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FEATURE

Leading in a low-carbon future

A “system of systems” approach to addressing climate change

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DELOITTE CENTER FOR INTEGRATED RESEARCH

How can executives drive industries and organizations to reverse course on climate change and lead a more sustainable economy? Adopting systems thinking can help with a successful transition to a low-carbon future.

SPURRED ON BY the climate crisis, the world has begun moving—unevenly but inexorably—toward a low-carbon future. This shift is every bit as transformative as the initial adoption of fossil fuel–powered machines and electricity. And the move toward "net zero"—emitting no more greenhouse gases than are removed[1]—needs to unfold with an urgency that exceeds previous industrial revolutions.[2] The global economy is being remade, and every business, government, organization, and individual has a role to play in accelerating this transition.

A growing array of businesses and governments are, indeed, confronting climate change, announcing emissions goals and climate initiatives daily. While worthy in and of themselves, these efforts are often focused narrowly on the organization's own operations. What's needed is a more holistic *system of systems* approach that unlocks critical opportunities in the transition to a low-carbon economy by working at the intersection of emerging low-carbon initiatives.

The system-of-systems approach recognizes that existing industries will be reconstituted as a series of complex, interconnected, emissions-free systems: energy, mobility, industry and manufacturing, agriculture and land use, and negative emissions. Government, finance, and technology can play a catalytic role to underpin and enable the emergence of those systems. A diverse set of societal and economic forces—from fluid and shifting consumer preferences to the rise of stakeholder capitalism and growing demands for climate action now—can drive the transition.

Accelerating progress toward net-zero emissions and tackling our toughest climate challenges will require extraordinary levels of collaboration and coordination across emerging systems. These efforts should be built around a global stewardship ethos that envisions us not as owners, managers, or consumers, but as caretakers of our organizations, our communities, and our planet. What lies ahead of us is daunting, and the stakes could not be higher. But we confront this challenge knowing what needs to be done and having most of what is needed to do it. Now, in this decisive decade,[3] we must act, with urgency and boldness and care for our common home.[4]

Why we should take a systems view of the emerging net-zero economy

Many business and government leaders around the globe have steadily moved climate change higher on their agendas.[5] Hundreds of companies have set science-based targets consistent with the Paris Agreement,[6] publicly committed to using 100% renewable energy,[7] or made other climate pledges.[8] And yet progress, as measured by declining emissions, has thus far been negligible, even considering the year of COVID-19 lockdowns. The United Nations' 2020 Emissions Gap Report notes: "Carbon dioxide emissions are predicted to fall up to 7 per cent as a result of the pandemic slowdown. But this dip only translates to a 0.01°C reduction of global warming by 2050." The report calls existing pledges "woefully inadequate."[9]

Many factors account for this dismal report card, but part of the problem lies in many organizations' tendency to approach the climate challenge through a lens focused narrowly on the single business or industry.[10] The typical sustainability road map looks almost exclusively inward, taking stock of the existing emissions footprint, setting mitigation targets, and then developing a plan to achieve them; current leading commitments may pledge to influence suppliers or reduce so-called Scope 3 emissions (indirect emissions across the value chain).[11]

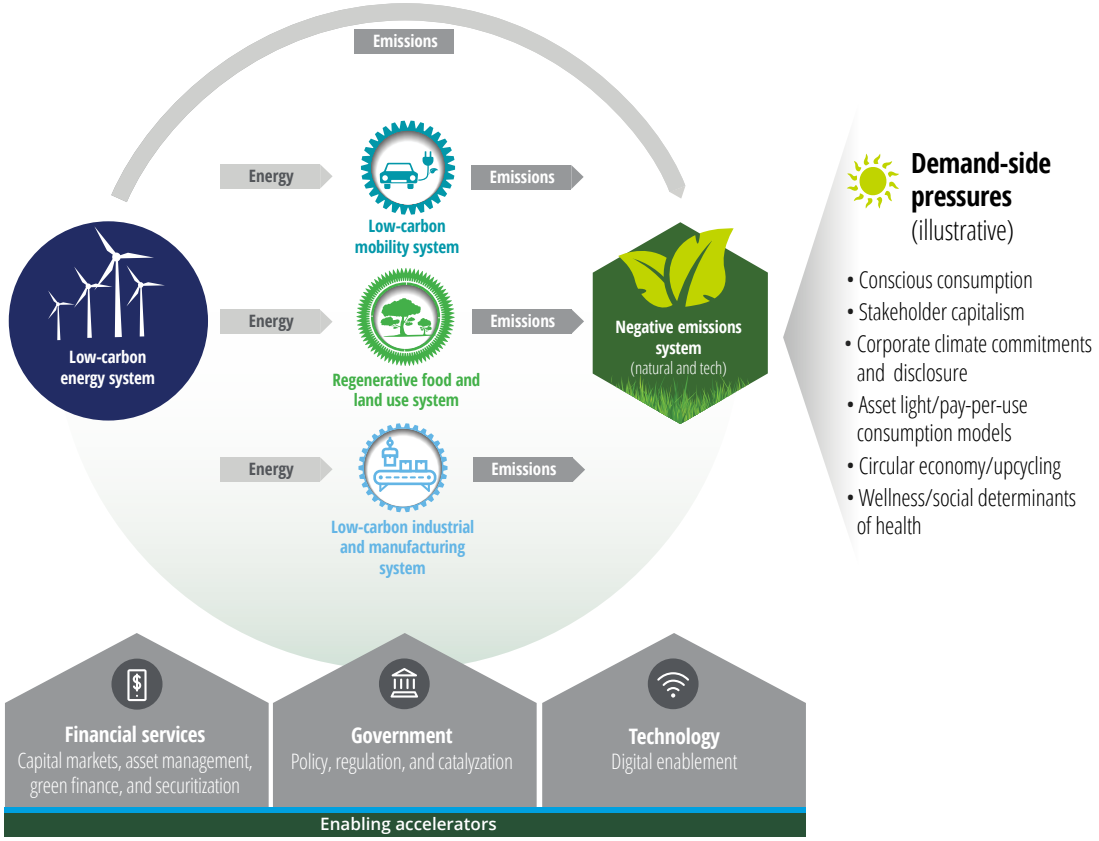
An electrified vehicle fleet significantly addresses climate change only if it is charged with clean, renewable electricity and manufactured with circular, low-waste processes using sustainably extracted raw materials.

These approaches ignore a critical, overarching point: The transition to a low-carbon economy demands the synchronized transformation of multiple, interdependent systems. An electrified vehicle fleet significantly addresses climate change only if it is charged with clean, renewable electricity and manufactured with circular, low-waste processes using sustainably extracted raw materials. It is only by adopting a more comprehensive view of the emerging low-carbon economy that we can begin visualizing the critical connection points and contingencies, in turn allowing organizations to work collaboratively to remove barriers, reach critical tipping points, and accelerate adoption of some of the most impactful climate solutions. Isolated initiatives miss the essential synergies in this transition.

The key is in harnessing a shift that has been underway for years: Traditional industry lines have been blurring and giving way to new business ecosystems comprising diverse sets of participants.[12] The race to address climate change only accelerates those shifts and brings them to new corners of the economy. The complex and interconnected systems that are emerging may resemble yesterday's industries, but under the surface, they will likely be driven by the rapid adoption of new technologies, deep shifts in operating processes, and the transformation of business models, with entirely new sets of players working together in novel ways (figure 1). Sources of value creation in the low-carbon economy will shift profoundly, as will capital allocations.[13] How and when these evolve will vary by system, but in every case, they offer tremendous opportunities for both legacy incumbents and disrupters if they're proactive in helping direct the market toward a net-zero economic future.

FIGURE 1

The building blocks of the low-carbon economy



Source: Deloitte analysis.

Demand-side forces are shaping and accelerating these systems-level transformations. As consumers grow more conscious of their own ecological footprints, they're insisting on more sustainable practices from businesses and increased transparency about their purchases.[14] And as companies across a range of sectors adopt climate change goals, they're creating demand for more renewable energy, low-emissions transportation, and high-quality carbon offsets.[15]

THE CLIMATE CRISIS

We are in the midst of a defining moment in human history, facing what is likely to be the most disruptive and destructive challenge any of us will grapple with in our lifetimes: anthropogenic climate change.

All of human civilization evolved within the context of a stable climate,[16] but that stability is now gone. The environment in which we live now—and for the foreseeable future—is truly unprecedented. Humans have not witnessed today's levels of atmospheric greenhouse gases (GHGs) since the Neolithic Revolution and the beginning of agriculture and settlements, roughly 12,000 years ago.[17] The impact of a global climate subject to unpredictable, frequent, and increasing extremes—of heat, cold, drought, and deluge—will likely be catastrophic. It would be an understatement to say that the fate of human civilization depends on organizations' and institutions' ability to respond to, mitigate, and reverse climate change.

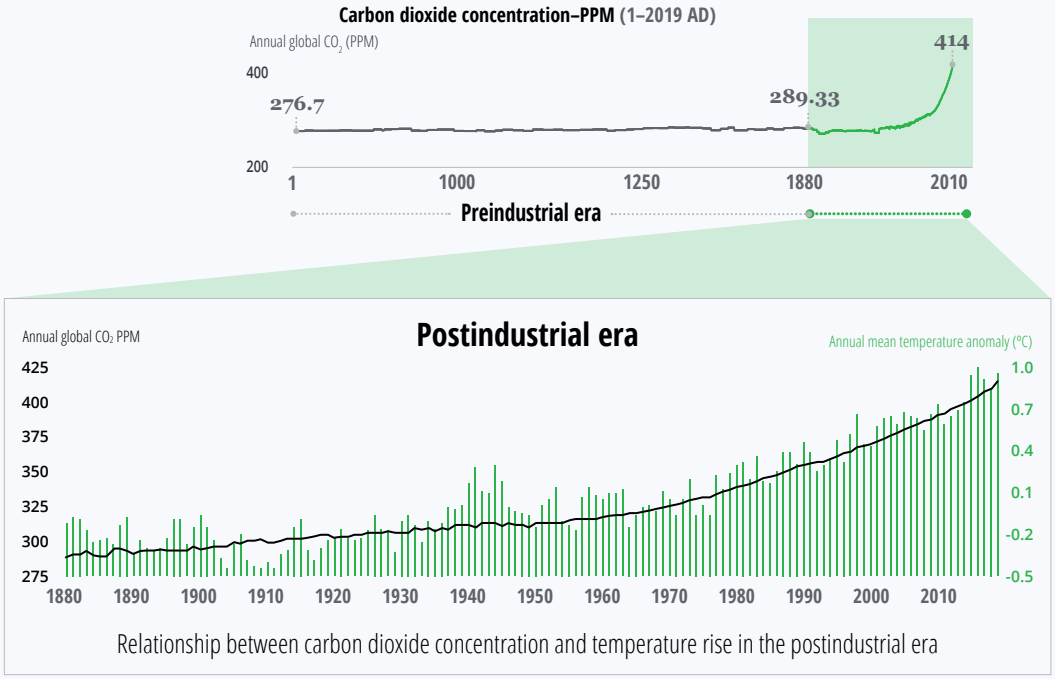
Human actions—primarily burning fossil fuels, but also deforestation and other activities—have resulted in a rapid increase in the concentration of GHGs in the atmosphere. GHGs, including carbon dioxide, methane, and nitrous oxide, trap heat close to the surface and cause global temperatures to rise. Since the industrial revolution, CO_2 concentrations have risen by more than 30%—currently 420 parts per million, up from 180 to 300 ppm historically over the prior several hundred million years.[18] The result has been an average global temperature increase of approximately 0.2°C per decade. Today, mean surface temperatures are approximately 1.2°C (2.1°F) warmer than in the preindustrial period—enough to destabilize large ecosystems around the globe.[19]

Scientists' climate models have thus far been remarkably accurate at predicting global temperature rise.[20] And forecasts have generally *underestimated* the speed and severity of the impacts of a changing climate—for example, glaciers and ice sheets—are melting far more quickly than most climate scientists expected even just five years ago.[21] Today, many scientists see a range of once-unlikely climate tipping points—including the rapid collapse of ice sheets, thawing permafrost in the Arctic, and the disruption of critical ocean currents—as "too risky to bet against."[22] Any one of these (factors/tipping points/possibilities) is potentially cataclysmic in its impact, and is a plausible outcome within our lifetimes.

The Intergovernmental Panel on Climate Change states that keeping mean surface temperature increases to no more than 1.5°C over preindustrial levels is critical for avoiding the most devastating impacts.[23] The panel assesses that doing so means cutting global GHG emissions roughly in half by 2030 (from 2010 levels) and reaching net-zero emissions—releasing no more carbon into the atmosphere than is removed—by 2050.[24] And achieving that net-zero goal will almost certainly require a top-to-bottom transformation of the global economic system, across industries.

FIGURE 2

The increase in carbon dioxide concentration has led to rising temperatures over time



Sources: NASA; NOAA.

How different systems move toward net zero

We see five core, interconnected systems in the net-zero economy, roughly corresponding to the major sources of today's GHG emissions plus the critical processes to take carbon out of the air: energy, mobility, industrials and manufacturing, food and land use, and negative emissions (both natural and technological). Figure 3 offers a snapshot of each: where it is today, where it's headed, and some of the key steps needed to make the transition toward a low-carbon footing (see the appendix for additional details on each system). These are meant to be suggestive, not determinative, of the path these systems might follow. Regardless, participants in each of these systems—including, to some degree, everyone reading this article—will likely face deep transformations of processes, technologies, supply chains, and business models.

Note, too, that in every case, effecting the transition will almost certainly require collaboration and contributions from multiple systems. While here we discuss these systems independently, they are deeply enmeshed, and the borders between them are both blurred and somewhat arbitrary.

In addition, across a range of additional areas of the economy, shifts in processes, technologies, products, and services are equally critical to enabling and accelerating this transition:

- **Financial services** will likely fund much of the shift to a low-carbon economy that could require US$30 to US$60 trillion of additional capital investment to reach net zero by 2050.[25] Much of that could flow to the rapid buildout of proven low-emission technologies and infrastructure, but major capital infusions also are likely to go toward advancing, piloting, and

FIGURE 3

A snapshot of low-carbon systems

System	Current state	Low-carbon future	Select transition actions
Energy	Coal and natural gas generate most electricity, but renewables are rapidly gaining and, in many markets, are already the cheapest source of power. The oil sector produces roughly 100 million barrels per day, mostly for transportation fuel and industrial processes.	Nearly all electricity is supplied by renewable energy, with expanded and diverse storage technologies and a more robust, resilient, and intelligent grid helping to address increased but uneven loads. As transportation and industrials decarbonize, oil demand would decline.	• De-emphasize fossil fuels • Rapidly expand installed renewable capacity • Build out transmission infrastructure and accelerate smart grid deployment • Develop large-scale and long-term storage
Mobility	Road transport accounts for the vast majority of emissions. Only 1 percent of vehicles are electric, but growth has been rapid. Aviation and ocean shipping are smaller contributors, although their emissions have been rising quickly.	Low-emissions powertrains dominate, led by electric motors and hydrogen fuel cells. Biofuels and green hydrogen adoption increases, especially for heavy. Urban mobility becomes more seamless and integrated, with walking, cycling, electric micromobility, and accessible mass transit providing alternatives to private cars.	• Shift vehicle production to electric and fuel cell platforms • Expand battery and fuel cell production • Rapidly build out charging infrastructure • Employ smart logistics and "control towers" to increase efficiency and agility
Industrials and manufacturing	Most emissions come from consumed energy during production, but direct emissions from cement and chemicals manufacturing are significant. Hard-to-abate processes in heavy industry, such as steel, have few viable low-carbon alternatives.	Hard-to-abate heavy industries increase use of green hydrogen and electrification. Manufacturing continues to gain efficiency, complementing and accelerating the broader shifts toward smart factories and digital supply networks already underway.	• Shift emissions-intensive processes to electric, hydrogen, or other technologies • Adopt holistic circular manufacturing approaches • Deploy and scale additive manufacturing to reduce waste
Food and land use	Livestock husbandry, crop burning, and deforestation account for most emissions, with meat and dairy the most greenhouse gas (GHG)–intensive. Almost one-fifth or more of global food production is wasted.	The food system becomes a net carbon sink through widespread deployment of regenerative farming practices and agroforestry. Shifts toward less meat-intensive diets drive down emissions, and monitoring technologies reduces waste.	• Deploy and scale regenerative techniques • Advance meat alternatives and dietary shifts • Reduce food waste through supply chain enhancements, improved transparency and monitoring, and revised regulatory guidelines
Negative emissions system	Natural carbon sinks such as forests, grasslands, and oceans are being rapidly depleted. Technological carbon removal is limited, costly, and fragmented.	Reaching the point of GHG drawdown will require a robust carbon capture and sequestration system, deploying a mix of natural solutions, such as massive reforestation and ecosystem restoration, and technologies, such as direct air capture. A well-functioning, liquid, and transparent carbon trading market accelerates progress.	• Create policy and regulatory frameworks and financial incentives for emergence of carbon markets • Widespread ecosystem restoration and conservation • Significant R&D to mature nascent carbon removal options

Source: Deloitte analysis

deploying nascent solutions, such as carbon direct air capture. Players across the financial services industry have a tremendous opportunity to support a variety of sectors that are poised for rapid growth in the coming decade.

- **Governments** at all levels will play an instrumental role, setting clean energy standards, emissions targets, carbon prices, and other regulatory and policy mechanisms—and also acting as a catalyst through procurement (the US government is the world's largest buyer[26]) and as an ecosystem architect, proactively building and nurturing the cross-cutting networks of public sector agencies, businesses, academics, NGOs, and citizens needed to collaboratively develop and rapidly scale innovative climate change solutions.

- **The technology sector** has a critical role to play in providing the digital infrastructure and solutions to enable a decarbonized economy. Nearly all of today's powerful technologies—big data analytics, advanced artificial intelligence (AI), Internet of Things (IoT), blockchain and distributed ledgers, cloud, and more—have applications in the transition to and operation of emerging low-carbon systems.

Accelerating progress by working across low-carbon systems

Some of the most powerful and impactful opportunities to address the climate crisis and create new value lie at the intersection of emerging low-carbon systems. An array of climate solutions currently face critical bottlenecks or fragmented approaches. In many instances, supply and demand are mismatched or operate on different time horizons. For example, many consumers resist buying electric vehicles because charging stations are not widely available, but charging providers balk at installing more infrastructure without clearer evidence that it will get regular use.

Indeed, a number of decarbonization technologies are likely to require billions in capital investment to occur before there is any certainty about viability or scalability. Challenges such as these can only be unlocked and accelerated by leaders across industries adopting a system-of-systems view that looks at the interdependencies and connections across the core systems of the global economy in new ways; in turn, opening up possibilities to aggregate demand to send clear signals to tip markets or pool risk to accelerate investment.

Consider one such cross-system opportunity: carbon credit markets. While some markets exist in particular geographies and at various levels of sophistication and maturity, scaled, well-functioning carbon credit trading markets could help incentivize a wide range of players to remove and store carbon or otherwise reduce emissions while also providing critical funding for early-stage technologies. Such markets could also attract more capital because of the ability to buy and sell credits, accelerating and expanding programs that create high-impact carbon sinks. But we're a long way from a functioning system. Carbon credits today often have fragmented, bespoke standards and certifications with few connection points, and have uncertain, dubious, or outdated impacts. Few markets are truly liquid, there is a lack of transaction transparency, and project developers can add opacity by selling directly to companies and individuals or through brokers or exchanges.[27] A functioning global market—one with a liquid, exchange-traded contract at its core, trading as spot and futures—needs price transparency, consistency, and clarity. That contract would also form the basis for an over-the-counter market that could reflect different types of carbon offsets.

Getting there will require broad cooperation across multiple systems of the low-carbon economy. Suppliers of carbon credits—ranging from

reforestation projects and agriculture to direct air capture and more—would have to collaborate with buyers spanning energy, mobility, industry, and beyond that are looking to offset their most stubborn emissions. Financial institutions have key roles to play, potentially providing credit certification, brokerage, and portfolio management. Robust, open technology platforms could enable rapid execution of transactions, with specific credits potentially logged and tracked via digital ledger methods. Governments can shape the overlying incentive structure through policies, such as emissions caps and carbon pricing, while ensuring that credit markets do not undermine the critical need for absolute emissions cuts, and financial regulators could set common standards. Ultimately, reference contracts could bundle producers' products and buyers' preferences to allow for significantly more efficient matching of supply and demand.

This is just one of many potentially transformative opportunity spaces that only the combined efforts of numerous low-carbon systems can unlock. We'll explore carbon markets and others in much greater depth in subsequent articles, focusing on how companies, governments, and others can enable their emergence and adoption.

Value creation, tipping points, and the case for speed

The sheer magnitude and complexity of the challenge can be overwhelming. Where should you start, and what does the journey look like?

Begin with a systems view. Set aside existing frameworks about what your industry looks like and who your competitors are. Instead, consider how the economy is likely to be reconfigured as it moves toward a low-carbon footing. We've laid out the broad strokes, but a much more granular perspective is needed to effectively set strategy. Detailed modeling of both the climate and the economy can help inform the perspective.

Understand where value is likely to be created—and destroyed. There are four

CREATING A JUST AND EQUITABLE TRANSITION TO A LOW-CARBON FUTURE[28]

Climate change exacerbates many of the damaging features of our natural environment: storms, flooding, droughts, fires, heat waves. But it also worsens the flaws in our social and economic systems. The impacts of a changing climate will fall squarely on the shoulders of those who are most vulnerable—and who have done the least to cause the problem.[29] The world's richest 1% emit twice as much as the poorest 50%; the wealthiest 10%—those earning at least US$38,000 per year—were responsible for more than half of cumulative global emissions between 1990 and 2015.[30]

It matters tremendously not only that we achieve a net-zero economy by 2050, but how we get there. Local communities, especially so-called front-line and fence-line communities,[31] need a voice and a seat at the table. Minority and low-income communities that have been disproportionately exposed to environmental harms should be safeguarded. Workers in emissions-intensive industries need to see a clear path toward a brighter economic future. These issues are devilishly complex, requiring a careful blend of public policy, private sector action, and community engagement, a detailed treatment of which is beyond this article's scope. But without centering climate justice and equity in every decision, mitigation efforts might deepen economic inequality and systemic racism and create a new divide between climate haves and have-nots.

fundamental sources of value in the low-carbon economy:

- *Use less.* Implementing sustainable production and consumption, increased energy efficiency, and reduced waste: building retrofits, smart heating and lighting, HFC-free refrigeration, etc.
- *Emit less.* Providing clean alternatives to carbon-intensive processes: renewable energy, electric vehicles, green steel, etc.
- *Regenerate, restore, and repair.* Removing carbon and restoring natural capital: nature-based solutions, reforestation, regenerative agriculture, direct air capture, etc.
- *Measure, verify, disclose, value, and track.* Monitoring progress toward net zero and ensuring transparency: unified climate standards, emissions life cycle analysis and Scope 3 assessments, reporting and compliance, etc.

It's just as important to understand what services and assets may cease to be viable. The clock is ticking on high-emissions business models.

Determine where to play and how to win at the scale and speed needed to avert catastrophic climate change. Identify opportunity spaces within or at the intersection of nascent low-carbon systems by looking for chances to apply the drivers of low-carbon value in new ways. In some cases, they could be a natural evolution of your organization's current role. In others, it might require a significant pivot and business transformation. Also consider the likely timelines. Some solutions can be scaled today, such as improving building efficiency and deploying solar and wind power. Others, like truly low-emissions aviation, are likely years away from widespread application, but the hard work of developing and piloting should begin now. Assess what it takes to accelerate adoption and who are your natural collaborators to make tomorrow happen today.

For those with legacy business models built on carbon-intensive processes, inertia is a powerful force to overcome: Shifting away from proven and still-profitable activities into new and uncertain areas can be daunting or even seemingly prohibitive. Understandably, incumbents across a range of industries have sought to manage the transition to a low-carbon future by taking small steps, creating optionality, and extending the timeline over which the shift will play out.

A decade ago, a go-slow strategy might have been justifiable from a business perspective; today, that approach is fraught with risk, as the transformation of the global economy to a low-carbon footing accelerates.[32] We've already seen the economics of one critical segment—electricity generation—tip critically in favor of renewable sources in many markets, to the detriment of incumbent coal and, to a lesser extent, natural gas generation.[33] Other areas are likely not far behind: Electric powertrains will soon surpass their internal combustion counterparts on nearly every relevant performance dimension, for example.[34] We are already seeing the beginnings of a sea change in financial markets, with investments increasingly flowing to climate-friendly businesses and away from carbon-intensive models that lack a clear path toward a lower-emissions footing.[35] And as capital allocations accelerate from both the public and private sectors, and regulatory requirements grow more stringent, a host of nascent solutions—from direct-air carbon capture and green hydrogen to biofuels and decarbonized cement—could move rapidly down the cost curve.

Into uncharted waters

The best predictor of the future, it is often said, is the past. But what happens when that maxim no

longer holds? As the profoundly stable climate upon which all of human civilization has been built recedes into memory, every organization will have to question its foundational assumptions about how the world works and what tomorrow will look like. And yet, at one level, we know where we're headed—a net-zero (and ultimately net negative) economy comprising of radically remade and interconnected systems spanning energy, mobility, industry, and more—and we have many of the tools needed to get us there.

As leaders look to navigate through this inevitable transition, the strong temptation is to do what's expedient today and respond to key stakeholders by setting appropriate emissions reduction targets, disclosing robust and assured climate data, and adjusting the business to a more sustainable footing. That's important and necessary work which every company should be undertaking.

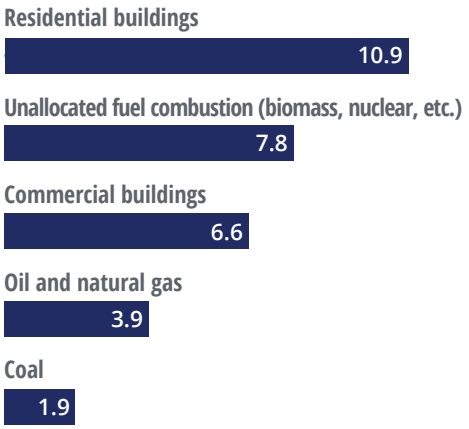
But it shouldn't—and can't—stop there. Positioning an organization to truly thrive in the low-carbon future requires a much more transformative and farsighted approach. It demands a systems lens that grapples with the complex and multifaceted net-zero economy, and looks for opportunities to speed decarbonization and create new value at the interstices. It's about identifying where to play and how to win in the low-carbon future, in which winning is as much about averting a planetary catastrophe as it is about profitability, growth, or market share. It's about having the courage and fortitude to make massive bets on a highly uncertain and unknowable future. Every day, markets are demonstrating that they'll punish those who remain steadfast to the past—and reward those who are pioneers.

Appendix: A snapshot of low-carbon systems

LOW-CARBON ENERGY SYSTEM

FIGURE 4

Energy system emissions (in gigatons of CO2e)



Source: Our World in Data, "Sector by sector: Where do global greenhouse gas emissions come from," last accessed May 6, 2021.

Energy production, primarily electricity generation and heating, accounts for **~31% (~15 gigatons CO2e) of global GHG emissions.**[36] Coal and natural gas are the two largest sources of electricity generation, accounting for roughly 60% of the total power produced.[37] Nearly all of the remainder comes from low-carbon sources, a mix of renewables (largely wind, solar, and hydropower) and nuclear.[38] Wind and solar growth has outpaced other generation sources; combined, they are forecast to become the largest source of installed global electricity generation capacity by 2025.[39] In many markets, renewables are already the cheapest source of electricity.[40] The oil sector produces approximately 100 million barrels per day,[41] most used as transportation fuel and in industrial processes.

The goal—a net-zero energy system—will likely see nearly all electricity supplied by renewable energy, likely dominated by a mix of utility-scale and distributed photovoltaic solar and onshore and offshore wind. Energy storage provided by batteries,

hydrogen, physical systems, and other technologies can help address uneven supply. A variety of other low-carbon power generation technologies—potentially including bioenergy with carbon capture and sequestration, geothermal, modular nuclear, and natural gas with carbon capture—could all play roles as well. Significant transmission capacity and a more robust, resilient, and intelligent grid could support the widespread electrification of other sectors (for example, home heating and electric vehicles) and the dynamic load balancing and management of distributed energy resources such as rooftop solar.

With the industry critical to how *everything* functions, new ideas and technology will no doubt materialize, but the transition to a low-carbon energy system will likely entail:

- De-emphasizing fossil fuel assets, and in ways that do not simply shift extraction to other players such as national oil companies and smaller, private firms. Market dynamics, regulation, and investor and activist pressure, as well as strong signals sent by some leading oil majors themselves,[42] are already moving toward that outcome, with transportation and industrial systems shifting to a low-carbon footing for which less oil will be needed, rapidly expanding installed renewable energy capacity and grid integration. This will likely require significant training and reskilling programs to grow the renewables workforce, working with governments to create a more streamlined permitting and siting process in many markets, and expanding manufacturing capacity to meet rising demand.

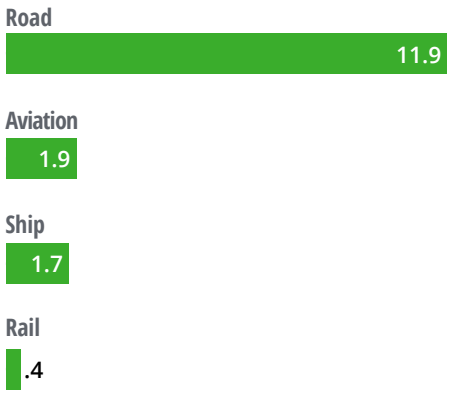
- Building out transmission infrastructure to handle increased grid loads and move renewable energy to load centers, and deploying more sophisticated, integrated smart grid technologies to dynamically balance loads. This could require a new mindset for many utilities and a willingness to work with software providers and technology companies to develop and implement robust, enterprise-grade solutions.

- Developing large-scale and longer-term storage capacity, likely using a mix of technologies. Working with researchers and manufacturers to advance battery technology and performance will likely be key, as well as expanding overall supply. Private-sector investors and government funding can provide risk capital to develop and pilot other additional storage technologies.

LOW-CARBON MOBILITY SYSTEM

FIGURE 5

Mobility system emissions (in gigatons of CO2e)



Source: Our World in Data, "Sector by sector: Where do global greenhouse gas emissions come from," last accessed May 6, 2021.

Transportation accounts for **~16% (~8 gigatons CO_2e) of global GHG emissions**.[43] The vast majority comes from road transport—cars and trucks to move people and goods—with most of the rest from aviation and ocean shipping. Roughly 1% of the automobiles in operation globally are electric, but the number has been growing rapidly, encouraged by favorable government policy and incentives; almost half of those vehicles are in China.[44] Modal share varies widely around the globe,

with more than 90% of trips occurring in private cars in some American cities, while cycling and public transport dominate elsewhere.[45]

Over the next decade or so, a low-carbon mobility system will require the near-complete replacement of the vehicle fleet. Passenger cars will likely be dominated by plug-in battery electric vehicles, perhaps with some use of fuel cell technology, as will last-mile delivery vehicles such as small trucks and vans. Charging infrastructure, provisioned by a mix of public and private sector providers, will become ubiquitous. Heavier freight vehicles will likely see greater deployment of green hydrogen. In urban areas, walking, cycling, electric micromobility (shared bikes and scooters), and public transport will increasingly replace private car trips as infrastructure and regulation become more conducive to those modes. Harder-to-abate sectors, such as aviation and shipping, could rely on technological advancements in biofuels and green hydrogen. Demand for gasoline, diesel, and other petroleum-based fuels is likely to drop precipitously.

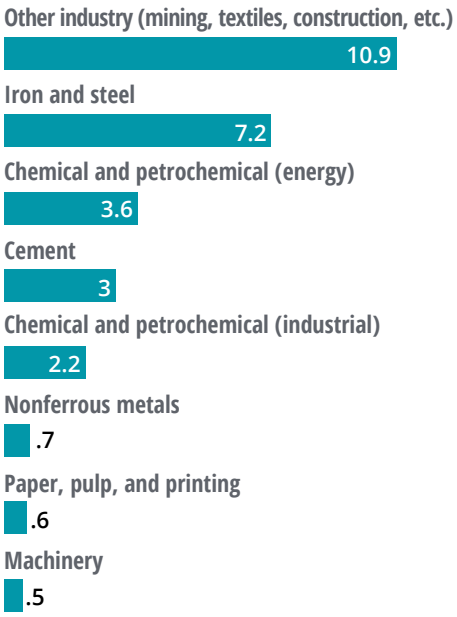
The transition to a low-carbon mobility system will likely entail:

- Shifting production to electric and green hydrogen powertrains, including retooling manufacturing facilities, reskilling workforces, and reconfiguring supply chains and customer-facing sales/service/after-sales practices.
- Expanding battery and fuel cell production, including working with the mining industry and governments to secure new sources of critical minerals (i.e., lithium) and establishing scaled and more sustainable battery recycling capabilities.
- Coordinating the build-out of ubiquitous rapid-charging infrastructure with grid integration for load balancing, in collaboration with utilities, real estate owners, governments, and others.
- Deploying smart logistics to increase efficiency and reduce electricity and fuel consumption and transition to more fit-for-purpose models—for example, mobile lockers and small electric vans for last-mile delivery.
- Shifting consumer attitudes and behavior to make clean mobility the easiest and cheapest choice. Expanding EV model options and adapting marketing messages, improving upfront cost parity with internal combustion vehicles, and implementing seamless integrated mobility technologies to enable and accelerate adoption of multimodal travel without private cars could all be important, necessitating collaboration between automakers, city governments, transit agencies, and others.

LOW-CARBON INDUSTRIAL AND MANUFACTURING SYSTEM

FIGURE 6

Industrial and manufacturing system emissions (in gigatons of CO2e)



Source: Our World in Data, "Sector by sector: Where do global greenhouse gas emissions come from," last accessed May 6, 2021.

Industrial manufacturing accounts for **~28% (~14 gigatons CO_2e) of global GHG emissions**.[46]

The bulk are the result of energy consumption during production across industries, although direct emissions as a byproduct of cement and chemicals manufacturing are significant contributors. Emissions have been flat or trending upward over the last decade:[47] The carbon-intensive nature of many processes has challenged manufacturers seeking to transition toward lower-emission alternatives, increase efficiency, remove waste, and embrace circular approaches, especially in heavy industry. Such hard-to-abate operations currently have few viable low-carbon alternatives.

A low-carbon manufacturing and industrials system will likely see changes in every sector and along nearly every step of the value chain, many complementing and accelerating the broader shifts toward smart factories and digital supply networks already underway.[48] Cement, steel, aluminum, and other hard-to-abate heavy industries could see much wider use of green hydrogen and electrification, with on-site carbon-capture technology playing an important role. Many of these technologies are nascent and will have to rapidly mature and scale. Further downstream, manufacturing could continue to see gains in efficiency, reducing emissions intensity through more efficient supply chains and shop floors and enabled by greater visibility through widespread sensor deployment and analytics. Additive manufacturing, lean production, circular-by-design, and more robust material recycling practices can reduce waste and emissions.

The transition to a low-carbon manufacturing and industrials system will likely entail:

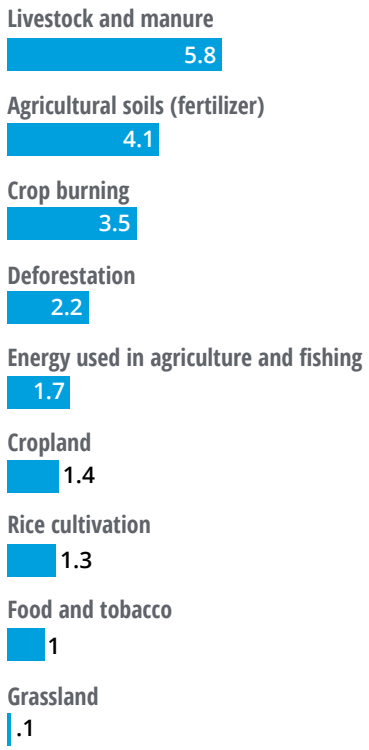
- Shifting emissions-intensive processes to electric power or alternative fuels such as hydrogen. Collaborative efforts working with competitors, startups, and researchers to develop, pilot, and deploy viable alternatives could help speed innovation and spread risk. Working with participants in the energy system to secure renewable electricity and a significant supply of green hydrogen (current production is negligible) will also be key.

- Widespread adoption of holistic, circular manufacturing approaches. This encompasses everything from designing more durable products and improving repairability to reducing energy and materials intensity, optimizing supply chains, and reducing waste and expanding recyclability. Working across the entire value chain, from source to end user and from product design to retirement, will be essential.

LOW-CARBON FOOD AND LAND USE SYSTEM

FIGURE 7

Food and land use system emissions (in gigatons of CO2e)



Source: Our World in Data, "Sector by sector: Where do global greenhouse gas emissions come from," last accessed May 6, 2021.

Agriculture and land use change account for **~21% (~10 gigatons CO_2e) of global GHG emissions**,[49] largely from livestock husbandry, crop burning, and deforestation. Taking all factors into account, cows (beef and dairy) and lamb have the highest emissions per kilogram produced.[50] And wastage plays a huge role: Though some 700 million people worldwide are chronically undernourished,[51] an estimated 17% of total food production—931 million metric tons—is wasted.[52] Wastage alone accounts for roughly 6% of total global GHG emissions.[53]

Reimagining agriculture and land use could transform the system from being one of the largest sources of emissions to a net carbon sink—and feed the world more efficiently. Getting there will likely require widespread implementation of farming techniques designed to capture and sequester carbon in soil. So-called regenerative practices, including no-till, use of cover crops, and rotating livestock and crop types, are likely to become more mainstream, although questions remain about the techniques' scalability and efficiency.[54] Additional changes to land use, including agroforestry and improving the productivity of existing agricultural land (and thus averting additional deforestation) could also help capture and keep carbon in the soil.[55] On-farm systems, such as anaerobic digesters, can help address powerful-but-short-lived methane emissions. At the same time, the balance of food production—and, accordingly, global diets—would almost certainly have to shift to be more plant-based; meat and dairy substitutes, whether cell-based or plant-derived, could play a significant role.[56]

The transition to a low-carbon food and land use system will likely entail:

- Deploying and scaling regenerative farming techniques and reducing and optimizing fertilizer use. Yields from regenerative agriculture can match or exceed those of conventional farming in some circumstances, but more widespread deployment of data analytics, advanced AI, precision planting, and other smart farming technologies may help offset any potential reductions.[57] Feed additives and on-site anaerobic digesters can help reduce and capture potent methane emissions.

- Advancing meat substitutes and alternatives to other carbon-intensive foods,[58] collaborating with startups to develop and refine new products. Extensive marketing and modified government guidelines are likely to be important to shift consumer attitudes.

- Reducing food waste through supply chain efficiencies and transparency, improved monitoring via IoT and other technologies, and revised standards. Working across the entire food value chain, from farm to fork, to deploy digital solutions to track fresh food holds tremendous potential to cut spoilage.[59]

NEGATIVE EMISSIONS SYSTEM

Every credible analysis of achieving net zero by 2050, including the Intergovernmental Panel on Climate Change's benchmark 2018 report on limiting warming to 1.5°C, factors in significant carbon removal.[60] But to date, carbon capture, utilization, and storage (CCUS) efforts remain limited, costly, and fragmented. Currently, there are only ~20 large-scale CCUS facilities globally, built to capture emissions from existing gas processing plants, fertilizer facilities, and the like, with a combined capacity to capture and store around 40 million tons of CO_2 annually (total annual global CO_2 emissions exceed 30 *billion* tons[61]). Nature-based solutions such as afforestation and reforestation are relatively inexpensive (US$5–50 per metric ton of CO_2[62]) but suffer from uncertain accounting, a limited supply

of viable projects, larger physical footprints, potential impermanence, and misaligned incentives between donors, NGOs, and land managers and local communities. Bioenergy with carbon capture and storage (BECCS) technology has already shown potential, but requires significant amounts of land (to grow biofuel feedstock), some of which might be diverted from food production, carbon-storing forests, or other uses.[63] And emerging direct-air-capture technology is expensive (US$135–345 per metric ton of CO_2),[64] energy-intensive, and unproven at scale. For buyers, the costs of nearly all of these options exceed so-called "avoidance offsets" that aim to forestall some emitting activity.[65]

CCUS will likely emerge as a cornerstone of the low-carbon economy, employing multiple approaches at scale and enabled by a well-functioning, transparent, and liquid carbon-credit markets. Widespread adoption of regenerative agriculture, agroforestry, and aquaculture could turn those activities into significant carbon sinks. Reforestation and afforestation could expand, aided by enhanced planting and monitoring techniques (drone planting, satellite-based and AI-enabled tracking), and offering significant co-benefits. Technical solutions could also be deployed at scale, with captured CO_2 both repurposed for other uses and stored permanently. The International Energy Agency's Sustainable Development Scenario envisions global capacity for carbon removal, by 2050, exceeding 1 gigaton of CO_2 per year using BECCS and direct-air-capture technologies.[66] Much of that captured CO_2 would be transported through an extensive network of pipelines—perhaps more than 100,000 kilometers' worth—in the United States by 2050.[67]

The transition to a robust carbon capture system will likely entail:

- Creating a policy and regulatory framework that supports and incentivizes the creation of a sustainable and viable market for CCUS, including establishing scaled carbon trading markets built on standardized, transparent credits and in which carbon prices incorporate the full breadth of externalities associated with GHG emissions.

- Widespread ecosystem restoration, employing techniques designed to maximize long-term carbon capture and create co-benefits for local communities.

- Significant infrastructure and facilities build-out and modification. This includes retrofitting existing emissions-producing facilities with CCUS, especially in the developing world where decommissioning of fossil fuel–based plants is less economically feasible in the near term. Dedicated transportation and storage infrastructure would also be needed, including repurposing existing oil and natural gas pipelines, identifying geologically suitable storage locations, and securing siting permits.

- Rapid and catalytic investment and R&D in carbon capture solutions and technologies for hard-to-abate processes. Venture capital and innovation funding would be needed to develop solutions and reduce costs. Expanded availability of renewable energy is key to maximizing the impact of CCUS technologies.

Enabling accelerators

FINANCIAL SERVICES: FUNDING THE TRANSITION TO A LOW-CARBON ECONOMY

The success of the transition to a low-carbon economy hinges in large measure on the ability to mobilize capital at the requisite speed and scale. The financial services industry has already begun to play an important enabling role in addressing climate change. More than 500 investors with over

US$50 trillion in assets have joined Climate Action 100+, an effort to push companies to do more to address climate change through direct engagement and via support for shareholder proposals.[68] A growing array of institutional investors and insurers are pulling back or divesting completely from fossil fuel positions.[69] Climate finance flows exceeded US$600 billion in 2019.[70]

These initial moves are likely just a small fraction of the opportunity for the financial services industry. Globally, reaching net zero by 2050 will demand perhaps US$30–60 trillion of additional capital investment.[71] Much of that could flow to the rapid buildout of proven low-emission technologies and infrastructure.[72] But investors will also likely direct major capital infusions toward advancing, piloting, and deploying still-nascent solutions such as carbon direct air capture.

Players across the financial services industry today have a tremendous opportunity to support a variety of sectors that appear poised for rapid growth; indeed, several top banks and asset managers are already directing billions of dollars toward restructuring high-emitting companies to help them transition. Insurance companies are ramping up resilience and risk-service capabilities to anticipate and adapt to the effects of climate change on infrastructure, property, and equipment. On a larger scale, new financial markets to efficiently price carbon impact are emerging and will likely be mainstream relatively soon. The challenge: Given the uncertainty surrounding many low-emissions technologies and business models, finding ways to de-risk capital flows will likely require the cooperation of multiple financial players as well as government.[73]

GOVERNMENT: ADDRESSING MARKET FAILURES, ACCELERATING ADOPTION, AND ENSURING A JUST TRANSITION

Governments at all levels, around the world, will play an instrumental part in the shift to a low-carbon future. The climate crisis can be understood as among "the greatest market failure(s) the world has ever seen," and addressing such failures has long been a critical public sector role.[74] Setting clean energy standards, emissions targets, carbon prices, and other regulatory and policy mechanisms will be essential to aligning market signals and properly accounting for the wide range of externalities associated with emissions-intensive activities. Funding early-stage research also often falls to the public-sector. At the same time, agencies can signal leadership by visibly shifting their own operations to a more sustainable footing. In many countries, too, the public sector represents the largest purchaser of goods and services,[75] and governments can drive demand by adopting renewable energy, low-emissions vehicles, and building efficiency improvements.

But that two-pronged approach focused on regulation and operations is likely to give way to a broader effort to combat climate change by serving as a catalyst for the low-carbon transition. As a catalyst, governments will play an important role as an *ecosystem architect*, proactively building and nurturing the cross-cutting networks of public sector agencies, businesses, academics, NGOs, and citizens needed to collaboratively develop and rapidly scale innovative solutions. And because the impacts of both climate change and the transition will be deeply unequal and hit the most vulnerable communities hardest, governments should serve as the ultimate guarantor that the shift to a low-carbon future will be equitable and just.

TECHNOLOGY: CREATING THE TOOLS NEEDED FOR LOW-CARBON APPROACHES

The technology sector has a critical role to play in providing the digital infrastructure and solutions to enable a decarbonized economy. Nearly all of today's powerful technologies—big data analytics, advanced AI, IoT, edge computing, blockchain and distributed ledgers, cloud, and more—have applications in the transition to and operation of emerging low-carbon systems.

In manufacturing, a range of smart factory and supply chain solutions can reduce waste and boost efficiency through widespread sensor deployments and advanced analytics.

In energy, smart grids that can incorporate a range of connected devices, from electric vehicles and rooftop solar systems to refrigerators and water heaters, and dynamically balance loads and usage are expected to be a key piece of a power sector increasingly dominated by renewables. In mobility, applications to optimize vehicle charging and battery life can help make electric powertrain ubiquitous across a wide range of use cases, and integrated mobility-as-a-service platforms can make it easier to get from A to B without a private car. In manufacturing, a range of smart factory and supply chain solutions can reduce waste and boost efficiency through widespread sensor deployments and advanced analytics. In agriculture, high-resolution GPS, IoT sensors, and data analytics can let farms produce more with less, even as technology enables better supply chain visibility of foodstuffs, decreasing spoilage. In carbon capture, cloud-based digital platforms will be key to allowing producers of carbon credits to seamlessly trade with buyers using standardized, blockchained carbon tokens.

Technology companies will need to rapidly develop and deploy these and many more open-source solutions to achieve net-zero goals, working with a range of players across nearly every industry, in government, in academia, and in nonprofits. And companies have an opportunity to catalyze the transition via their own actions to reduce emissions. By sourcing renewable power, developing more efficient AI and data centers, shifting to more sustainable hardware sourcing and manufacturing processes in semiconductors and elsewhere, and building more durable products, tech companies can help create the market demand for the transformation of other low-carbon systems.

Endnotes

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Acknowledgments

The authors would like to thank the many Deloitte colleagues who offered insights on this article, including **Kathryn Alsegaf**, **Heather Ashton Manolian**, **Jolyon Barker**, **Matthew Budman**, **Ellen Carter**, **Libbey Davis**, **Duane Dickson**, **Bill Eggers**, **Shay Eliaz**, **Jason Girzadas**, **Kate Hardin**, **Richard Longstaff**, **Ricardo Martinez**, **Kwasi Mitchell**, **Lisa Newman-Wise**, **David Novak**, **Jay Parekh**, **Stanley Porter**, **Michael Raynor**, **Alicia Rose**, **Suzanna Sanborn**, **Elisabeth Sullivan**, **Kristen Sullivan**, **Kyle Tanger**, **Sharon Thorne**, **Geoff Tuff**, and **Rasheq Zarif**.

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