 65 percent of these employees will not return to the same industry, complicating matters for companies.[2]

This environment presents a particularly acute challenge for industries such as renewable energy, in which specific technical expertise and experience are crucial elements of success. The pressure intensifies when those industries are also growing rapidly. McKinsey estimates that the global installed capacity of solar and onshore and offshore wind projects will have quadrupled from 2021 to 2030.[3] This huge surge in new wind and solar installations will be almost impossible to staff with qualified development and construction employees as well as operations and maintenance workers (Exhibit 1).

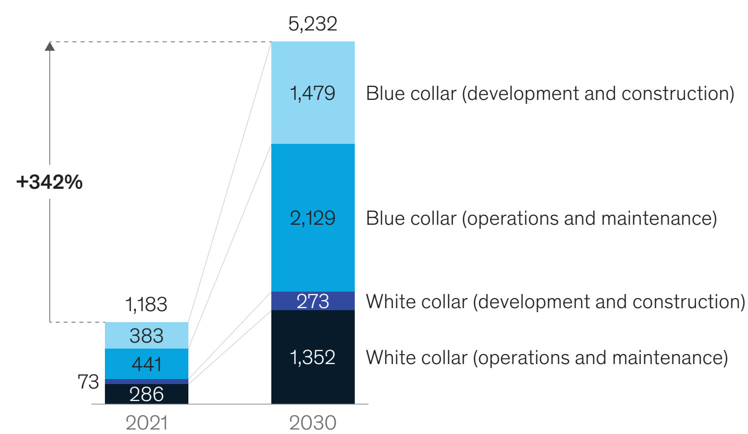
Even if today's demand for workers in the renewables industry could be met, it's unclear where these employees will come from in the future. There are too few people with specialized and relevant expertise and experience, and too many of them are departing for other companies or other industries. Once employees leave, replacing them can be extremely difficult for companies.

In this article, we delve into the talent challenges the renewables industry faces as it plans for massive scaling and expansion—and what players can do to get ahead of the game.

Exhibit 1

Estimated full-time-equivalent needs for the global development, construction, and operation of wind and solar assets will more than quadruple by 2030.

Estimated annual full-time-equivalent demand, thousands



Note: Excludes China.
Source: McKinsey analysis

[1] Aaron De Smet, Bonnie Dowling, Marino Mugayar-Baldocchi, and Bill Schaninger, "'Great Attrition' or 'Great Attraction'? The choice is yours," *McKinsey Quarterly*, September 8, 2021; Aaron De Smet, Bonnie Dowling, Bryan Hancock, and Bill Schaninger, "The Great Attrition is making hiring harder. Are you searching the right talent pools?," *McKinsey Quarterly*, July 13, 2022; Table 4. Quits levels and rates by industry and region, seasonally adjusted, US Bureau of Labor Statistics, October 4, 2022.
[2] "The Great Attrition is making hiring harder," July 13, 2022.
[3] In comparison with 2021, excluding China; from the Achieved Commitments scenario in *Global Energy Perspective 2022*, McKinsey, April 26, 2022.

The global renewables industry will need an additional 1.1 million blue-collar workers to develop and construct wind and solar plants and another 1.7 million workers to operate and maintain them.

A scarcity of specialized talent in both blue- and white-collar jobs

The sheer size of the talent gap is staggering. Our analysis suggests that between now and 2030, the global renewables industry will need an additional 1.1 million blue-collar workers to develop and construct wind and solar plants and another 1.7 million workers to operate and maintain them.[4] These include construction laborers, electricians, and operating engineers. Prior to the Great Attrition, the market for such on-site technical occupations was already small and subject to the significant employee turnover common in blue-collar jobs. In Europe, some of these blue-collar professions needed for renewable energy expansion, such as electricians, are in the shortest supply.[5] Making matters worse, time to hire in the energy industry is long. For instance, with 1.7 vacancies per unemployed energy technician in Germany, the average time to fill a vacancy for this role is more than six months.[6]

White-collar workers will also be difficult to find. Until 2030, projects will require a total of 1.3 million additional wind and solar project developers, project managers, finance experts, legal staff, and many other roles to install, operate, and maintain the projected capacities.[7] Individuals with successful track records and more than half a dozen years of experience will represent the biggest shortage for these white-collar roles. When companies do manage to hire these workers, keeping them will be crucial.

The reasons these employees switch jobs or industries go beyond salaries. For example, one major driver is a lack of career development opportunities, including the chance to switch roles (such as from project manager to technical expert) or to progress quickly in one's current role. For experienced high performers, compensation mechanisms with limited opportunities for bonuses or upsides also play a role. Additionally, employees in the renewables industry sometimes leave their jobs for cultural or personal reasons. For example, at large utilities that have gone through periods of fast growth over the past decade, decision-making processes and collaboration styles have not kept pace with the changing times and have led to employee frustration.

4 In comparison with 2021 to 2030, excluding China; calculations based on International Renewable Energy (IRENA) reports on wind and solar and *Global Energy Perspective 2022* Achieved Commitments scenario; *Renewable energy benefits: Leveraging local capacity for onshore wind*, IRENA, 2017; *Renewable energy benefits: Leveraging local capacity for offshore wind*, IRENA, 2018; *Renewable energy benefits: Leveraging local capacity for solar PV*, IRENA, 2017.
5 *Report on labour shortages and surpluses*, European Labour Authority, November 2021.
6 *Reported vacancies by occupation (bottleneck analysis)*, German Federal Agency for Work, September 2022.
7 In comparison with 2021 to 2030, excluding China; calculations based on International Renewable Energy (IRENA) reports on wind and solar and *Global Energy Perspective 2022* Achieved Commitments scenario.

Once these white-collar talents leave for more attractive options, they are often removed, at least temporarily, from the job market. Their new employers may use long-term incentives, such as equity options on renewables assets, to bind them to the company for as long as possible, thus exacerbating the scarcity of white-collar talent.

Broad increases in salary levels across the industry

As talent has grown scarce, salaries paid by companies in the renewables industry have risen and are expected to keep growing.[8] Notable variations exist among geographies, individual positions, and company types. Unsurprisingly, US companies pay significantly more than their European counterparts: the average US salary is roughly 40 percent higher. The highest salaries belong to senior-management positions in the United States, such as directors or vice presidents of renewables business units. Across different companies—utilities, renewables developers, oil and gas majors, and financial firms—average salaries are comparable but the ranges differ. Utility salaries often don't reach beyond a certain level, whereas other players, especially oil and gas majors, have more flexibility to offer prospective employees higher salaries and more upside potential (Exhibit 2).

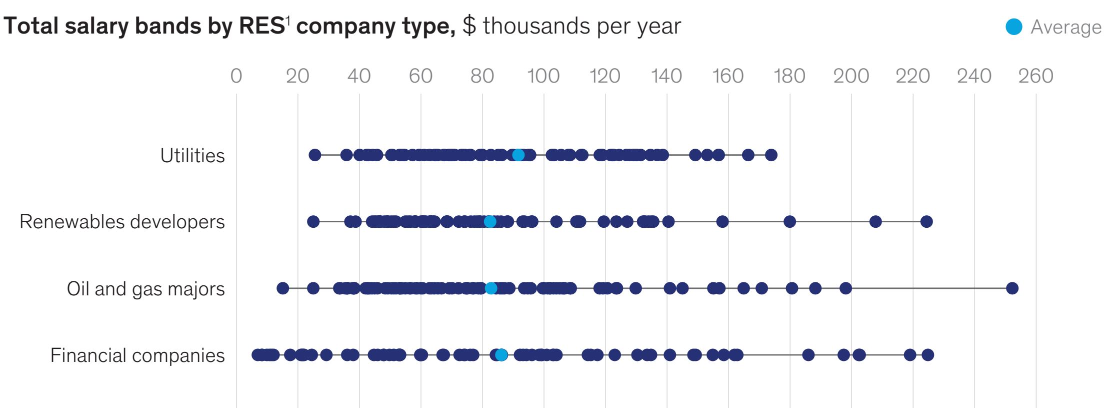
These differences confer a competitive advantage on companies with the flexibility and financial power to make the best offers. A decade ago, most people in the renewables industry worked for small and medium-size developers, utilities, or independent power producers. In recent years, large oil and gas companies and financial firms have entered the market. These well-heeled competitors exert pressure on the search for land, wind and solar project returns, M&A options, and talent. They try to attract top performers with offers that include high salaries, bonuses, and long-term incentives. In response, small and medium-size developers have upped their game by offering employees unconventional incentives, such as equity participation in new wind and solar projects.

Traditional utility companies, independent power producers, and large renewables developers are having difficulty keeping pace. Although their average salaries are in line with the market, the upside potential they offer to experienced high

Exhibit 2

On average, salaries are similar across renewables players, but utilities pay less for top jobs.

Total salary bands by RES[1] company type, $ thousands per year



[1]Renewable energy sources.

[8] August 2022 Glassdoor job portal analysis of more than 300 renewables job vacancies, including 27 companies in Brazil, Europe, India, and the United States; salaries include base pay and average additional pay (such as bonuses).

performers is limited. As oil and gas majors increasingly expand their renewables businesses via organic growth instead of acquisitions, the stakes will heighten. These companies will lure more talent from the open job market with attractive offerings, making it even harder for utilities to compete. As a result, utilities risk being left behind in the race to hire top talent.

How to thrive on the bumpy road ahead

To find the right talent at affordable salaries, renewables players will have to rethink critical HR and recruitment strategies and processes. While they can apply some best practices from other industries, ambitious companies will also want to consider new and unconventional ways of attracting and retaining talent. Five approaches can help companies thrive in this world of increasing talent scarcity:

— *A strong brand that is visible to employees.* Attracting a large pool of new talent can present challenges if few people have heard of you or know you are in the renewables business. Companies will want to consider how they are perceived by potential employees in their primary market and across the globe. Global players with a strong brand in their home country tend to underestimate the value of regional branding, which they will need to attract the employees—including those with much-needed specialized talents—that will help them grow in new locations.

  Additionally, when targeting both blue- and white-collar workers, a strong brand outside of the renewables industry is important. Being part of the clean-energy transition is not enough of an appeal to compete with other thriving industries, such as tech or other construction sectors, that offer explicit and attractive benefits for employees.

— *Clear career path development for key job positions.* A lack of career development opportunity is a major driver of employee attrition. If employees can visualize a future path at their company, they are more likely to want to follow it and stay at the company. Renewable-energy companies will need to articulate their plans for employee development along many paths, offering multiple tracks with different specializations, such as technical, management, and project management. As companies in the renewables industry increasingly go global, they will also need to make temporary relocation to other countries part of an attractive career path. For many decades, companies in the oil and gas industry have been sending their top managers across the globe for their exploration and production businesses; now it is time for pure-play renewable-energy companies to learn from them.

— *Employee incentives.* Ambitious and highly educated employees are often motivated to work for companies that allow them to share in its success. Along with classic stock options and awards, long-term incentive programs, such as equity options for newly built wind and solar projects, could help attract new talent and increase the chances that employees will stay for longer. Although these awards might take longer to materialize due to development and construction lead times, they can be a competitive advantage over industries without aggressive growth expectations.

— *Early capture of high-potential employees.* The talent scarcity problem is only going to get worse. Recruiting initiatives at the early phases of someone’s career, such as efforts at target universities and vocational schools, can help secure future talent and build a strong bond. At the same time, companies should make sure they have adequate regional recruiting programs so relocated employees can eventually be replaced with local talent.

— *Hiring by acquiring.* In a world in which talent is one of the scarcest assets in a renewables business, buying a company for its top talents is an expensive but effective way of acquiring new workers. This form of talent acquisition could become a more common phenomenon, especially for companies looking for very specific technical capabilities, such as energy technicians for renewables operations and maintenance, or for specialized talents in a particular environment, such as developers in a country with an immature renewables industry.

— *Structured training.* Having sufficient technicians and other blue-collar workers is a major pain point for the construction, operation, and maintenance of new wind and solar plants. To attract and retain these workers, employers should go beyond wages and use training programs that focus on clear, long-term career path development. This can apply particularly to roles that are temporary. Individuals who begin constructing solar plants in the coming years, for instance, could spend their entire careers doing this type of work, depending on the size of build-out.

Given the growth ambitions of the renewables sector, attracting and retaining much-needed workers is crucial. Companies in this sector need to be ahead in the talent game to succeed.

Paul Daume is a partner in McKinsey's Cologne office, where **Jan Krause** is a senior partner; **Florian Heineke** is a consultant in the Frankfurt office; **Nadine Janecke** is an associate partner in the Hamburg office; **Holger Klärner** is a partner in the Berlin office; and **Raffael Winter** is a partner in the Düsseldorf office.

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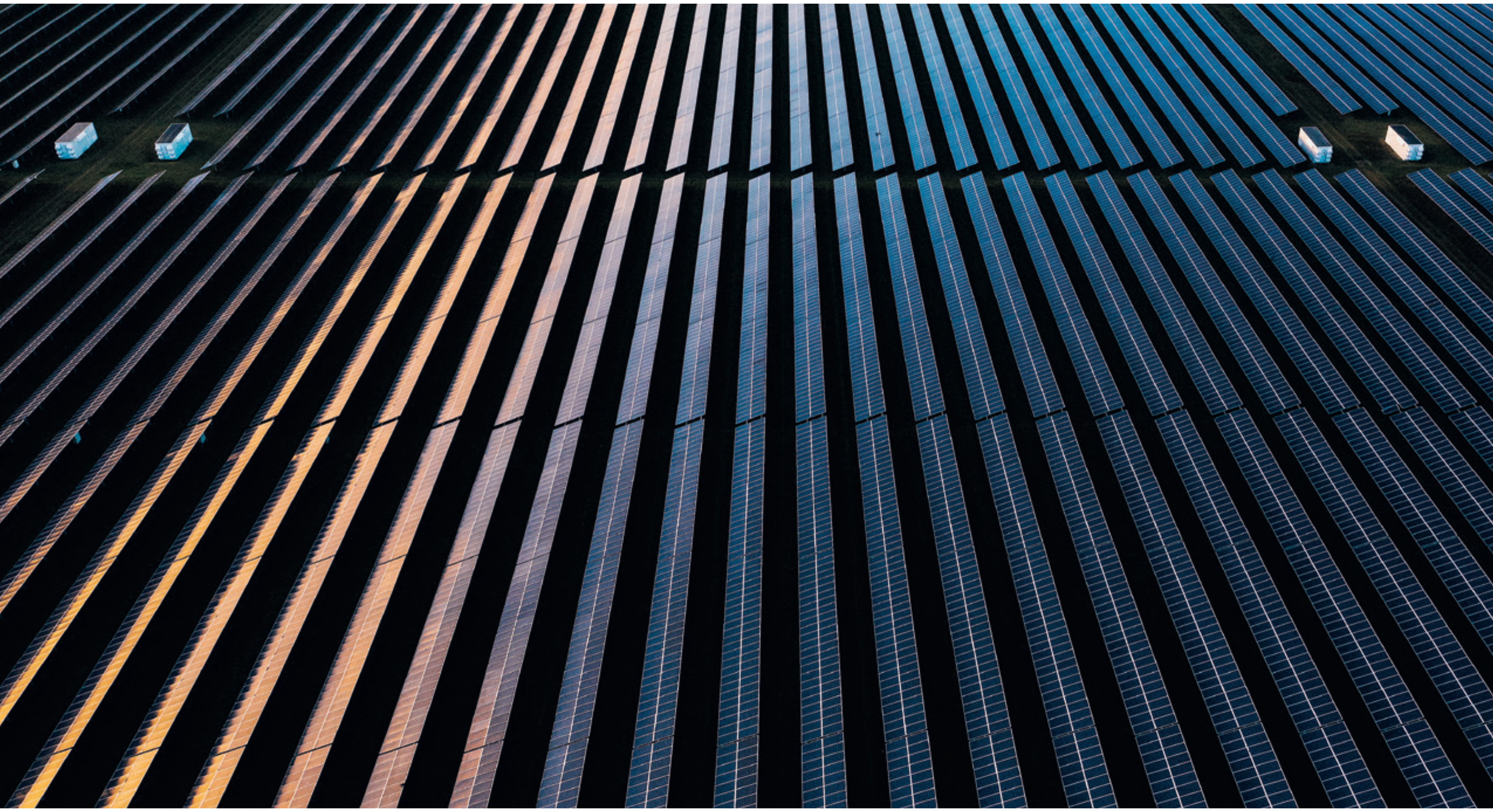
Building resilient supply chains for the European energy transition

To ensure a timely and orderly energy transition, companies and other stakeholders urgently need to strengthen each step of the already-stretched supply chains of key technologies.

This article is a collaborative effort by Stathia Bampinioti, Harald Bauer, Nadia Christakou, Luigi Gigliotti, Emil Hosius, Friederike Liebach, Lorenzo Moavero Milanesi, Humayun Tai, and Raffael Winter, representing views from McKinsey's Advanced Industries and Electric Power & Natural Gas Practices.



In earlier research on solving the net-zero equation,[1] we described the nine key requirements we believe must be met for an orderly energy transition. These fall into three broad categories: physical building blocks; economic and societal adjustments; and governance, institutions, and commitments. This article focuses on the first area, particularly on the ability to create at-scale supply chains and support infrastructure for key decarbonization technologies.

The energy transition is already well under way in Europe, but it will need to accelerate significantly to meet the European Union's Fit for 55 targets and deliver on REPowerEU, an energy security action plan developed in response to events in Ukraine.[2] One measure in the REPowerEU plan, for example, mandates the installation of 320 gigawatts (GW) of new solar photovoltaics (PVs) by 2025 and 600 GW by 2030. Meeting this goal will require a threefold to fivefold increase in the solar PV installation rate.

Increased (and increasing) demand for the technologies that enable decarbonization—such as electrification technologies across industrial processes, buildings, power supply, and the mobility industry—creates many knock-on opportunities. Companies at each step of the affected value chain have the opportunity to benefit, as we discussed in a recent article focused on electrification.[3]

Those looking to take advantage of these opportunities will need to be cognizant of a number of risks and act to avoid them. Avoiding bottlenecks in already-stretched supply chains is particularly important, especially in the context of recent geopolitical events; bottlenecks create risks around volume shortages, price volatility, geographical-sourcing dependency, long lead times, and issues with quality. These risks can affect all key energy transition technologies and every step of the supply chain. Particular challenges are expected around the procurement of raw materials, manufacturing of components, and availability of labor for construction and installation.

Businesses and other key stakeholders looking to shore up supply chain resilience for an orderly energy transition can take a range of mitigation actions. Fast and decisive action to analyze and strengthen supply chains and a willingness to invest judiciously can help position Europe and its businesses to capture the substantial opportunities of an orderly energy transition. A lack of action will increase the risk that Europe may fall behind in achieving its important, ambitious energy goals—or even miss out on these opportunities entirely.

The energy transition is under way, and the pace of decarbonization will only increase

The drive toward decarbonization, increasing cost competitiveness, and geopolitical considerations have further accelerated the energy transition and significantly increased the pace of electrification.

But the rate of decarbonization will need to more than triple to meet the European Union's Fit for 55 target of a 55 percent emissions reduction from 1990 levels by 2030.[4] There will need to be a dramatic shift toward renewables in power supply and toward electrification technologies in demand.

These top-level targets have profound implications for the products and technologies that enable electrification and thus decarbonization. Renewable-energy sources (RES), for example, will need to constitute 70 percent of the generation mix by 2030.[5] Increased demand for electricity will further complicate the transition.

The result of these shifts will be a strong and growing demand for electrification-enabling technologies. These technologies include wind, solar PV, and battery storage in the power industry; heat pumps for buildings and industrial processes; and batteries and charging infrastructure for the mobility sector, to name just a few. This burgeoning demand will be synchronized along the entire value

[1] For more, see "Solving the net-zero equation: Nine requirements for a more orderly transition," McKinsey, October 27, 2021.
[2] "Fit for 55," European Council, June 30, 2022; "REPowerEU Plan," European Council, May 18, 2022.
[3] For more, see "Unlocking opportunities from industrial electrification," McKinsey, July 18, 2022.
[4] "EU greenhouse gas emissions fell in 2019 to the lowest level in three decades," European Commission, November 30, 2020.
[5] *Global Energy Perspective 2022*, Achieved Commitments scenario, McKinsey, April 2022.

chain, from raw and processed materials and manufacturing of components and assemblies all the way to logistics and construction.

Supply chains are facing significant—and growing—challenges

Supply chains for key energy transition technologies are already stretched, and recent geopolitical events have further exacerbated the situation. The global pandemic disrupted supply chains, resulting in multiple-month production halts while major supplier countries went into lockdown.

For example, more than two years into the pandemic, the gap between chip supply and demand has widened across all semiconductor-enabled products. This semiconductor shortage will likely persist in selected technology nodes for the next three to five years. For mature node sizes, for example, shortages are expected to persist until 2026.[6]

More recently, the war in Ukraine has disrupted the supply of oil and gas and has driven many European countries to make decisions that will have a long-term impact on where and how they source their energy supply. There have also been disruptions around other key raw materials for which Russia and Ukraine are key suppliers. For example, 43 percent of the global production of palladium is sourced from Russia, 33 percent of global semifinished steel imports are supplied by Russia or Ukraine, and 17 percent of global class 1 nickel is produced in Russia.[7]

These events and trends could amplify five risk areas related to supply chains: volume shortage, price volatility, geographical-sourcing dependency, long lead times, and issues with quality (Exhibit 1).

Key industry players are increasingly aware of the need to act—and many have already started to do so. In 2022, for example, the World Economic Forum noted the risk of choke points in the supply of commodities such as lithium and copper and advocated for global standards as well as increased innovation to boost supply diversity.[8] In September 2021, the European Raw Materials Alliance introduced a plan calling for governments and manufacturers to support mining and processing through a mix of subsidies and sales quotas.[9]

Exhibit 1

Supply chains are associated with five areas of potential risk.

1	2	3	4	5
Volume shortage	**Price volatility**	**Geographical-sourcing dependency**	**Long lead times**	**Quality**
Supply chain cannot deliver the quantity of material or component required at sufficient scale, either due to lead times required to scale up or fundamental limits (eg, constraints in mining capacities)	Material or component is exposed to market forces that lead to consistently rising or volatile prices	Material or component production is significantly concentrated in a region where geopolitical, social, regulatory, or other factors could affect trade flows	Material or component takes a long time to be procured	Material or component may suffer from low quality due to massive increase of demand and decrease of quality controls to speed up the process

[6] Ondrej Burkacky, Johannes Deichmann, Philipp Pfingstag, and Julia Werra, “Semiconductor shortage: How the automotive industry can succeed,” McKinsey, June 10, 2022.
[7] “Share of global production and rank for selected minerals and metals in Russia, 2020,” IEA, last updated May 20, 2022; “List of exporters for semi-finished products of iron or non-alloy steel,” Trade Map, International Trade Centre (ITC), accessed September 10, 2022; McKinsey MineSpans.
[8] Joisa Saraiva and David G. Victor, “Rethinking global supply chains for the energy transition,” World Economic Forum, January 31, 2022.
[9] Elisabeth Behrmann, “EU makes $2 billion push to curb reliance on China’s rare earths,” Bloomberg, September 30, 2021.

Risks exist along each step of the supply chain

Supply chain risks can affect procurement, manufacturing, logistics, and construction. These risks have the potential to cause serious disruption for all key energy transition technologies (Exhibit 2). For a deep dive on how supply chain risks threaten every step of the value chain for heat pumps, see sidebar, "Vulnerabilities in the heat pump supply chain."

Individual risk profiles and the actions needed to minimize them vary for each step of the value chain, with particular challenges expected in raw materials, components, and labor.

Exhibit 2

Supply chains for key energy transition technologies are stretched.

Selected examples, nonexhaustive

Drivers of risk ● Volume shortage ● Price volatility ● Geographical-sourcing dependency ● Long lead times ● Quality

Raw- and processed-material procurement

Wind turbines
EU provides only 1% of raw materials for wind turbines; expected supply shortage for neodymium and praseodymium

Batteries
1% of materials from EU; 74% dependence on China (lithium and cobalt), Russia (class 1 nickel), Africa (cobalt), and Latin America (lithium)

Grids
Potential shortage of copper driven by demand increase

Component manufacturing and assembly

Solar
China's role becomes quasi-monopolistic in solar-PV[1] components, providing > 70% of solar-cell and module components

Batteries
China supplies 66% of finished lithium batteries; EU fully dependent on battery cell imports, yet European capacity expected to ramp up

Wind turbines, solar, and batteries
High dependence on Asia for power electronics, with China, Japan, Korea, and Taiwan accounting for ~75% of global production

Logistics

Wind turbines
Potential shortage of XL vessels for offshore wind turbines after 2025

Construction and labor

Wind turbines, solar, batteries, and grids
Demand for construction workers will increase more than threefold by 2030; blue-collar workers are already scarce today

[1]Photovoltaic.
Source: *Critical raw materials for strategic technologies and sectors in the EU: A foresight study*, European Commission, September 3, 2020; expert interviews; Technologies and Innovations; *The raw-materials challenge: How the metals and mining sector will be at the core of enabling the energy transition*, McKinsey, January 10, 2022

Vulnerabilities in the heat pump supply chain

Heat pumps can be used to electrify both space and water heating in the residential- and commercial-buildings sector, where they replace gas and oil boilers. They can also be used to electrify industrial processes such as in the chemicals, pulp and paper, and food and beverage industries.

Historically, heat pumps have been significantly more expensive than alternatives in terms of total cost of ownership. At 2019 fuel prices, for example, the cost of heating an average German residential dwelling was about 50 percent higher with air-to-water heat pumps than with a condensing gas boiler.[1] However, rising commodity prices and direct subsidies are rendering these pumps increasingly cost competitive. In addition, carbon taxes and policies will further encourage the installation of heat pumps, which are both a short-term lever to reduce European dependency on Russian oil and gas and a key longer-term decarbonization lever.

As a result, the European Commission has set a target to double the rate of deployment of heat pumps over the next five years.[2] An analysis of heat pump supply chains, however, reveals a number of potential vulnerabilities:

Procurement of raw and processed material. Steel and copper are among the key raw materials for the creation of heat pumps. While steel production will likely not face bottlenecks in supply, increased demand for green steel and increasing energy prices might significantly drive up steel prices. There will also likely be a near-term undersupply of copper. Demand will increase as a result of grid expansion, increasing renewable energy, and the adoption of electric vehicles (EVs), while supply will be limited by aging mining assets and weak project pipelines.

Component manufacturing. While components such as fans and valves are highly commoditized, and therefore no sourcing constraints are expected, inverters and electrical components may fall victim to the semiconductor bottleneck.

Components assembly. Increased use can increase the output of existing assembly lines, but there are high barriers to entry for new players in the heat pump market; complex systems and licensing requirements in certain cases result in a lead time of up to 12 months to open new plants.

Construction and labor. While increasing worker shifts can provide some labor scale-up flexibility, labor shortages might slow down the uptake of heat pumps. To meet governmental targets, for example, the United Kingdom will need to add 5,000 to 7,000 heat pump installers per year from 2025 until 2035.[3]

Furthermore, the ability to retrofit heat pumps into existing buildings is restricted by space limitations in urban housing and bureaucratic hurdles, such as the need for owner communities' approval and preservation orders.

Enabling strong heat pump uptake may therefore require businesses and other relevant stakeholders to consider the following actions:

- Advocate for supportive policies (including subsidies and carbon taxes), launch awareness campaigns to increase local demand, and engage in large-scale skilling and reskilling efforts for technicians.

- Make corporate commitments in commercial real estate to accelerate the adoption of heat pumps in stakeholders' building portfolios.

- Create innovative designs to enable the retrofitting of buildings and allow for heat pump installation in small urban apartments.

- Scale up assembly-line production capacity with a focus on automated-manufacturing practices.

[1] "Are renewable heating options cost-competitive with fossil fuels in the residential sector?," IEA, December 1, 2021.
[2] "Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions," European Commission, May 18, 2022.
[3] "Shortage of trained heat pump installers could set back net zero," Nesta, July 7, 2022.

Procurement of raw and processed materials
The main supply chain risks that are likely to affect raw materials are supply shortages and geographical-sourcing dependency.

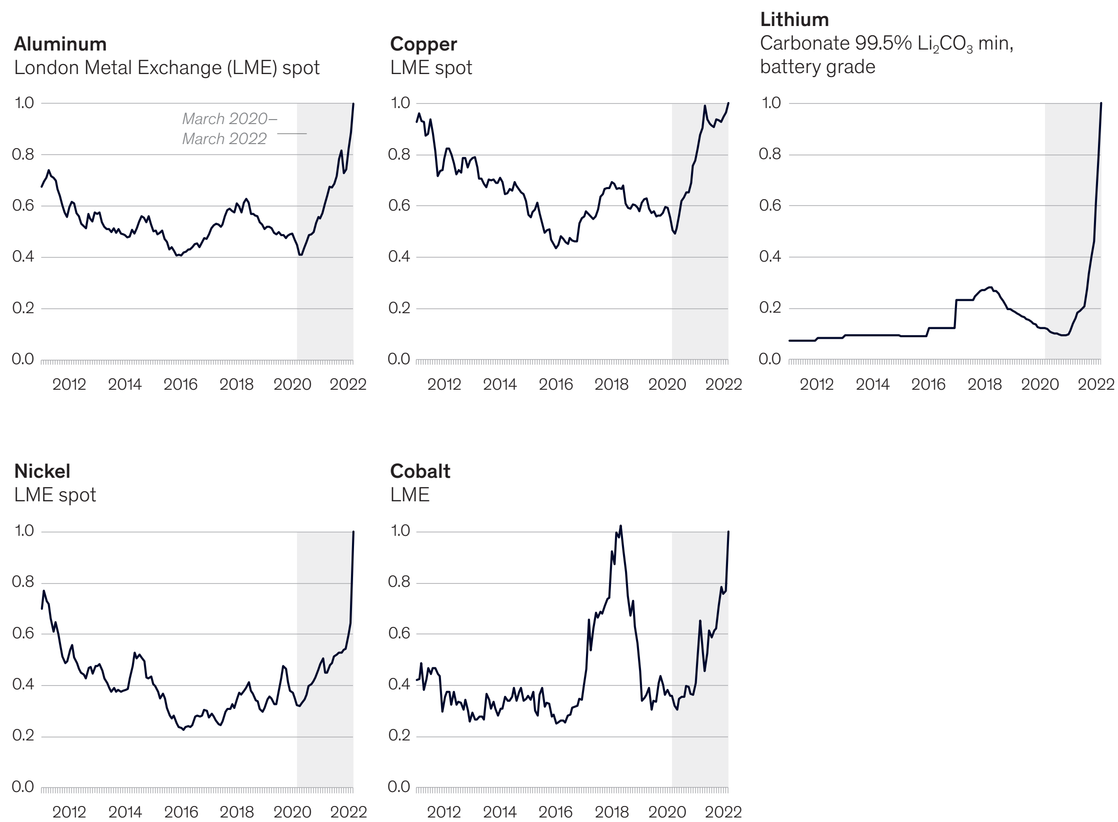
These risks will be particularly severe for rare-earth materials. Neodymium and praseodymium, for example, are key components of the permanent magnets used in wind power and electric vehicles (EVs) and will see a surge in demand in the coming years. Substitution options are limited, which may create risks in the future because the industry is highly dependent on China's refining capacity. Recycling will therefore be a key focus area, but based on expected capacity growth plans, we nevertheless predict an undersupply of 50 to 60 percent in 2030, leading to significant price spikes.[10]

Other raw materials will also be affected. For example, the energy transition and electrification will significantly increase demand for metals such as nickel, lithium, cobalt, aluminum, and copper. Demand is already rising, which has driven price increases (Exhibit 3). We expect that opportunities for increasing supply, recycling, and substitution will maintain a relative equilibrium between supply and demand for aluminum, copper, and cobalt, but we expect to see supply shortages of class 1 nickel and lithium in 2025.

Exhibit 3

There is an unprecedented extent of price increases across commodities.

All prices indexed to March 2022 = 100, VAT exclusive



Source: MySteel Global; *Metal Bulletin*; S&P SBB

[10] Dolf Gielen, "Engineering is key to easing the supply crunch of critical materials for clean energy," Engineering for Change, October 20, 2021.

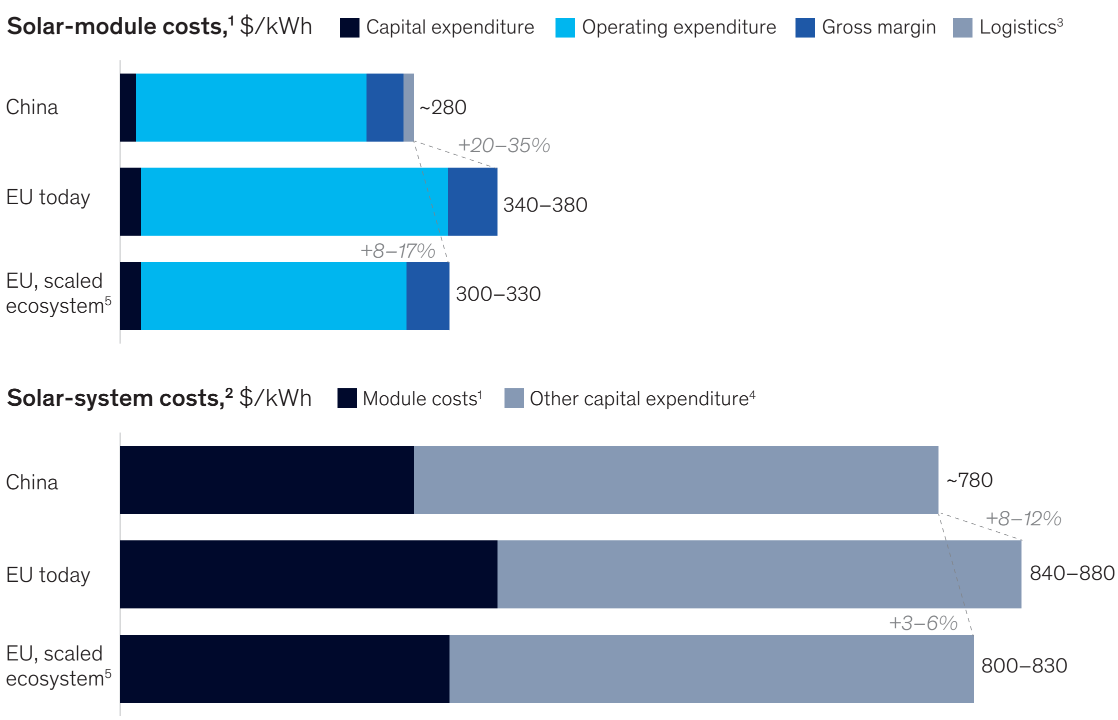
Component manufacturing and assembly
Increased demand for assets will increase demand for components, but the share of components that are made in Europe is decreasing. Dependency on non-EU countries for the sourcing of key components could therefore become a major risk, particularly for solar PV, batteries, and power electronics.

China is (and is set to remain) the dominant producer along the value chain; it currently provides more than 70 percent of solar-cell and module components and 66 percent of finished lithium batteries.[11] Most semiconductors are also produced in Asia—22 percent in China, 19 percent in Taiwan, 17 percent in Korea, and 16 percent in Japan—with France and Germany together accounting for only 5 percent of global front-end production.[12]

The steady decrease in the number of domestic EU production facilities for many components has mainly been driven by commoditization, which has led to competition based predominantly on price with few opportunities for product differentiation. European companies will struggle to compete on price; solar PV module costs are currently 20 to 35 percent higher in Europe than in China, primarily driven by higher costs for labor, materials, and CO_2.[13] Scaling the local manufacturing ecosystem could decrease price differences by eight to 17 percentage points, but this will take at least three to five years (Exhibit 4).

Exhibit 4

Regionalizing solar-module manufacturing can close the cost gap between European and Chinese solar-PV systems.



[1]Like-for-like comparison for Tier-1 Mono PERC modules. [2]For utility-scale projects. [3]Assuming logistics costs reach prepandemic levels in the medium term. [4]Includes balance of system, grid connection, installation, and soft costs, which are independent of module costs. [5]Benefits of scaled ecosystem expected once annual manufacturing capacity in Europe reaches 10–20 GW, which will take at least 3–5 years.
Source: Expert interviews; International Renewable Energy Agency (IRENA); *McKinsey Global Energy Perspective 2022*; National Renewable Energy Laboratory (NREL)

[11] "Critical raw materials for strategic technologies and sectors in the EU," European Commission, September 3, 2020.
[12] "World Fab Forecast," SEMI, Q4 2021.
[13] *Global Energy Perspective 2022*; McKinsey analysis.

Western turbine manufacturers dominate the European market for wind power. In the past several years, however, Western OEMs have faced profitability issues due to lower-than-expected build-out and increased price competition driven by a shift to purely cost-driven tender design in many countries. As a result, many European countries—including Denmark, Germany, and Spain—have experienced job losses and factory closures.[14]

More recently, rising commodity prices have further eroded profitability. Many OEMs are fully exposed to increasing prices, resulting in double-digit negative EBIT margins for some European OEMs in the first quarter of 2022.

The Western world should build on learnings from the solar industry and strive to maintain a strong domestic industry and supply chain. As an example, refining tender designs to also incorporate more qualitative criteria—such as sustainability, carbon footprints, and system integration—could help ease pressure on the wind supply chain.

Logistics

There are also risks to an orderly energy transition related to the transportation of key technologies to the location of installation. These risks generally manifest as volume shortages.

Logistics is likely to become increasingly challenging in offshore wind. Increases in both capacity installation and, as a result of rapid technological advancement, turbine size are likely to lead to a shortage of appropriate installation vessels starting in 2025. We project that in 2026, about three GW of planned capacity will not be able to be installed because of the undersupply, and the size of this gap will increase over time.[15] The lead time for supersized installation vessels is considerable, which means that without prompt action, this mismatch between supply and demand is likely to be of considerable duration.

Construction and labor

Skilled labor to work on RES in the European Union is already scarce today, and employers experience a high level of competition from adjacent sectors. In 2019, for example, there were 1.8 job vacancies in Germany for every unemployed energy technician.[16]

This labor scarcity will get significantly worse: the demand for blue- and white-collar workers to develop and construct wind and solar assets in the European Union, for example, is expected to increase by a factor of between three and four by 2030 (Exhibit 5).[17] Labor shortages will be further exacerbated by an increasing demand for workers to operate and maintain these wind and solar projects; the lack of technicians is expected to be a particular pain point.

Stakeholders can act to minimize supply chain risks—and seize the opportunities

Businesses and other relevant stakeholders could take a range of mitigation actions to guard against supply chain risks. These actions are not just about mitigating risk, however: building supply chain resilience can also be an opportunity and a catalyst for collaboration and partnerships, as well as a driver of innovation—for example, to replace materials and increase productivity.

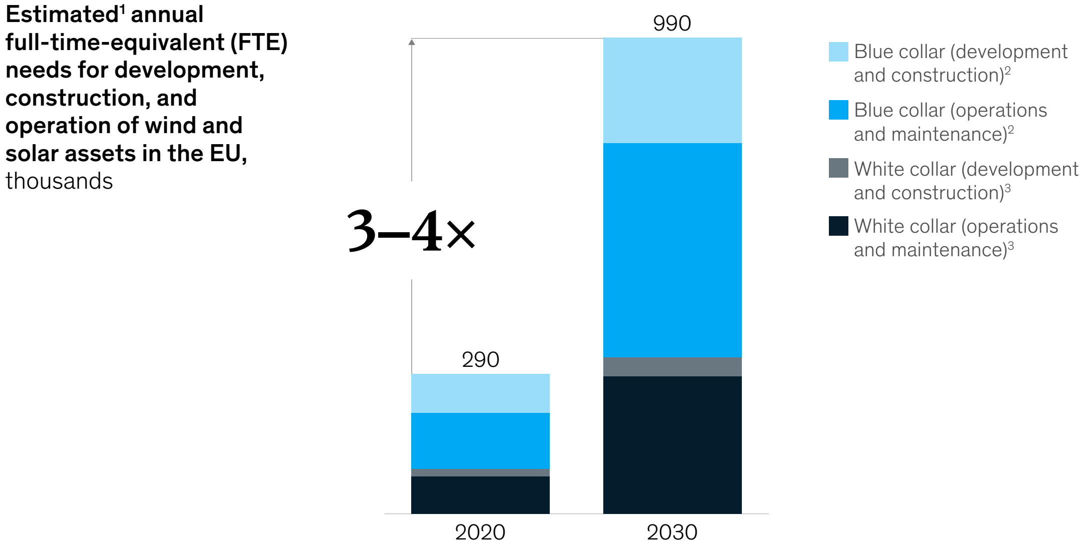
Potential actions for businesses

The right next steps will vary by the type and the specifics of individual businesses, but the following resilience-boosting actions can be beneficial to businesses along the supply chain:

[14] Maz Plechinger, "Nordex to lay off a fifth of staff in Germany," *EnergyWatch*, March 1, 2022.
[15] *Global Energy Perspective 2022*, Achieved Commitments Scenario; "Installation Vessel Supply and Demand Q1 2022," 4C Offshore, April 2022; McKinsey analysis.
[16] "Bottleneck Analysis," Federal Employment Agency, December 2019.
[17] *Renewable energy benefits: Measuring the economics*, IRENA, January 2016; *Global Energy Perspective 2022*, Achieved Commitments Scenario.

Exhibit 5

Demand for workers to develop and construct wind and solar assets in the European Union is set to increase by a factor of between three and four by 2030.



Note: Figures may not sum, because of rounding.
[1]Estimate based on current and expected build-out, and full-time-equivalent workers per GW estimates based on different publications from IRENA; learning rates have not been applied.
[2]Practical workers (eg, construction workers, technicians, ship crew, and operators).
[3]Remaining workers (eg, electrical, industrial, mechanical, and telecommunication engineers, and safety and regulation experts, financial analysts, and lawyers).
Source: *McKinsey Global Energy Perspective 2022* Accelerated Transition scenario; *Renewable energy benefits: Measuring the economics*, IRENA, January 2016

— *Diversify and localize supply chains* for critical raw materials and components across multiple suppliers and geographies.

— *Explore opportunities for cross-industry pooled procurement* of raw materials.

— *Invest in recycling, innovation, and research around substitutes* for critical materials.

— *Explore opportunities for vertical integration* to secure critical raw materials and decrease price volatility, either through alliances and partnerships or through targeted acquisitions.

— *Optimize procurement strategies* by targeting long-term supply agreements or developing streaming agreements with advance lump-sum payments for future production.

— *Send clear demand signals* via long-term target and volume commitments, such as by announcing target developments in offshore wind to drive the upgrade of vessels.

— *Attract and retain workers* from the European Union and beyond by conducting early outreach in schools and offering targeted reskilling programs.

— *Reduce labor demand* through automation and digitalization.

Potential actions for other stakeholders

Other stakeholders could consider the following actions:

— *Scale up regional supply chains* to a critical minimum; for example, use incentives (including both taxes and subsidies) or insert sustainability and local content criteria into tenders and policies.

— *Encourage innovation,* including around substitutes for critical and scarce raw materials.

— *Harmonize regulations* and streamline permitting processes.

— *Introduce intra-European Union alliances to source strategic raw materials,* including rare-earth materials.

— *Increase OEM recycling of raw materials* such as aluminum, lithium, and cobalt by creating financial incentives and setting standards regarding higher levels of reuse.

— *Communicate and commit* on growth plans to build the confidence that will allow businesses to make proactive investments.

— *Invest in labor programs* for blue-collar energy transition jobs focused on metallurgy and RES manufacturing capabilities. Programs could include skilling and reskilling while also facilitating international and cross-sector utilization.

— *Attract and retain workers* from the European Union and beyond—for example, by facilitating migration, activating passive workforce segments, and ensuring a predictable and steady project pipeline.

The supply chains for crucial energy transition and electrification technologies are only as strong as their weakest links. Therefore, businesses and other relevant stakeholders may benefit from plotting out and mitigating potential risks along every step of the supply chain. This is a significant endeavor, but it is also a real opportunity for innovation and collaboration among stakeholders. Those that can build resilient, future-ready supply chains will be well positioned to reap significant benefits as the energy transition continues to gather momentum.

Stathia Bampinioti is a consultant in McKinsey's Athens office; **Harald Bauer** is a senior partner in the Frankfurt office, where **Friederike Liebach** is a consultant; **Nadia Christakou** is an associate partner in the Geneva office, where **Luigi Gigliotti** is an associate partner; **Lorenzo Moavero Milanesi** is a partner in the Milan office; **Humayun Tai** is a senior partner in the New York office; and **Raffael Winter** is a partner in the Düsseldorf office, where **Emil Hosius** is a consultant.

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Five charts on hydrogen's role in a net-zero future

Hydrogen has great potential as a carbon-free energy carrier. Here's a look at the momentum behind this widely applicable technology.

by Bernd Heid, Alma Sator, Maurits Waardenburg, and Markus Wilthaner

Hydrogen could play a central role in helping the world reach net-zero emissions by 2050. As a complement to other technologies, including renewable power and biofuels, hydrogen has the potential to decarbonize industries including steel, petrochemicals, fertilizers, heavy-duty mobility (on and off-road), maritime shipping, and aviation, as well as to support flexible power generation (among other applications). In 2050, hydrogen could contribute more than 20 percent of annual global emissions reductions.

Hydrogen's potential role in the broader energy transition is explored in a series of industry reports coauthored by McKinsey and the Hydrogen Council—a global, CEO-led initiative with members from more than 140 companies. The reports explore, for example, how demand for hydrogen could reshape current power, gas, chemicals, and fuel markets; the need for scaling hydrogen production, particularly clean hydrogen (which is made with renewables or with measures to lower emissions); and what must happen in the coming decade to reach net-zero targets.

The momentum behind hydrogen has accelerated in the past year, as described in *Hydrogen Insights 2022*,[1] a recently published perspective on the state of the hydrogen industry. Both investment and project development have ramped up. However, a funding gap remains.

The following five charts show how hydrogen could play a key role in a low-carbon future.

Part of the net-zero equation

By 2050, clean hydrogen could help abate seven gigatons of CO_2 emissions annually, which is about 20 percent of human-driven emissions if the world remains on its current global-warming trajectory.[2] Complementing other technologies, such as renewables and biofuels, hydrogen has the potential to decarbonize a variety of sectors, for example: industry (steelmaking, ammonia synthesis for fertilizer production); long-range ground mobility (as a fuel for heavy-duty trucks); maritime shipping and aviation (to produce synthetic fuels for vessels); and building heating. Hydrogen can also be used for flexible, long-term storage for power grids. Industry and transportation account for most of hydrogen's abatement potential, which has a cumulative emissions reductions upside of 80 gigatons of CO_2 through 2050 (Exhibit 1).

In 2050, hydrogen could contribute more than 20 percent of annual global emissions reductions.

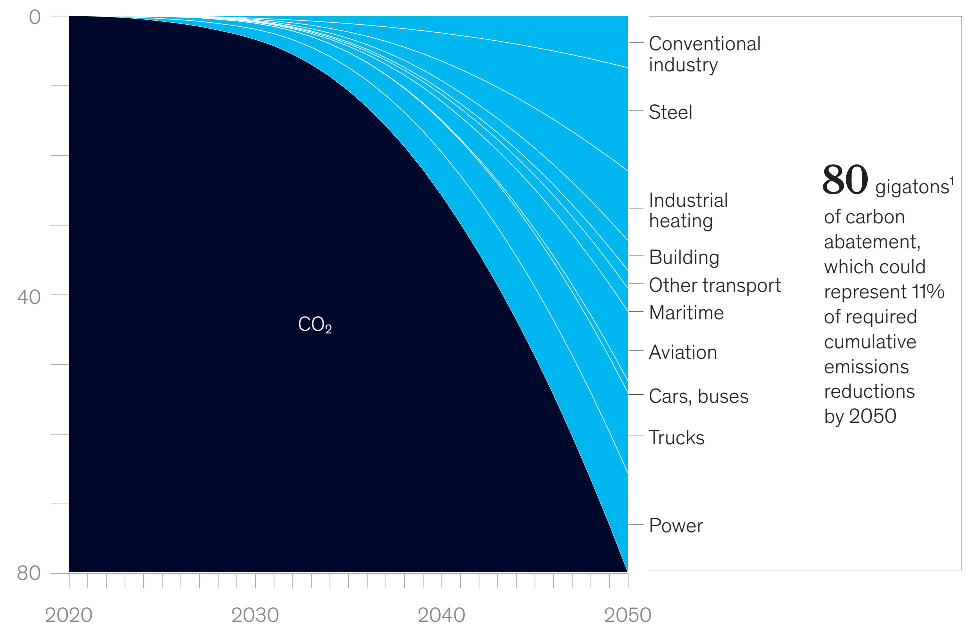
[1] *Hydrogen Insights 2022: An updated perspective on hydrogen market development and actions required to unlock hydrogen at scale*, Hydrogen Council and McKinsey, September 2022.

[2] Assumes 35 gigatons anthropogenic emissions in 2050 in the current trajectory. For more on hydrogen's potential role in achieving net-zero emissions, see *Hydrogen for net-zero: A critical cost-competitive energy vector*, Hydrogen Council and McKinsey, November 2021.

Exhibit 1

Clean hydrogen can contribute as much as 80 gigatons of CO_2 abatement by 2050, with most coming from industrial uses and transport.

CO_2 abated from hydrogen end use, gigatons of CO_2 (cumulative reduction)



[1]The 80 gigatons (Gt) cumulative CO_2 abatement potential through 2050 constitutes approximately 11% of the emissions reductions required to stay within the carbon budget of 420 Gt needed to limit global warming to 1.5–1.8°C.
Source: Hydrogen Council Decarbonization Pathways; McKinsey Hydrogen Insights

Investment is growing

More than 680 large-scale hydrogen projects have been announced globally,[3] amounting to $240 billion in direct investments. The projects include gigascale production, large-scale industrial usage, transport, and infrastructure. In Europe, which accounts for 314 of the announced projects, hydrogen is expected to play a significant role in meeting decarbonization targets, with usage across industrial applications, transportation, and power generation. Within Asia, China accounts for roughly half the total announcements. Among announced projects in China, most focus on hydrogen use in transportation. In North America, hydrogen production should help boost the region's domestic supplies of low-carbon energy across multiple applications.

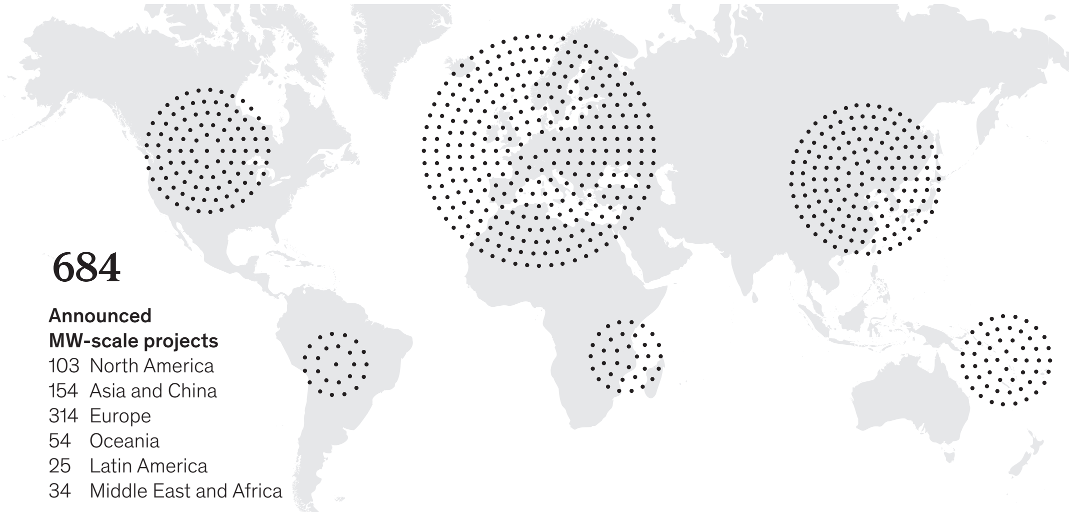
Additionally, hydrogen export hubs have been announced in Africa, Latin America, the Middle East, and Oceania. These hubs could feed growing demand in Asia and Europe, for example (Exhibit 2).

[3] As of May 2022. Approximately 80 percent of the projects have announced full or partial commissioning before 2030, with the remainder coming online after 2030 or not having announced a commissioning date yet.

Exhibit 2

More than 680 large-scale hydrogen projects have been announced globally, with a focus on production, industrial usage, transport, and infrastructure.

684 announced megawatt-scale projects[1]



61

Gigascale production Renewable H_2 projects >1 gigawatt, low-carbon H_2 projects >200 kilotons per annum

332

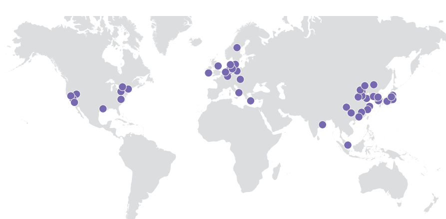
Large-scale industrial usage Refinery, ammonia, methanol, steel, and industry feedstock

78

Integrated H_2 economy Cross-industry and projects with different types of end uses

150

Transport Trains, ships, trucks, cars, and other hydrogen mobility applications



63

Infrastructure projects[2] H_2 distribution, transportation, conversion, and storage

[1]As of May 2022. Focus on large-scale projects including commissioning after 2030, >1,000 small-scale projects and project proposals not included.
[2]Includes 9 hydrogen production projects in China without announced end use.
Source: Hydrogen Council Decarbonization Pathways; McKinsey Hydrogen Insights

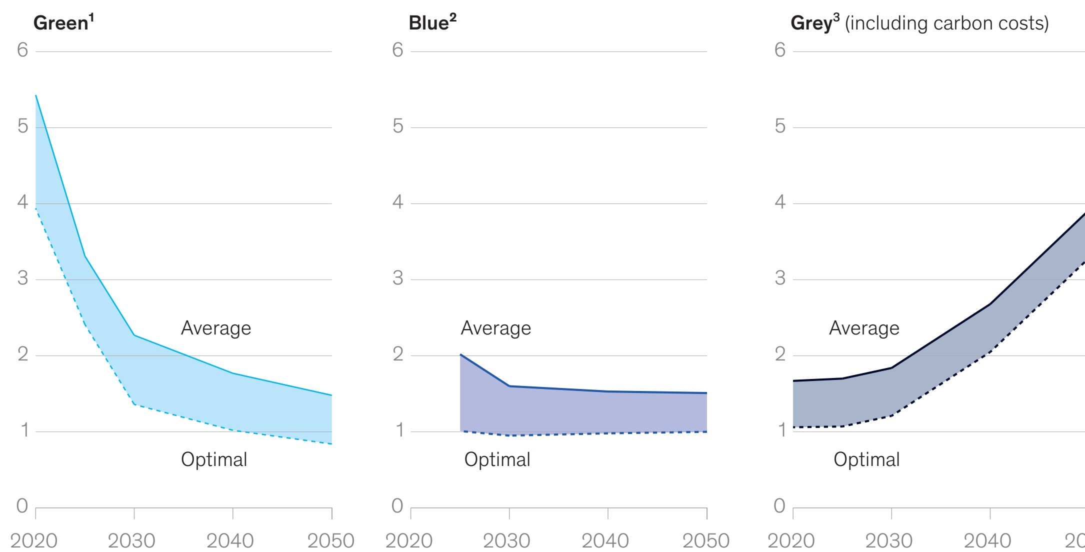
Cleaner future

Today, most hydrogen is produced with fossil fuels, also known as grey hydrogen. Fulfilling hydrogen's potential as a decarbonization tool will require a significant scale-up of clean hydrogen, which can be produced with renewables (often described as green hydrogen) or with fossil fuels combined with measures to significantly lower emissions, such as carbon capture, utilization, and storage (often called blue hydrogen). Demand for clean hydrogen could grow to approximately 660 million metric tons annually by 2050. Total planned production for green and blue hydrogen through 2030 has reached more than 26 million metric tons annually—a figure that has roughly quadrupled since 2020. The production costs of clean hydrogen are expected to rapidly decline over the next decade. At a production cost of approximately $2 per kilogram, clean hydrogen could become cost competitive in many applications (Exhibit 3).

Exhibit 3

Clean hydrogen costs are expected to decline over the next decade.

Production cost of hydrogen, $ per kilogram



[1]Based on alkaline with size classes of 2 megawatts (MW) (2020), 20 MW (2025), and 80 MW (from 2030); based on levelized cost of energy of $25–73/megawatt-hour (MWh) (2020), $13–37/MWh (2030), and $7–25/MWh (2050).

[2]Gas price of flat $2.6–6.8/million British thermal units (MMBtu); based on $30/ton CO_2 (2020), $50/ton CO_2 (2030), $150/ton CO_2 (2040), and $300/ton CO_2 (2050). Assumes autothermal reforming with carbon capture and storage and 98% CO_2 capture rate.

[3]Steam methane reforming without carbon capture. Gas price of flat $2.6–6.8/MMBtu; based on $30/ton CO_2 (2020), $50/ton CO_2 (2030), $150/ton CO_2 (2040), and $300/ton CO_2 (2050).

Source: Hydrogen Council Decarbonization Pathways; McKinsey Hydrogen Insights

Greening steel

Steel is one of the world's highest CO_2-emitting industries. Largely due to the use of coking coal in the production process, steel accounts for about 8 percent of global annual emissions. While it will require initial investment to make the transition, hydrogen-based steelmaking has the potential to greatly reduce the industry's footprint: steel is expected to generate about 8 percent of clean-hydrogen demand in 2030 but could account for nearly 20 percent of emissions avoided via hydrogen that year.[4] More than 50 steelmaking projects with green-hydrogen ambitions have been announced worldwide, with Europe as a center of early growth (Exhibit 4).

Funding gap

Despite hydrogen's momentum, a significant investment gap remains for it to fully contribute to decarbonization. Achieving a pathway to net zero will require additional direct investments of $460 billion by 2030[5]—closing the gap between the $240 billion of announced projects and $700 billion in required investments. The investment gap breaks down into three categories:

— *Production.* Clean-hydrogen production has the highest amount of announced investments; however, it's also the segment with the biggest investment requirements. The current investment gap is roughly $150 billion through 2030.

Exhibit 4

Globally, 52 steelmaking projects with green-hydrogen ambitions have been announced, with early growth centered in Europe.

Locations of plants or projects that have made green-hydrogen announcements

Source: Hydrogen Council Decarbonization Pathways; McKinsey Hydrogen Insights

[4] This disproportionate relationship is due, in part, to hydrogen's potential in replacing coking coal, a relatively high carbon emitter when burned, as a fossil source. Other hydrogen applications, for ammonia production or road transport, for example, would replace different energy sources that might be relatively less emissions-intensive (natural gas or diesel, for instance).

[5] As of May 2022.

- *Transmission, distribution, and storage.* Investments in this part of the value chain are critical to enabling access to cost-competitive hydrogen supplies, for example, connecting the regions with the lowest production costs to demand hubs, developing refueling infrastructure for vehicles, or building pipelines to supply industrial plants. An investment gap of more than $165 billion remains.

- *End-use applications.* Meeting projected demand in hydrogen's various end-use applications, including steel production and transportation, will require additional investments of $145 billion, with the largest absolute gap in mobility. New industry applications such as steel will require significant investments—about $35 billion—for outlays like new plants. However, steel is also one of the most advanced segments among announced investments, with about half of required investments announced (Exhibit 5).

How leaders could help maximize hydrogen's potential in the net-zero economy

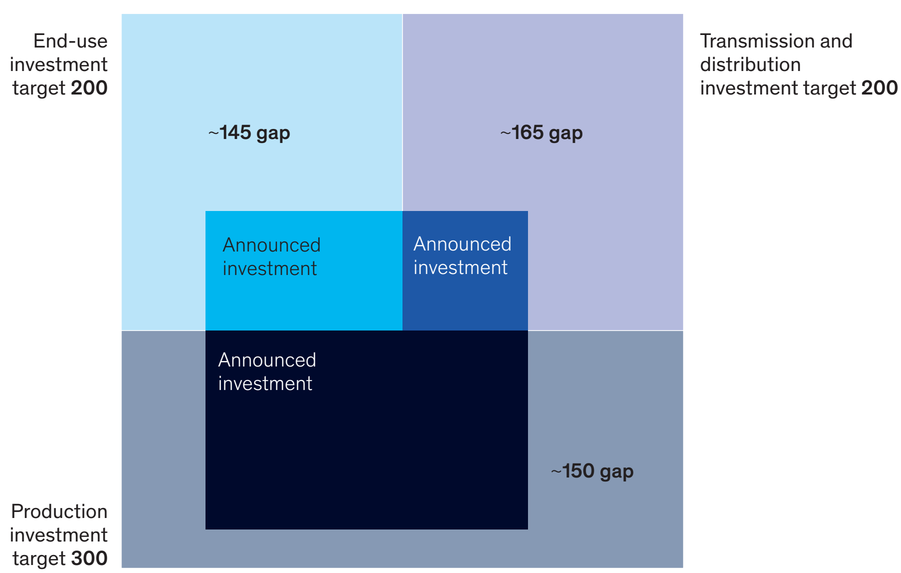
For hydrogen to become a pivotal player in the energy transition, scale-up over the next decade is critical. Policy makers and business leaders can consider actions in three key areas:

- *Creating demand.* Companies could play a role by pursuing industry-wide transition commitments while policy makers could create incentives—for instance, by introducing direct support mechanisms and mandating quotas or targets.

Exhibit 5

An investment gap of roughly $460 billion remains across the hydrogen value chain.

Announced and required direct investments into hydrogen until 2030, $ billion



Note: As of May 2022.
Source: Hydrogen Council Decarbonization Pathways; McKinsey Hydrogen Insights

For hydrogen to become a pivotal player in the energy transition, scale-up over the next decade is critical.

— *Developing infrastructure.* Up-front investments are required to develop large-scale infrastructure that enables distribution, such as pipelines and refueling infrastructure.

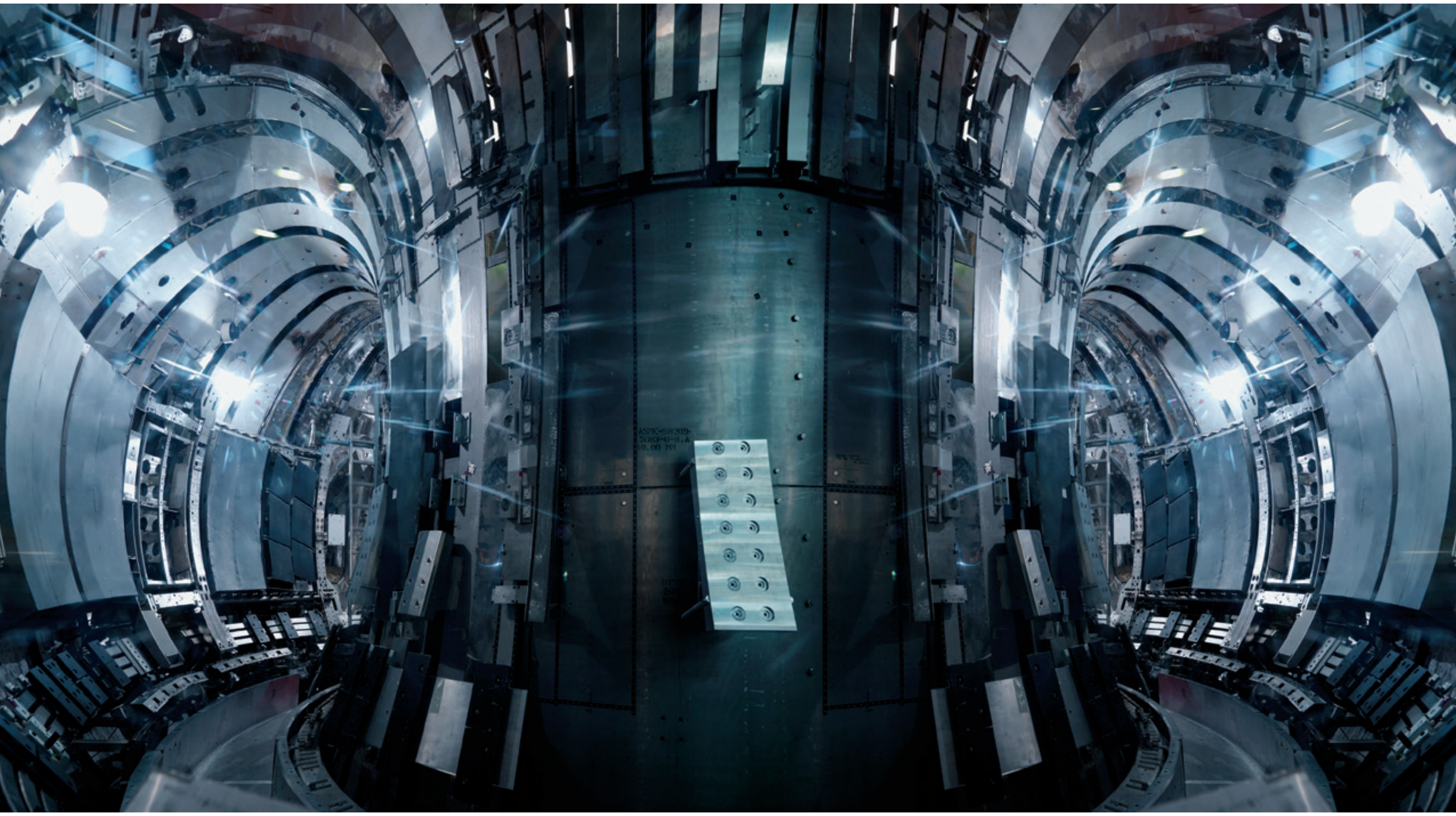
— *Scaling up production.* Hydrogen demand will reach mass-market adoption only when low-cost clean-hydrogen supply is available. This will require a scale-up in electrolysis capacity and accompanying renewable-energy capacity, as well as the build-out of carbon capture, utilization, and storage infrastructure. The sooner these investments in gigascale production are made, the earlier hydrogen will reach cost competitiveness.

Bernd Heid is a senior partner in McKinsey's New York office; **Alma Sator** is an associate partner in the Oslo office; and **Maurits Waardenburg** is an associate partner in the Brussels office, where **Markus Wilthaner** is a partner.

Will fusion energy help decarbonize the power system?

Nuclear fusion has long been considered a near-impossible clean-energy solution. But technological advances—and the need for a flexible zero-carbon power grid—have made fusion worth considering.

by Miklós Dietz, Bill Lacivita, Amélie Lefebvre, and Geoff Olynyk



What if a technological breakthrough could help the power sector decarbonize—and help prevent the worst effects of climate change?

Power generation currently accounts for approximately 30 percent of global CO_2 emissions. To meet the Paris Agreement's target of full decarbonization by 2050, many governments and utilities are shifting away from fossil fuels as a primary energy source and turning to renewable-energy technologies. The goal for many power sector players and their regulators is a zero-carbon energy grid. Volatility in the energy markets and geopolitical challenges may have complicated the transition to net zero in the short run, but in the longer run, the economics of renewable-power sources will drive likely investment into them.

In addition, as other industries transition away from fossil fuels, the demand for zero- or low-carbon electricity will increase. For example, as electric vehicles replace internal-combustion vehicles, more electricity generation will be required. McKinsey's Global Energy Perspective 2022 projects that power consumption could triple by 2050. For countries to hit their decarbonization goals, it is thus essential that not just existing but also all *added* generation be zero carbon.

Renewable energy from wind and solar is currently the most cost-efficient form of new zero-carbon electrical generation, and by 2030 it is expected be the lowest-cost of *any* kind of generation in most markets. The continued development of wind and solar technologies and construction techniques is expected to continue, which means that the bulk of new near-term clean-electricity generation will probably come from these two sources. But wind and solar have their limitations: they are *nondispatchable*—that is, they generate electricity when the wind blows or the sun shines, not necessarily when the grid needs it. One example of such limitations: energy shortages in Europe that began in 2019—before Russia's invasion of Ukraine—that were partly caused by historically low wind speeds lasting for months.

Other forms of dispatchable zero-carbon energy, such as geothermal or tidal power, are encouraging. But they are generally more expensive than wind and solar, can function only in a limited number of sites, and are less technologically mature. Grid-scale batteries and other forms of energy storage are increasingly promising, but they are still cost prohibitive at the required durations and have not yet reached the level of technological readiness for large-scale deployment.

Nuclear-fusion energy could help provide flexibility for zero-carbon electricity grids. Fusion—different from nuclear fission, which releases energy by splitting an atom in two—creates energy by combining two atoms, typically hydrogen isotopes. Fusion is dispatchable, which means that, unlike wind and solar, it does not rely on environmental or other external variables to generate power. The process of producing fusion energy creates no carbon emissions and no long-lived nuclear waste from spent fuel.[1]

In the past five years, fusion energy has reached a turning point in its development.

[1] Fusion machines do create waste from their irradiated walls, which would need to be stored after the decommissioning of a plant. See G. W. Bailey et al., "Waste expectations of fusion steels under current waste repository criteria," *Nuclear Fusion*, January 27, 2021.

The most valuable resources of a decarbonized grid are dispatchable zero-carbon generation sources—technologies that can be turned on during periods of low wind and solar output.

Historically, fusion machines have not been technically viable, because the energy input required to power the reaction has been larger than the energy produced by the machine. But in the past five years, fusion energy has reached a turning point in its development. Our analysis suggests that it could potentially play a large role in meeting 2050 decarbonization targets and may be worth considering in policies, plans, and investments.

A zero-carbon energy grid requires flexibility

A grid that relies on nondispatchable energy sources, like wind and solar, typically requires alternative sources of power generation. In other words, the minute-by-minute matching of the supply of wind and solar power to demand cannot occur in the way that energy from baseload-generating plants fueled by coal or natural gas can. Wind and solar are therefore sometimes referred to as variable renewable energy (VRE). A zero-carbon electrical grid cannot operate in a stable way with 100 percent VRE and will require sources of flexibility to back up, or firm, the VRE generation. In addition, land use for VRE and the required transmission infrastructure to connect it are increasing concerns. In Germany, for example, the construction of wind projects has not only slowed but also failed to achieve deployment goals for the past four years.

Flexibility—the ability to manage the intermittency of nondispatchable wind and solar—is thus crucial to achieving a zero-carbon energy grid. The real-time matching of supply and demand can be ensured in a number of ways. Gas and coal plants can adjust production up or down to smooth out fluctuations in the output of wind and solar power, for example, but relying on fossil fuels is not acceptable in a zero-carbon generation system unless carbon capture technology is used. 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 serve the power system as both a generator (when discharging) and a consumption point, or load (when charging). This need for flexibility is creating a wave of innovation across different technologies, including dozens of types of batteries and other energy storage technologies, natural-gas combustion with carbon sequestration, and digitally enabled demand-side aggregators.

To determine the optimal mix of zero-carbon technologies in a given region while preserving the reliability of the system, researchers and energy planners can use techno-economic grid modeling. Our research, using this technique, shows that the most valuable resources of a decarbonized grid are dispatchable zero-carbon generation sources. Unlike batteries or other electricity storage devices, which must be charged from the grid, these technologies generate net electrical energy and thus play a unique role in a decarbonized grid: they can be turned on during periods of low wind and solar output, without the duration constraints of batteries and with a high assurance of availability. Our modeling suggests that if this kind of dispatchable zero-carbon generation were available at a sufficiently low cost, the energy system in Europe, for example, could consist[2] almost entirely of some VRE plus dispatchable sources (Exhibit 1). Finding an affordable, scalable, and safe dispatchable zero-carbon generation technology would constitute a gigantic step toward a sustainable energy future for humanity. Fusion is potentially one of these technologies.

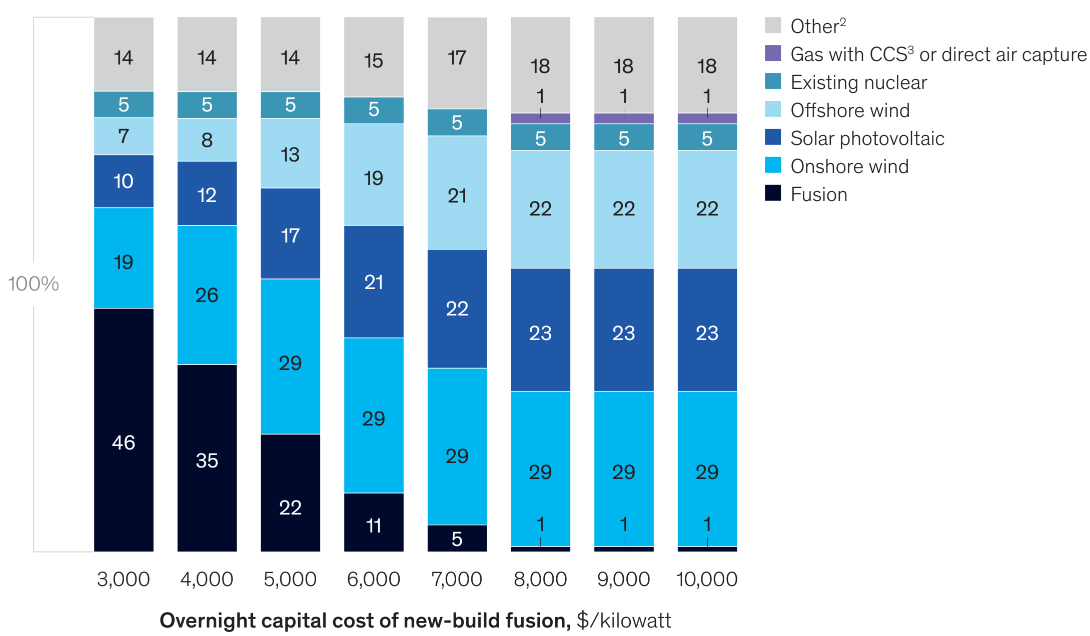
Fusion energy is potentially at a turning point

Fusion energy, also known as controlled nuclear fusion, has been pursued since the 1950s, first as a classified program and then, since a landmark conference in 1958, as an open, collaborative international effort. Simply put, fusion works by combining light atoms, such as hydrogen, into

Exhibit 1

Fusion could be the most cost-effective—and dominant—source of clean energy for Europe in a 2050 decarbonized power grid.

Share of grid generation capacity, by source, in a 2050 decarbonized European power grid, by overnight capital cost of new-build fusion,[1] %



Note: Figures may not sum to 100%, because of rounding.
[1]Based on techno-economic grid modeling of full European power grid. Does not include low-priced long-duration battery storage—modeling of batteries based on projected lithium-ion system costs.
[2]Primarily hydropower; also includes a small amount of conventional open-cycle gas turbines to provide flexibility (with emissions offset by direct air capture of carbon dioxide).
[3]Carbon capture and storage.

[2] While Russia's invasion of Ukraine may influence the near-term development of energy markets, it does not change the conclusions of this modeling, which is based on the optimization of an energy system that largely does not depend on fossil-fuel sources of energy.

heavier products, such as helium. The reaction releases enormous amounts of energy, which is then captured and converted into useful electricity by a fusion machine (Exhibit 2). There are many fusion machine designs, such as magnetic confinement (tokamaks and stellarators), inertial confinement, and magnetized target fusion.

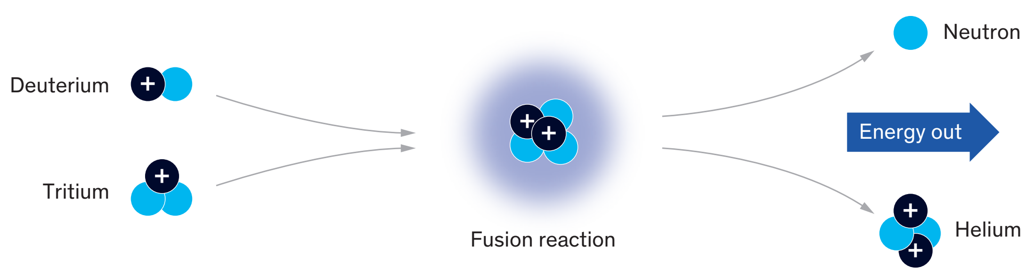
Fusion energy has some critical advantages over fission as a zero-carbon power source. It is fully controllable and thus creates dispatchable power with a ramp rate fast enough to complement renewables in a VRE-heavy grid. The fuel is readily available to all nations—for example, the required hydrogen isotopes for one commonly proposed fusion reaction can be extracted from seawater[3]; some companies, such as TAE Technologies, are proposing fuel cycles using ordinary materials like hydrogen and boron.[4] The fuel is slowly metered into the machine in a way that makes meltdowns or runaway events essentially impossible.[5] And fusion creates no carbon emissions and minimal nuclear waste—only the vessel itself.[6] Unlike today's fission plants, fusion produces no long-lived fuel waste.

These advantages are so substantial that fusion energy has long seemed the holy grail of energy technology. However, creating the temperature and pressure conditions required to initiate the reaction in the fusion machine is a great scientific and

Exhibit 2

In the most widely studied fusion reaction, hydrogen isotopes combine to form helium, releasing energy that is converted into electricity.

Deuterium–tritium fusion process



Hydrogen isotopes, in the form of gaseous fuel, are injected into the core of a fusion machine[1]

The isotopes are heated to extreme temperatures—on the order of 50 million degrees Celsius—and kept stable under intense pressure long enough to allow the nuclei to fuse

A fusion power plant converts the energy—which is originally in the form of fast-moving helium and neutrons—into electricity that goes into the grid

[1]Deuterium fuel is extracted from seawater. Tritium fuel is created by the fusion machine itself, using the neutron created in the reaction plus commonly available lithium metal.
Source: US Department of Energy, Office of Science

[3] "DOE Explains...deuterium-tritium fusion reactor fuel," US Department of Energy, Office of Science. The other fuel component of this reaction, tritium, is created by the fusion machine itself—except for a small amount required to initially start the machine. This small amount of tritium would have to come from an external source—other fusion machines, for example, or a nuclear reactor such as a Canada deuterium uranium (CANDU) machine.
[4] "TAE Technologies partners with Japan's Institute for Fusion Science (NIFS) for fusion fuel research," TAE Technologies, October 26, 2021.
[5] "What is a tokamak?," ITER, accessed July 31, 2022.
[6] "Fusion - Frequently asked questions," International Atomic Energy Agency, accessed July 31, 2022.

technological challenge—so much so that after more than 60 years of experimentation, a marketable solution remains elusive. Skeptics point out that practical fusion energy has been 20 years away for the past 50 years. The basic problem is the difficulty of preventing energy from leaking out, which means that fusion machines, so far, consume more energy than they create.

In addition, the machines are complex: they require the world's most advanced magnets, hard-to-engineer materials that can withstand the intense temperatures on the machine's inside wall, and submillimeter precision for machined parts several meters across. Conceptual designs, when costed out, have seemed too expensive to be competitive with other forms of generation. From the 1970s onward, governmental enthusiasm for funding fusion projects has therefore waned.

But now, there are reasons to believe that fusion energy could be at a turning point. These include the following:

1. *The development of enabling technologies has allowed fusion to break new barriers.* For example, additive manufacturing—often called 3-D printing—allows the complex geometrical shapes of parts required for the walls of fusion machines to be produced at low cost and designs to be iterated quickly. Rapidly increasing computer capacity has made it possible for simulation codes to represent fusion reactions in greater detail, so predictions about performance can be made without the expense of building large experiments. And rapid digital controls are improving the suppression of the vibrations that cause energy to leak out of the core fusion reaction. These and other technological advances have created the conditions in which fusion can develop more rapidly. In the same way, advancing lithium-ion battery technology has allowed electric vehicles to start proliferating after failing to achieve widespread adoption for 100 years, and manufacturing breakthroughs in low-cost polysilicon solar panels (by Chinese and other OEMs) from 2005 to 2008 largely enabled the massive scale-up of solar deployment in the past decade.

2. *There has been a sea change in the orientation of fusion research programs.* Most fusion research used to occur in science-oriented, publicly funded labs. Now there is a new wave of privately backed programs, as well as programs working toward commercial viability in both the public and private sectors. This development has been driven partly by the fact that enabling technologies have progressed enough for private investors to step in with confidence. The result is that numerous privately funded start-ups now hope to operate commercial fusion machines before the end of the 2020s. A few major public labs are also launching

Numerous privately funded start-ups now hope to operate commercial fusion machines before the end of the 2020s.

programs to build commercially viable operational fusion machines. For example, the United Kingdom's STEP program (out of the fusion research center at Culham) seeks to build a new fusion machine by 2040, and the Chinese fusion program recently accelerated plans for the China Fusion Engineering Testing Reactor, a prototype commercial fusion machine.

3. *Investment in private fusion funding has greatly accelerated.* Private investment in fusion energy has surged over the past 20 years, with the value of investments nearly tripling in 2021 (Exhibit 3). This increased funding is a combination of traditional technology venture funding; strategic investments by incumbent energy companies, such as Eni's and Equinor's investments in Commonwealth Fusion Systems; seed investments by ultra-high-net-worth individuals, such as Sam Altman's 2021 investment in Helion Energy; and government investments, such as the participation of the UK Innovation & Science Seed Fund in Tokamak Energy's series A venture round. Access to capital is allowing private companies to construct larger components for fusion machines and to design full-scale prototypes for construction later this decade.

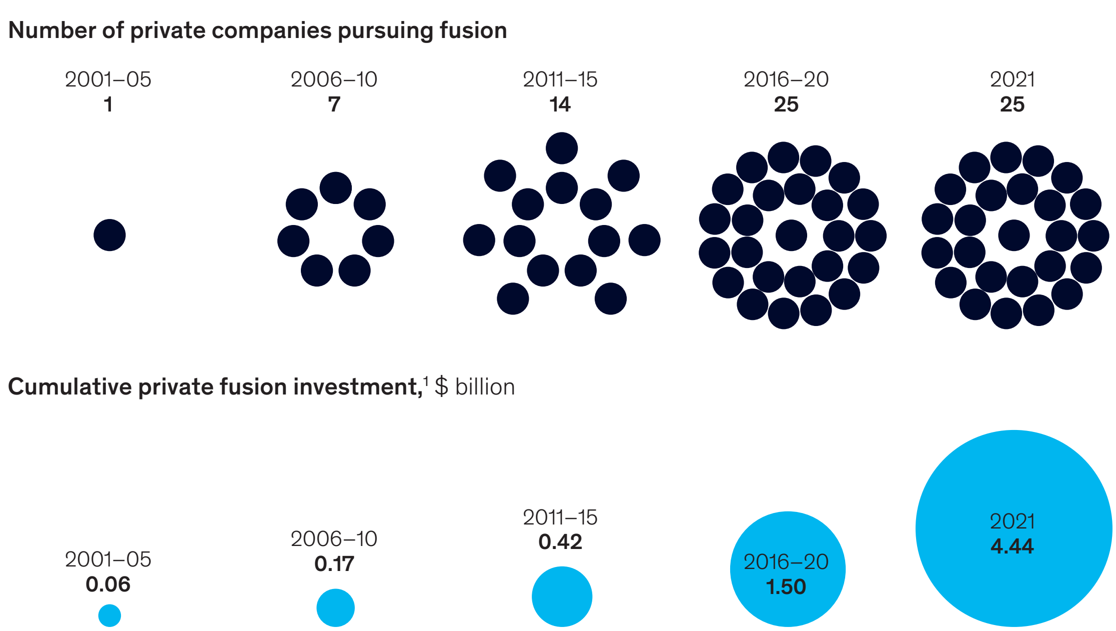
The next five to ten years will be critical for the development of fusion energy

Some key benchmarks over the next decade will help indicate whether fusion is truly on a trajectory toward implementation. Over the next five years, we would expect to see these advances:

1. *Demonstration of the core temperature and pressure conditions required for the fusion energy produced to exceed the heating energy injected into the reaction.* The temperatures required to produce energy from a fusion

Exhibit 3

Private investment in fusion energy has surged over the past 20 years, with the value of investments nearly tripling in 2021.



[1]Based on public information; companies analyzed include TAE Technologies, General Fusion, Commonwealth Fusion Systems, Helion Energy, Zap Energy, Tokamak Energy, and First Light Fusion. Additional investments in fusion research come through other public forms—for example, the US fusion budget (~$500 million per year), which supports ITER (multinational, ~$20 billion capex project).
Source: McKinsey analysis

reaction are on the order of 50 million degrees Celsius. The hotter the core of a fusion machine can get, and the more pressure it can withstand without leaking energy, the more net energy it can produce. This level of confinement, long a challenge in achieving net energy gain, is a necessity.

2. *Confirmation of component-level performance of various fusion concepts.* By 2025, leading private fusion players plan to demonstrate, or in some cases have already demonstrated, major subsystems. These include powerful high-temperature superconducting magnets (achieved by Commonwealth Fusion Systems in 2021), plasma injectors (such as the P13 injector demonstrated by General Fusion in 2017), radio frequency heating systems, and new wall materials that can survive the intense heat of a fusion machine's interior. Successful tests of these major subsystems and components by 2025 would mean that operational prototype plants could be functioning by the decade's end.

3. *Demonstration of fusion in conditions relevant for power plants and validation of the economics.* By 2026, we would expect to see at least one player integrating all major subsystems into a functioning prototype that can validate system level performance. Such a prototype would also make it possible, for the first time, to conduct a Class 4 (feasibility-study level) estimate of the costs of a fusion machine's parts manufacturing and assembly. This would be the first model of a fusion power plant's economics that could truly inspire confidence.

For fusion to play a major role in decarbonization before 2050, other key elements will also need to be in place within the next ten years:

1. *A regulatory framework for licensing fusion power plants.* As we have said, fusion machines are inherently less susceptible to serious safety incidents than nuclear-fission reactors. But it is unclear whether fusion machines will be licensed under fission frameworks, which are designed for nuclear plants based on existing fission technology and involve years of intensive design reviews.[7] The countries that first deploy fusion machines will need a regulatory framework designed to allow rapid development while ensuring safety. For example, in the autumn of 2021, the United Kingdom, which seeks to make fusion a part of its national decarbonization plans, embarked on an effort to develop a made-for-fusion licensing framework.[8] It will take into account the technical characteristics of fusion devices and allow the rapid deployment of fusion once a machine's design has been proved. For comparison, countries providing for flexibility in the traditionally heavily regulated rocket and spacecraft sector are seeing innovations from the private sector.

2. *The beginning of a scaled global supply chain and workforce for fusion energy.* From lithium fuel–producing modules to advanced radio frequency heating sources, fusion will require specialized parts now fabricated one-off for laboratory experiments. Increasing confidence in the viability of fusion could stimulate investments in supply chains that support the construction of multiple fusion power plants. In addition, engineers, construction workers, and plant operators will have to be trained through academic programs and apprenticeships.

3. *The first commercial power plants with traditional project finance.* Projects funded by equity investors, along with construction loans from banks and other financiers, would be a strong indication that fusion is on a path to adoption. There may be some de-risking loans by governments in the early days, but project development will not need to rely on the massive governmental de-risking loans and grants that fission plants have lately required in the West.

[7] "The regulation of fusion – a practical and innovation-friendly approach," Hogan Lovells, February 2020.
[8] *Towards fusion energy: The UK government's proposals for a regulatory framework for fusion energy*, UK Government Department for Business, Energy, and Industrial Strategy, October 1, 2021.

For leaders in business, financial management, and government, this is the time to start preparing for the development of fusion energy. Leaders can start to plan for the opportunities and risks by considering several moves:

— *Understand how the development of a working fusion machine could disrupt energy investments.* Techno-economic modeling can indicate the conditions under which fusion could supplant or complement battery storage, gas power using carbon capture, and other potentially less cost-effective technologies. Including fusion in at least some investment scenarios can give leaders a fuller picture of potential decarbonization pathways.

— *Consider the degree to which fusion should be built into decarbonization plans.* Fusion energy is not a sure thing—there are still major technical challenges, such as the performance of the magnets, the survivability of the first wall, plasma stability in confinement concepts other than tokamaks, and reliable heating systems. However, the potential upside could be great enough to make evaluating whether fusion should have a place in corporate or national energy plans worthwhile. A fusion-heavy grid would imply major shifts in investment over the next 30 years, including a partial shift from wind and solar with battery storage toward fusion machines. Such a grid will also require policy changes for the licensing of facilities. It is therefore worth starting the conversation today—these changes will take years to implement.

— *Understand the value chain of fusion energy.* Fusion power plants, like any complex system, will require a supply chain of parts and a value chain to develop and operate. That includes early-stage development, final development, construction, financing, operation, and end-of-life decommissioning. Leaders should begin to understand these supply and value chains to identify the potential control points and investment opportunities. Such preparations will lay the groundwork for capturing fusion's financial and strategic upside as the technology is proved and the industry ramps up in size. Of course, it will be necessary to recognize that the technology must advance further before an industry can grow up around it.

The technology still needs to develop, and there is no guarantee that recent fusion concepts will ultimately produce net energy. Yet this time may be different for the longtime dream of fusion energy. Fusion's characteristics as a zero-carbon, dispatchable source of electricity would allow it to play a key role in grids, along with wind, solar, carbon capture, and other technologies. For all leaders—especially policy makers and leaders in the energy sector and industries that are large consumers of energy—being prepared is prudent.

Miklós Dietz is a senior partner in McKinsey's Vancouver office, **Bill Lacivita** is a partner in the Atlanta office, **Amélie Lefebvre** is a consultant in the Montréal office, and **Geoff Olynyk** is a senior expert in the Toronto office.