POSITIVE DISRUPTION

LIMITING GLOBAL TEMPERATURE RISE TO WELL BELOW 2 C°

BY MARSHALL ABRAMCZYK, MARTHA CAMPBELL, AMAN CHITKARA, MIA DIAWARA, AILEEN LERCH, AND JAMES NEWCOMB

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ABOUT ROCKY MOUNTAIN INSTITUTE

Rocky Mountain Institute (RMI)—an independent nonprofit founded in 1982—transforms global energy use to create a clean, prosperous, and secure low-carbon future. It engages businesses, communities, institutions, and entrepreneurs to accelerate the adoption of market-based solutions that cost-effectively shift from fossil fuels to efficiency and renewables. RMI has offices in Basalt and Boulder, Colorado; New York City; Washington, D.C.; and Beijing.

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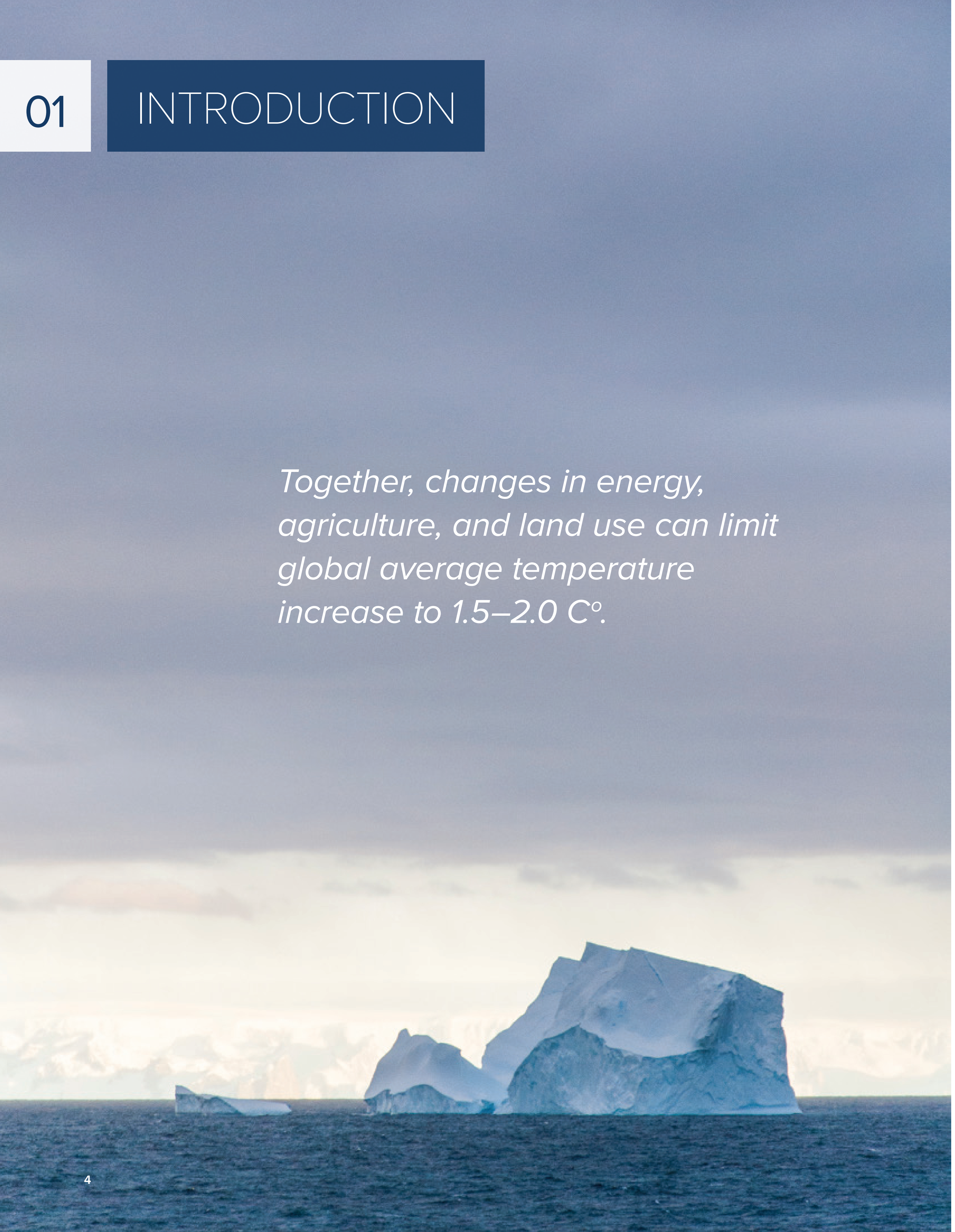

01 INTRODUCTION

Together, changes in energy, agriculture, and land use can limit global average temperature increase to 1.5–2.0 C°.

The news about climate change is increasingly bleak. Already, deep and consequential changes in the earth's systems, including the oceans, forests, and atmosphere, are occurring as a consequence of fossil-fuel emissions. Looking ahead, scientists warn that the window of opportunity is rapidly closing for taking actions that could keep global average temperature increase to less than 2 Celsius degrees (C°) above the preindustrial era.[i] According to the latest UN Emissions Gap Report, even if all signatories met the emissions reductions pledges in the Paris Agreement, the world would still be heading for a temperature rise of 2.9–3.4 C° by the end of this century.[1]

Scientists concur that consequences of global average temperature rise greater than 2 C° are potentially very grave. An analysis in 2016 indicates that even warming of around 2 C° could trigger feedbacks that would cause multi-meter sea level rise within as little as 50–100 years, as well as very significant increases in extreme weather events and dramatic changes in the ocean currents and circulation patterns around which human civilization has evolved.[2] In such a scenario, human societies and the global economy could face forces of disruption so great that dealing with the root causes of climate change would become impossible.[ii]

President Trump's decision to pull the United States out of the Paris Climate Agreement further undermines global efforts to reduce global emissions and meet the climate goals espoused in the agreement.[3] This shift in policy stance not only lends uncertainty to the U.S. greenhouse gas emissions trajectory, but also may jeopardize international governance structures built to address the threat of global climate change.

Today, many experts doubt that energy systems can decarbonize fast enough to prevent this scenario. But this belief is both dangerous and wrong—dangerous because despair undercuts the will to act; and wrong because this view does not take into account events already taking place that indicate a possible pathway to a rapid energy transition.

This paper describes scenarios for transitions in energy, agriculture, and land use that together are sufficient to limit global average temperature increase to 1.5–2 C°. Unlike conventional modeling approaches, these scenarios entail patterns of disruption, innovation, and nonlinear change, harnessed at global scale, that mirror the episodic and disruptive ways that individual industries and the economy as a whole have changed historically. The great transitions in the economy, such as the Industrial Revolution, have been driven by such self-reinforcing patterns of change. Their signs are all around us.

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[i] While most people are familiar with the expression "degrees Celsius" (°C), that expression signifies an absolute temperature that represents the coolness or warmth of something. The expression "Celsius degrees" (C°) refers to an interval between two measured temperatures, which in this paper denotes temperature rise above preindustrial levels.

[ii] James Hansen and colleagues conclude that: "Social disruption and economic consequences of such large sea level rise, and the attendant increases in storms and climate extremes, could be devastating. It is not difficult to imagine that conflicts arising from forced migrations and economic collapse might make the planet ungovernable, threatening the fabric of civilization." See Hansen, "Ice melt, sea level rise and superstorms."

Rather than a long and slow transition constrained by slow capital turnover, our scenarios describe a transition in which the pace of technological improvement gains momentum as it moves forward, that disrupts and revolutionizes today's conventional business models, and that diffuses rapidly throughout the global economy. Under the right conditions, positive feedbacks in the economy drive sustained, exponential improvements in technologies and rapid diffusion of new products and services, just as Moore's Law has driven far-reaching changes in the global economy.[iii]

Transitions of this kind, while they are rare, occur much faster than almost anyone anticipates, accelerated by feedbacks in industrial economics, social behavior, finance, and technology.[4]

The analysis we offer is a rough sketch of a rapid and disruptive energy transition, not a deep and rigorous technical and economic study. However, we believe it is a useful start in an unconventional direction. This study stands on the shoulders of Rocky Mountain Institute's detailed and rigorous national-level analyses—*Reinventing Fire* (U.S.) and *Reinventing Fire: China*—that describe how the transition to a clean energy economy can save trillions of net dollars while simultaneously supporting overall economic growth, slashing carbon emissions, and increasing energy system resilience.

Overall, our analysis demonstrates that limiting temperature increases to well below 2 C° will require more and deeper change in the years ahead than most analysts contemplate, with shifts not only in the energy sector but also in agriculture and land use. These changes are not inevitable, but will require urgent and extraordinary efforts to align policies, overcome finance bottlenecks, and speed market adoption of new solutions. Our assessment indicates that such changes may still be within reach, provided that enough subnational, national, international, and especially private-sector and civil-society actions can be launched and aligned to take full advantage of globally scaled production and deployment of clean energy technologies.

ANALYSIS FRAMEWORK

RMI undertook detailed modeling work to assess the climate implications of alternative pathways for energy demand and supply as well as for agriculture, forestry, and other land use (AFOLU). These pathways produce greenhouse gas and temperature scenarios that differ significantly from a business-as-usual forecast. Although our five scenarios show very different adoption levels for different technologies and somewhat different temperature changes relative to preindustrial temperatures, the important conclusion is that from the most conservative to the most aggressive, all five scenarios get us to the "well below 2 C°" goal. The most aggressive scenario—Scenario 1, which addresses growing fluorinated greenhouse gas (F-gas) emissions as well—limits global temperature change to 1.47 C° by the end of the century. Similar to other recent analysis, each of these scenarios entails global carbon emissions peaking around 2020, and decreasing exponentially thereafter.[5] (For specific scenario comparisons, see Appendix: Scenario Comparison Table.)

Photo courtesy Power Africa

FIGURE 1

GLOBAL AVERAGE TEMPERATURE CHANGE ABOVE THE PREINDUSTRIAL ERA UNDER DIFFERENT SCENARIOS

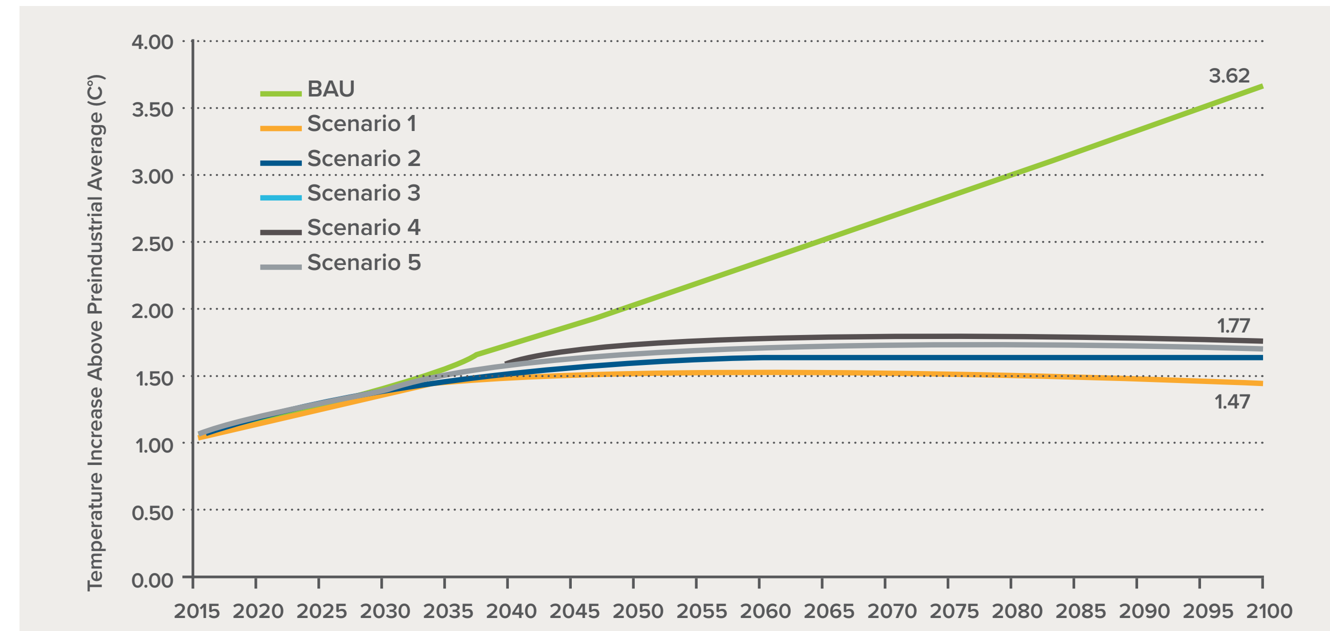
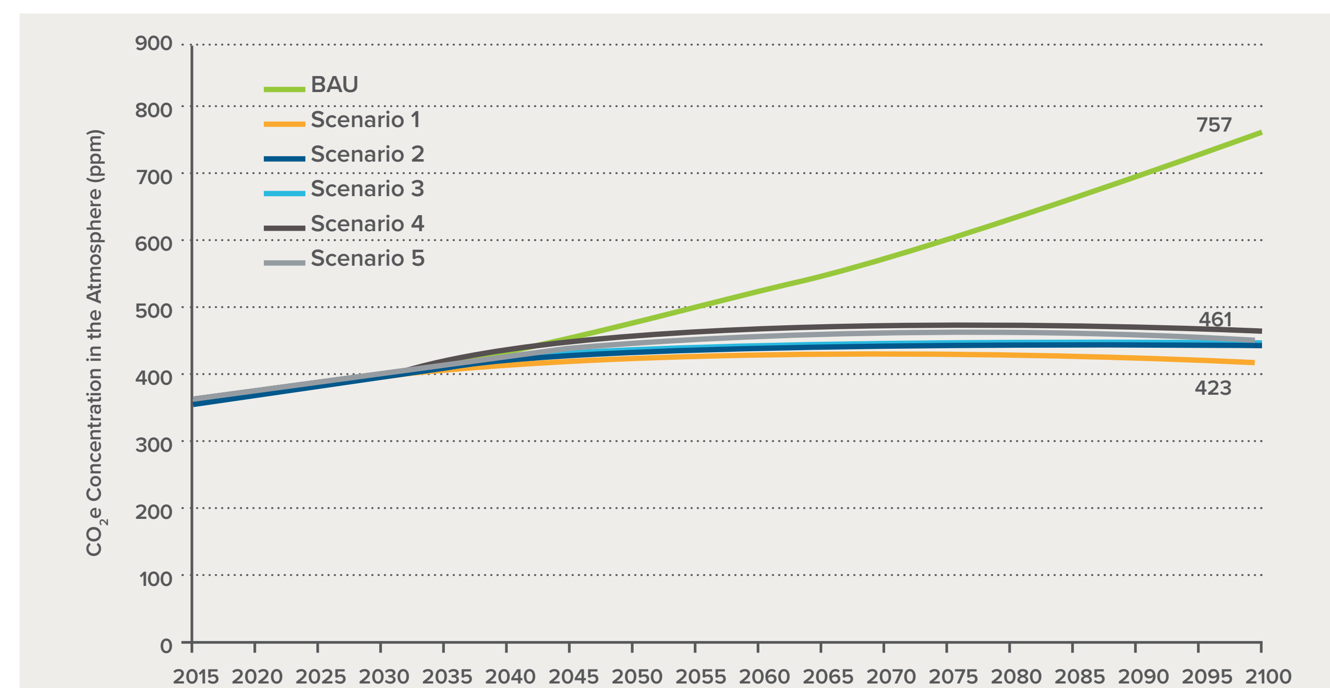


FIGURE 2

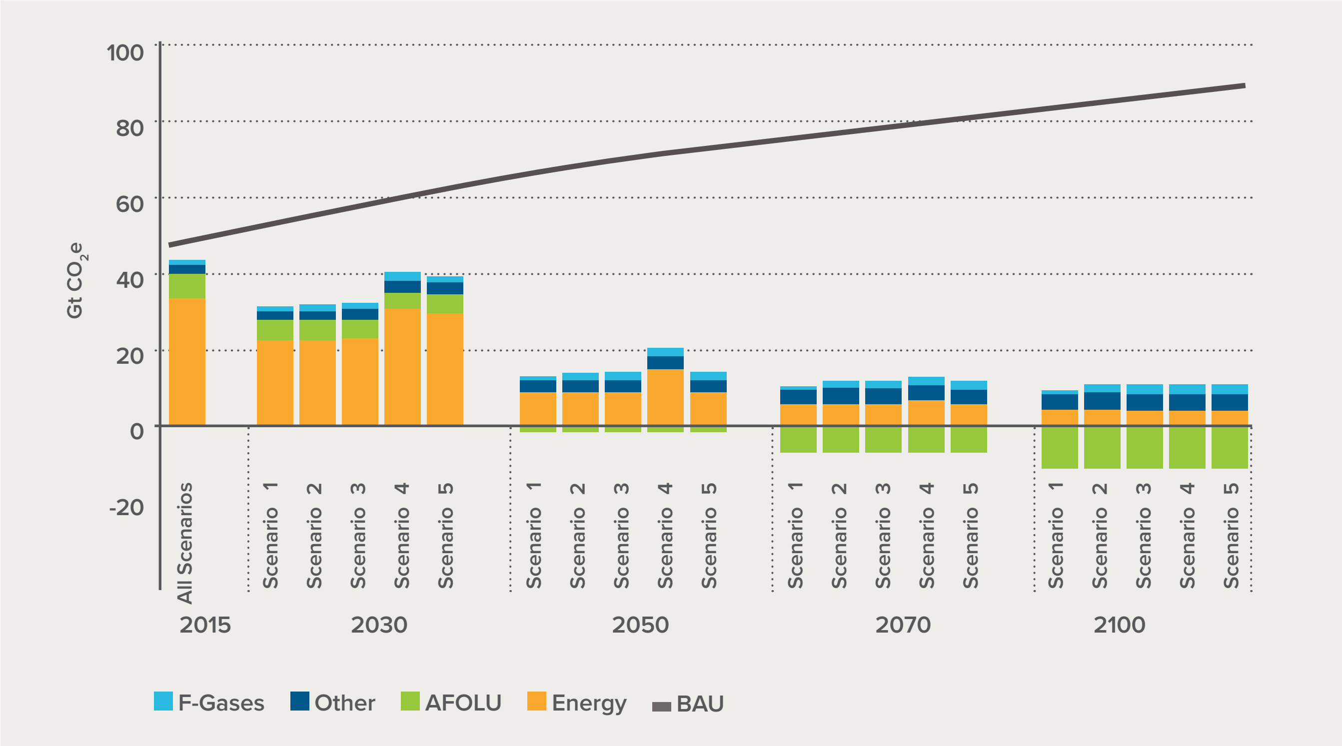
ATMOSPHERIC CO_2e CONCENTRATION UNDER DIFFERENT SCENARIOS



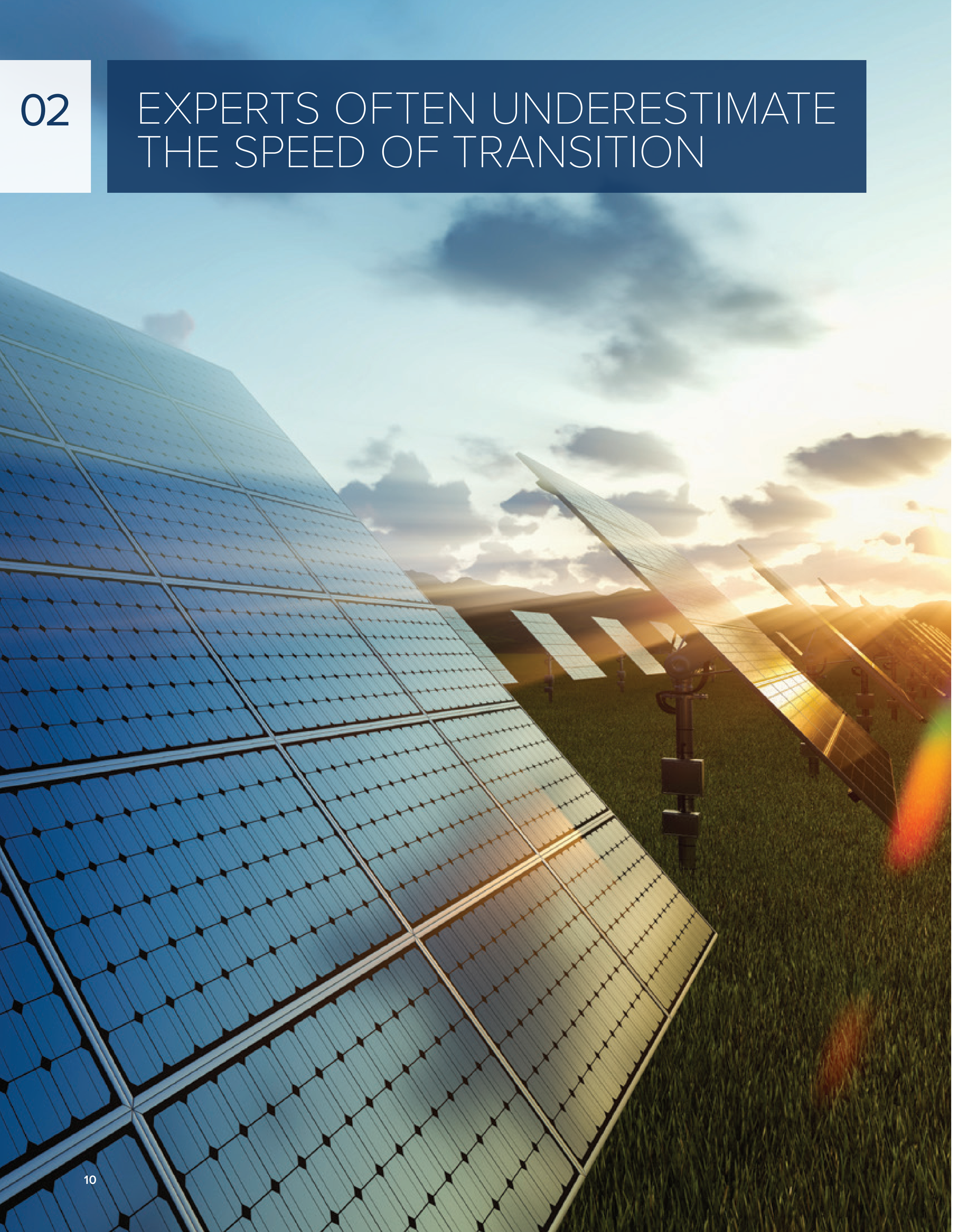
[iii] Moore's Law states that computer power doubles every two years at the same cost.

FIGURE 3

ANNUAL EMISSIONS FROM MODELED SCENARIOS SHOW RAPID DECLINES IN EMISSIONS FROM ALL SECTORS IN THE FIRST HALF OF THE CENTURY, WITH STEEP DECLINES IN ENERGY SECTOR EMISSIONS BY 2050. BEYOND 2050, ENERGY-RELATED EMISSIONS FROM ALL SCENARIOS ARE SIMILAR; GLOBAL ENERGY DEMAND IS REDUCED AND LARGELY ELECTRIFIED. IN THE SECOND HALF OF THE CENTURY, THE AFOLU SECTOR IS A NET SINK FOR CARBON FROM THE ATMOSPHERE.



02 EXPERTS OFTEN UNDERESTIMATE THE SPEED OF TRANSITION

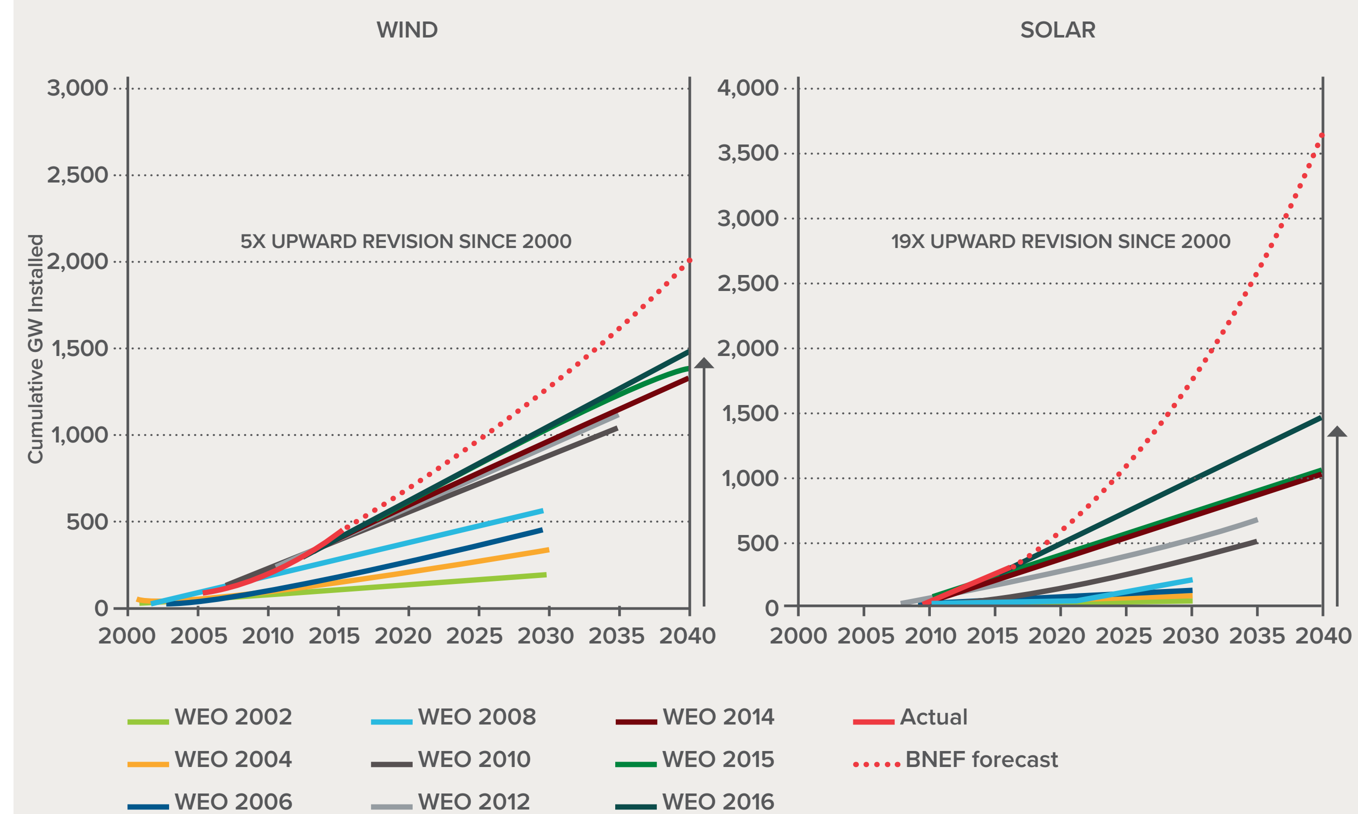


In energy, as well as in many other fields, experts often underestimate the speed of disruptive transitions. In 1980, for example, AT&T commissioned McKinsey & Company to predict U.S. cell phone usage by 2000. The consulting group argued that cellular telephony would be a niche market with about 900,000 subscribers. In fact, McKinsey's estimate was less than 1% of the actual figure: 109 million. Today the planet has more phones than people, and the speed of leapfrog transitions to wireless telephony in emerging markets has been extraordinary.

Similarly, the International Energy Agency (IEA) and many other mainstream analysts, such as the U.S. Energy Information Agency, have consistently underestimated the uptake of solar and wind—raising their forecasts without ever catching up with reality. Their models cannot capture the expanding returns that are obvious when we simply observe that the more renewables we buy, the cheaper they get, so we buy more, so they get cheaper.

FIGURE 4

FORECASTS HAVE CONSISTENTLY UNDERESTIMATED THE UPTAKE OF GLOBAL WIND AND SOLAR



Source: IEA WEO, BNEF (forecast from June 2015); slide inspired by Michael Liebreich's 2016 BNEF Summit keynote

The mainstream view of energy transitions, reflected widely in academic and policy literature and in energy industry analyses, is that major shifts in the energy system require decades. The standard argument is that even when new technologies offer significant performance and cost advantages, the pace of change is constrained by such forces as:

1. The vast scale and complexity of major energy transitions
2. The slow rate of capital turnover
3. The resistance caused by “lock in” or “path dependency” of existing energy systems
4. The active resistance of incumbent actors working to contain or subvert the transition.

Gert Jan Kramer and Martin Haigh, for example, argue in a paper published in *Nature* in 2009 that “physical limits” on the rate at which new energy technologies can be deployed constrain the speed of a major shift in global energy supply.[6] “Unlike with consumer goods,” they assert, “there are robust empirical ‘laws’ that limit the build rate of new and existing energy technologies and thereby the potential to deliver much of the hoped for transition [to renewables] by 2050.”

Based on historical data for oil, nuclear, natural gas, biofuels, solar, and wind, Kramer and Haigh observe that new energy technologies typically go through several decades of exponential growth before they are widely available. After reaching “materiality,” defined as delivering about 1% of the world’s energy mix, the growth rates for these technologies become linear until the technology captures its final market share. Accordingly, the authors bleakly conclude that “the best we could reasonably hope to achieve for new energy deployment” would be a scenario in which two-thirds of world energy supply still comes from fossil fuels in 2050.[7]

The facts on the ground, however, are already contradicting these forecasts. The growth in global renewable energy supply has already crossed the supposed 1% threshold and is continuing to grow at exponential rates with steeply falling costs. Modern renewables (excluding hydropower) contribute nearly 7.9% to the global electricity mix and roughly 2.4% of global final energy consumption.[8]

Increasingly, renewable energy is emerging as the mainstay of many countries’ energy supply. Currently, renewable energy contributes roughly 32% of total inland electricity consumption in Germany, up from 16% in 2010.[9] For Austria, Denmark, and Spain, renewable energy share in electricity generation is at 70%, 51%, and 37% respectively. Windpower in Iowa has grown to 36% of that state’s electricity needs and is expected to grow even further in the coming years.[10]

In 2016, investments in renewable energy in the developed and the developing world were quite comparable. China led this trend with total investments of US$78.3 billion in 2016, which accounted for nearly 32% of the global total—an investment larger than that of any other country.[11] In the first half of 2017, China installed more than 24 gigawatts of solar PV, adding more than 13 gigawatts in the month of June alone. India’s solar capacity has quadrupled in the past three years and is expected to double in 2017.[12] India has redoubled its commitment to combat global climate change, improve energy security, and reduce local air pollution. It has also announced a transition to a highly electrified passenger mobility system that is estimated to save nearly 900 million tonnes of petrol and diesel and 1 gigatonne of CO_2 between 2017 and 2030.[13] Yet the argument that renewables will inevitably be constrained to linear growth still persists.

One reason that experts tend to underestimate the possible speed of an energy transition is that they rely on the history of previous major energy transitions at national and global scales during the 19th and 20th centuries, such as the shifts from wood to coal and coal to oil as dominant sources of primary energy supply. Historically, the energy system has been based on large, centralized capital assets; complex centralized infrastructure and networks; and very long deployment and payback timeframes with large and slow-moving incumbents. Even there, evidence to the contrary exists, like the speed of market penetration of internal combustion engine automobiles in the U.S. at the beginning of the 20th century, or the rollout of natural gas in the Netherlands or London in the 1960s.

Importantly, the emerging future now looks different and is not centralized, large, and slow moving; it is decentralized, distributed, and rapidly changing, with small incremental capital assets, shorter deployment and payback periods, and competitors with fast-scaling new business models. Those who forecast the failure of efforts to arrest climate change tend to ignore four key factors:

1. The exponential improvement of core technologies
2. S-curves in market diffusion of disruptive technologies
3. Cascading systemic effects from converging changes across technologies
4. Leapfrog opportunity represented by new energy infrastructure still to be installed in developing countries.

1. EXPONENTIAL IMPROVEMENT OF CORE TECHNOLOGIES

Over the past five decades, Moore's Law has described the sustained exponential improvement in the performance of microprocessor chips, whose processing power (roughly measured by the number of transistors on a chip) has doubled every two years or so with a cumulative gain of roughly a billionfold since they were first introduced in the early 1970s. Is the kind of exponential technological progress demonstrated by the semiconductor industry a rare exception? Or is it something that we can learn from more generally as we think about the future of the energy sector and the economy more widely?

To answer this question empirically, researchers at the Santa Fe Institute built a dataset of 62 different technologies to test hypotheses about how cost and performance of technologies improve over time and in relation to cumulative production volumes. The conclusion: all the technologies studied—from information technologies to airplanes to beer production to gas pipelines—exhibited sustained exponential improvement, albeit at varying rates.[14]

In fact, the Santa Fe Institute's study found that the Moore's Law relationship for microprocessors, doubling performance every two years, was better described as a relationship between performance and the *cumulative production* of microprocessors (Wright's Law). If production increases exponentially, Moore's Law and Wright's Law are indistinguishable. But Wright's Law, first proposed in 1936, is the most successful general formulation describing technological progress, and is the standard description used in experience-curve analysis that Boston Consulting Group and others have applied to hundreds of technologies. For our purposes, the key conclusion from the Santa Fe Institute's research is that "technological progress is forecastable."[15]

The core technologies at the heart of the current energy transition—solar PV, wind turbines, batteries, and electric vehicles—all have demonstrated the potential for sustained exponential growth in capacity and energy production in the years ahead, especially in the context of a coordinated global transition to clean energy. These products can be produced at vast scale for deployment and integration into energy systems around the world, especially in such rapidly growing and ambitious societies as India and China. While we cannot predict the specifics of the technology advances that might lie ahead for these technologies, we can look for basic preconditions that have underpinned the sustained progress in microchip manufacturing to see how these conditions might be replicated.

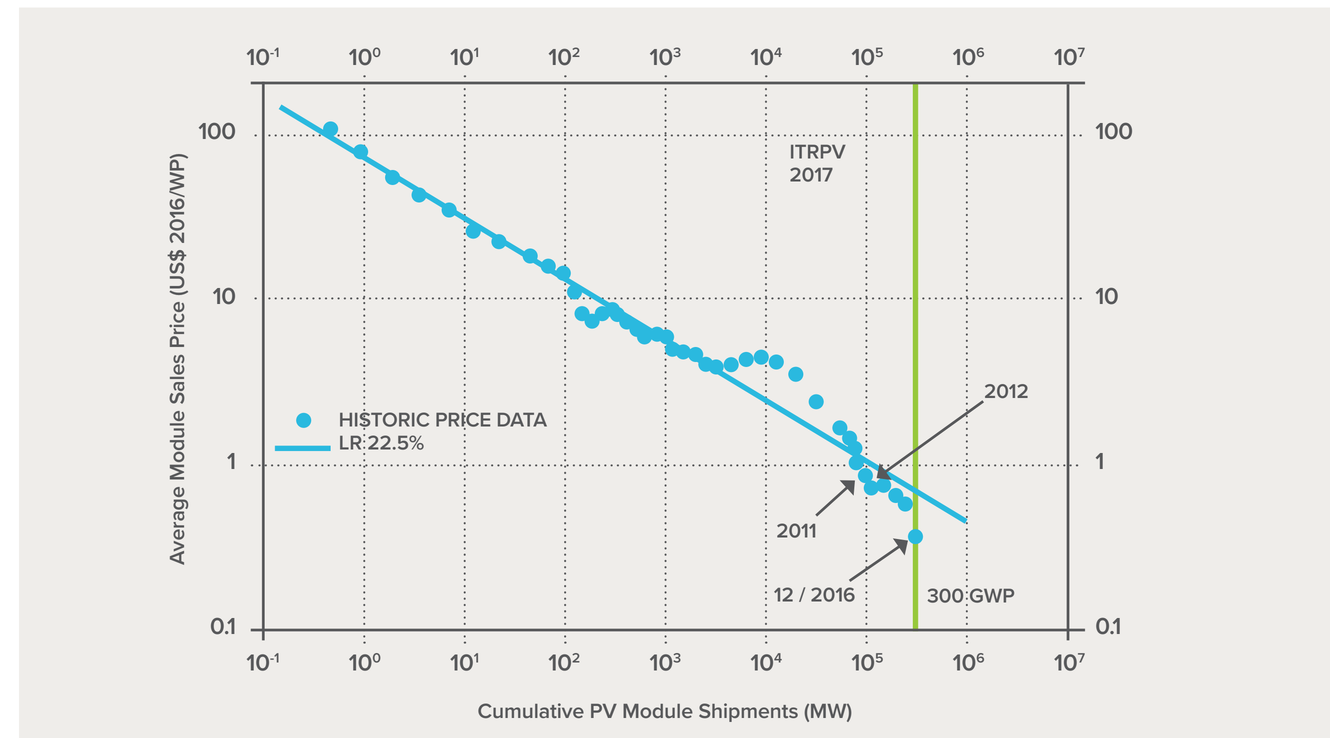
VERY LARGE MARKET POTENTIAL. The remarkable history of Moore's Law is not just a story of technological progress over time, but also one that describes the advance of technology *in conjunction with exponentially increasing production volumes.* Globally, production of semiconductor units has increased more than 26-fold from 1978 until today, with 2017 volumes exceeding one trillion units.[16] The steady increase in demand for microprocessor chips is an aspect of the story that gets less attention, but it is this increase that has enabled the huge investments in research and development that have sustained the progress of chip manufacturers. The self-reinforcing cycle is one that has allowed manufacturers to invest massively in chip fabrication plants while still dropping prices, spurring further increases in demand.[17]

Where increasing production volumes drive lower cost, a so-called "learning rate" describes how fast costs are falling. This is typically measured as the average percentage decline in costs that occurs for every doubling of cumulative production. As Figure 5 illustrates, this trend, true for semiconductors, is also obvious for the critical renewables technologies.[18]

Solar PV module costs have come down by roughly 22.5% every time the cumulative production doubles.[iv] For wind power, this number is between 10.5% and 18.6%,[19] and for Li-ion batteries, the learning rate is emerging to be between 14% and 22%.[20]

FIGURE 5

SOLAR PRICES AS A FUNCTION OF CUMULATIVE PV SHIPMENTS



[iv] Other estimates by Bloomberg New Energy Finance (BNEF) indicate that the learning rate for solar PV modules is closer to 26.5%. According to BNEF, global average PV module prices at the end of 2016 were around $0.41/W compared with $3.88/W in 2008. See Zindler, "Sustainable Energy In America: Factbook 2017."

COORDINATED INDUSTRY ACTION TO SUPPORT SCALING OF PRODUCTION. By the early 1990s, sustaining the high-tech industry's progress required a high degree of coordination among an increasingly complex network of materials suppliers and equipment makers. To address these challenges, U.S. manufacturers launched a technology road-mapping process in 1991, engaging hundreds of engineers from different companies to develop plans that could meet the industry's needs. In 1998, this process evolved further into the International Technology Roadmap for Semiconductors, bringing together the efforts of hundreds of companies globally.[21]

Along the same lines, the U.S. Department of Energy's SunShot Initiative aims to help the solar industry achieve similar progress through cooperative and coordinated action. Launched in 2011, this initiative set a goal to bring solar energy costs to parity with traditional sources of power generation by 2020. But SunShot exceeded its own targets by achieving 90% progress toward its 2020 utility-scale goals by November 2016. Buoyed by this success, SunShot has set even more ambitious goals, targeting roughly 50% further cost reduction between 2020 and 2030.

For batteries and electric vehicle technologies, while systematic industry coordination has not yet emerged, Tesla's 2014 decision to share intellectual property with other companies explicitly derived from similar types of considerations to those that inspired chip manufacturers to collaborate: the rewards from making the market grow faster exceed those from tightly protecting intellectual property. Tesla's open-patent announcement stated: "We believe that Tesla, other companies making electric cars, and the world would all benefit from a common, rapidly-evolving technology platform."[22]

The degree of coordination that might emerge among manufacturers in the key sectors focused on in our analysis is still unknown, but there are signals that recognition of the size of the prize will strengthen coordination and scaling in these industries. In India, manufacturers of electric vehicles, including automobiles and two- and three-wheelers, are taking steps to coordinate scaled production of common components to speed the scaling up of the industry there (including smart, swappable, modular batteries), with the ambition of achieving a fully electric passenger mobility sector as early as 2030.[23]

Battery production, a key part of the transition to a clean energy system, is showing all the signs of a Moore's Law-like self-reinforcing pattern of rapid scaling and cost decline. Already in 2017, plans for 10 new battery gigafactories have been announced, and Tesla is expected to announce another four gigafactories of its own soon.[24] Overall, global battery-making capacity is projected to more than double by 2021, while average costs are projected to fall precipitously from $273 per kilowatt-hour in 2016 to below $100 by 2030.[25]

DIVERSE AND DEEP SCIENCE AND TECHNOLOGY OPPORTUNITIES. Chipmakers have been able to discover and exploit diverse opportunities to improve performance through advances in product engineering, materials science, and manufacturing technology. On the applications side, an important new class of chip-based machines, from mainframe computers to laptops to smartphones, has emerged about once per decade.

From a technology perspective, experts see abundant opportunities for further advances in the performance of core clean energy technologies. For solar PV, for example, advances in materials science promise significant further improvements in module efficiency. And taking into consideration opportunities that have already been discovered but not yet deployed, new approaches to manufacturing and severalfold streamlining of the even larger, non-module systems costs can be expected to produce additional and larger cost reductions.

Top photo courtesy Tesla

2. S-CURVES IN MARKET DIFFUSION OF DISRUPTIVE TECHNOLOGIES

The core technologies that provide the backbone for the energy transition each share or potentially share the attributes described above.

Solar PV manufacturing volumes could potentially sustain rapid exponential growth for decades as a result of the same self-reinforcing production-scaling dynamic that drove Moore's Law. In our most aggressive scenario, for example, annual solar PV installations increase from 73 GW in 2015 to 1,500 GW by 2059. This figure may seem astonishing, but in the context of a fundamental transition in the economy akin to the Industrial Revolution, it is not unreasonable to expect that it could be achieved. In 2007, IEA analysts predicted that by 2020, cumulative global PV capacity would be about 200 GW.[26] But, with exponential growth, PV capacity exceeded that 2020 forecast by 2015, when it had already reached about 227 GW.[27]

A recent paper published in the journal *Science* by a group of leading experts shows the potential for future price reduction for solar PV based on extrapolating historical learning curves.[28] Superimposing this learning curve with expected cumulative PV installations in our most aggressive scenario (Scenario 1) suggests that solar module prices could breach the $0.25/W barrier by 2030. Bottom-up techno-economic analysis and technological road maps from major manufacturers confirm that this price target and volume growth is feasible. First Solar, for example, expects to achieve $0.25/W module production cost as early as 2020.[29] Solar tariffs in India in May 2017 also point to a faster-than-estimated price decline, with recent auctions clearing at 3.79 US¢/kWh, 25% below the auction price three months earlier.[30]

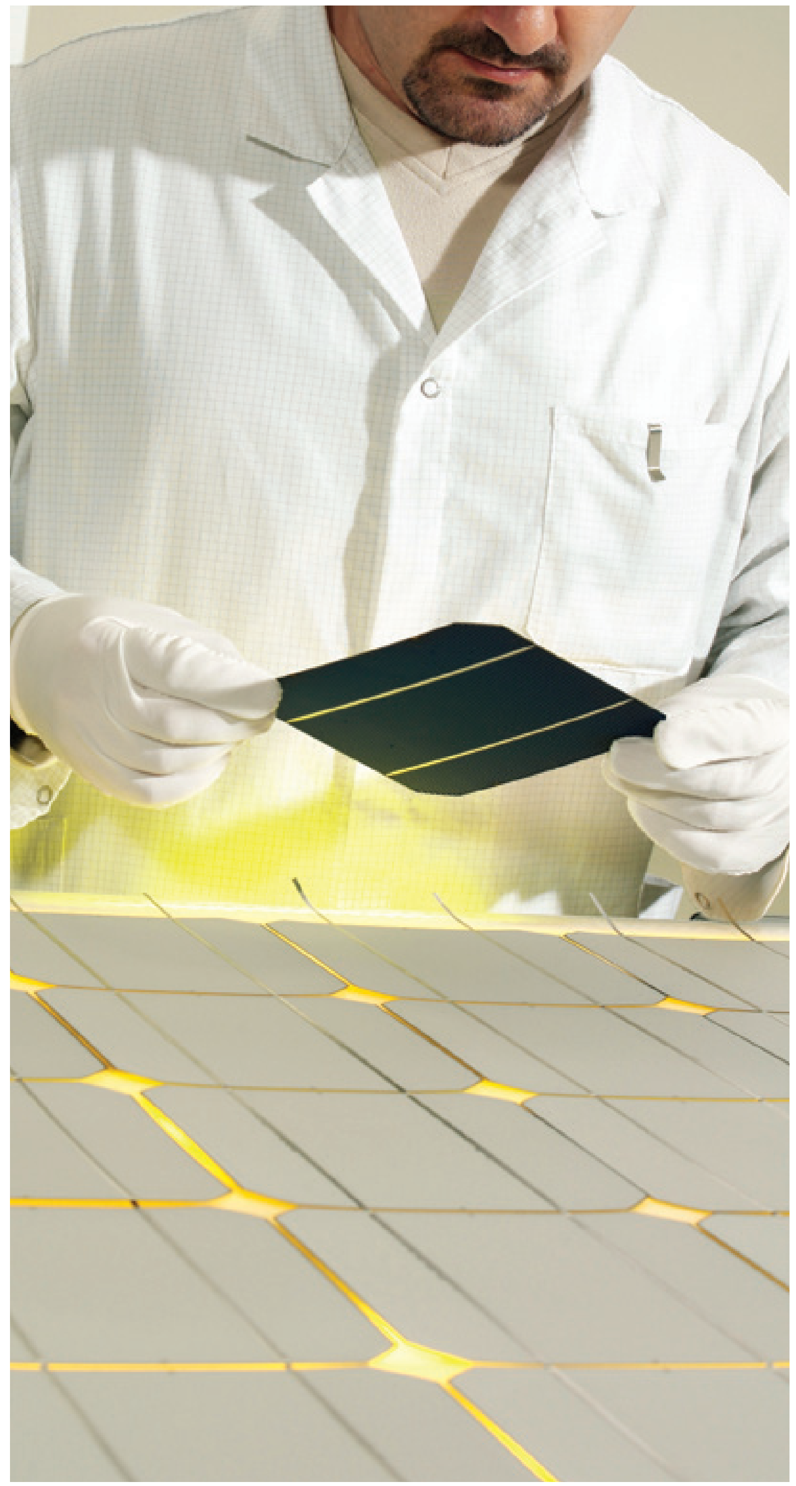


FIGURE 6

PROJECTED GROWTH IN CUMULATIVE PV CAPACITY IN THE MOST AGGRESSIVE SCENARIO (SCENARIO 1) FOLLOWS AN S-CURVE TRAJECTORY, WITH SLOW GROWTH IN INITIAL YEARS UNTIL THE MARKET HITS AN INFLECTION POINT LEADING TO EXPONENTIAL GROWTH IN THE LONGER TERM. GROWTH SLOWS DOWN AGAIN AS PENETRATION EVENTUALLY SATURATES ACCESSIBLE MARKETS.

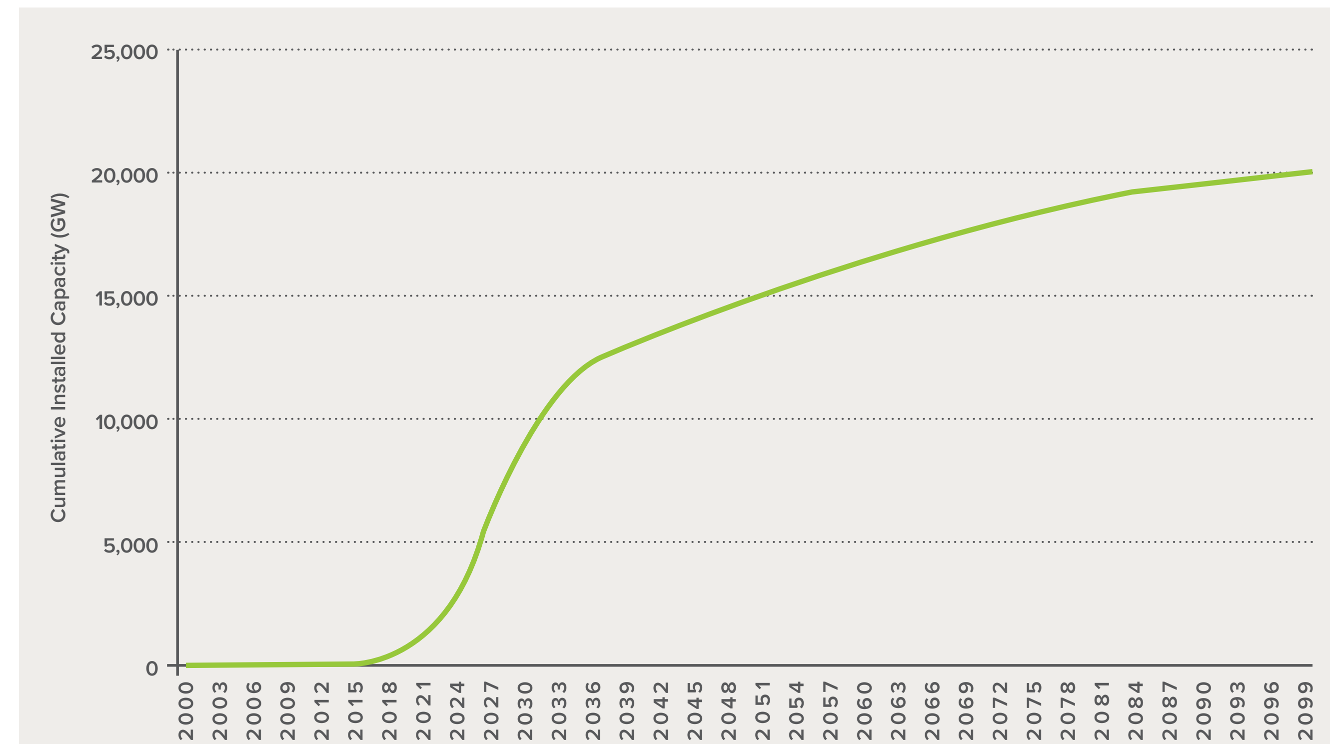
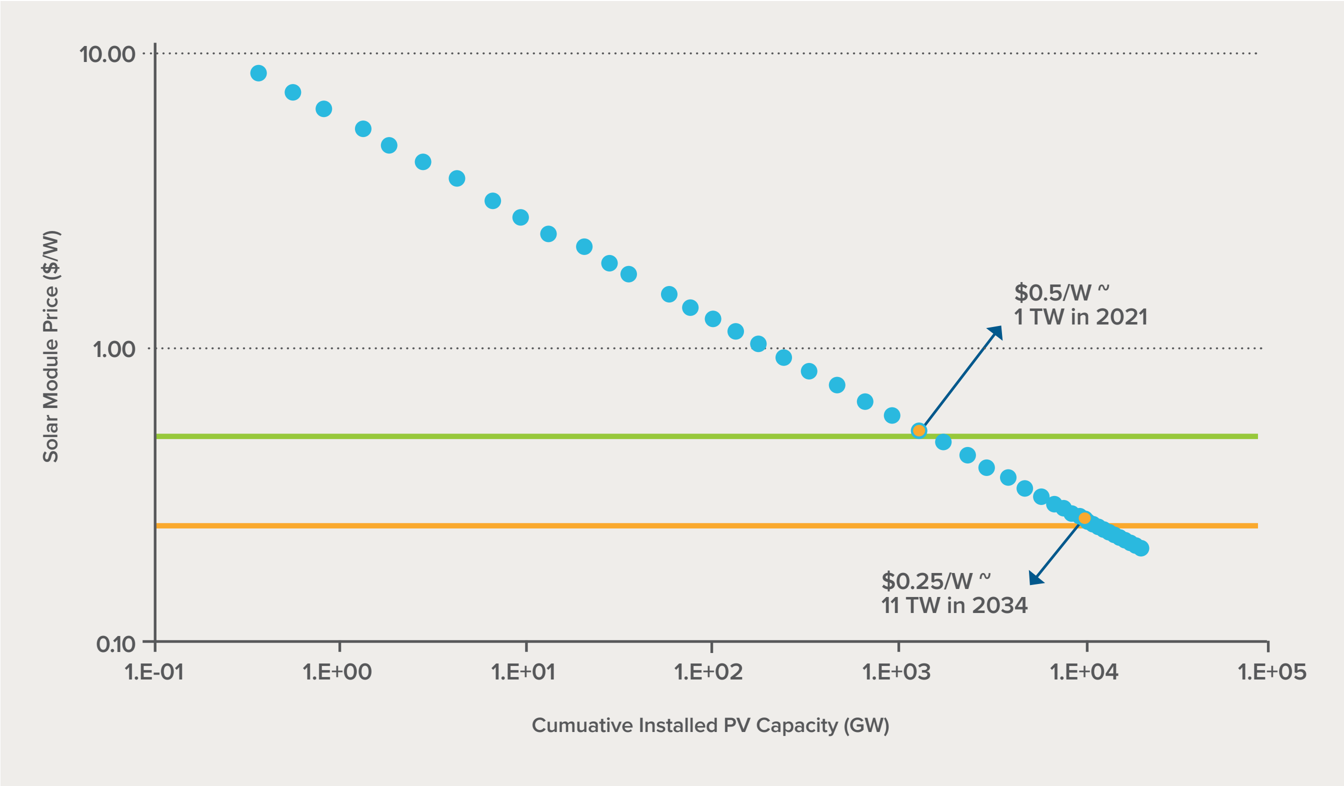


FIGURE 7

CUMULATIVE INSTALLED PV CAPACITY AND ESTIMATED MODULE PRICE FOR THE MOST AGGRESSIVE SCENARIO (SCENARIO 1)



Thierry Lepercq, head of research, technology, and innovation at the French company Engie SA, projects that the unsubsidized cost of solar electricity in the sunniest climates will fall from today's less-than 3¢/kWh to 1¢/kWh by 2025. Lepercq believes that "solar, battery storage, electrical and hydrogen vehicles, and connected devices are in a 'J' curve of upward growth potential."[31] He adds, "The promise of quasi-infinite and free energy is here."

3. CASCADING SYSTEMIC EFFECTS FROM CONVERGING CHANGES ACROSS TECHNOLOGIES

In the case of climate change, new technologies, such as S-curved growth in the deployment of solar PV, aren't the only factors that could profoundly change the energy system. The convergence of renewable energy, a revolution in mobility, and a transition to smart and efficient energy demand also has the power to transform. For example, the falling cost of batteries simultaneously encourages faster electric vehicle deployment, increases renewable energy penetration on the grid, and allows greater flexibility in energy use. In turn, more electric vehicles mean cheaper batteries, implying distributed solar everywhere; faster coal and nuclear power displacement; and a distressed natural-gas industry. Improvements in the cost and performance of the information technologies in electric vehicles also contribute to better functioning and faster deployment.

Advances in information technology, payment systems, and new business models will speed the transition to an all-electric, highly transactive energy system. Blockchain technology, with its potential to enable peer-to-peer transactions, could serve to integrate distributed energy and storage devices at high saturation levels based on unsubsidized market-based transactions.[32]

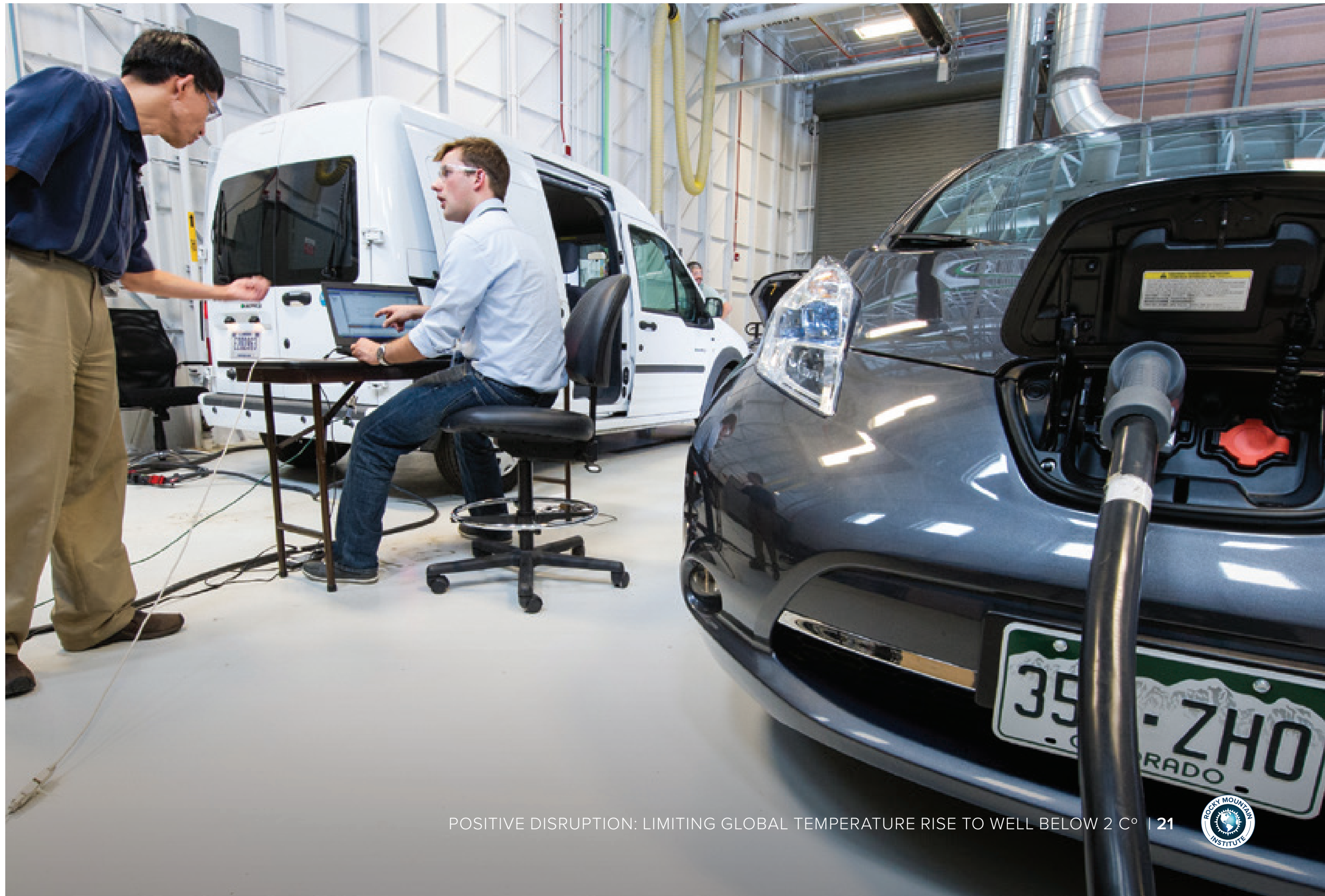
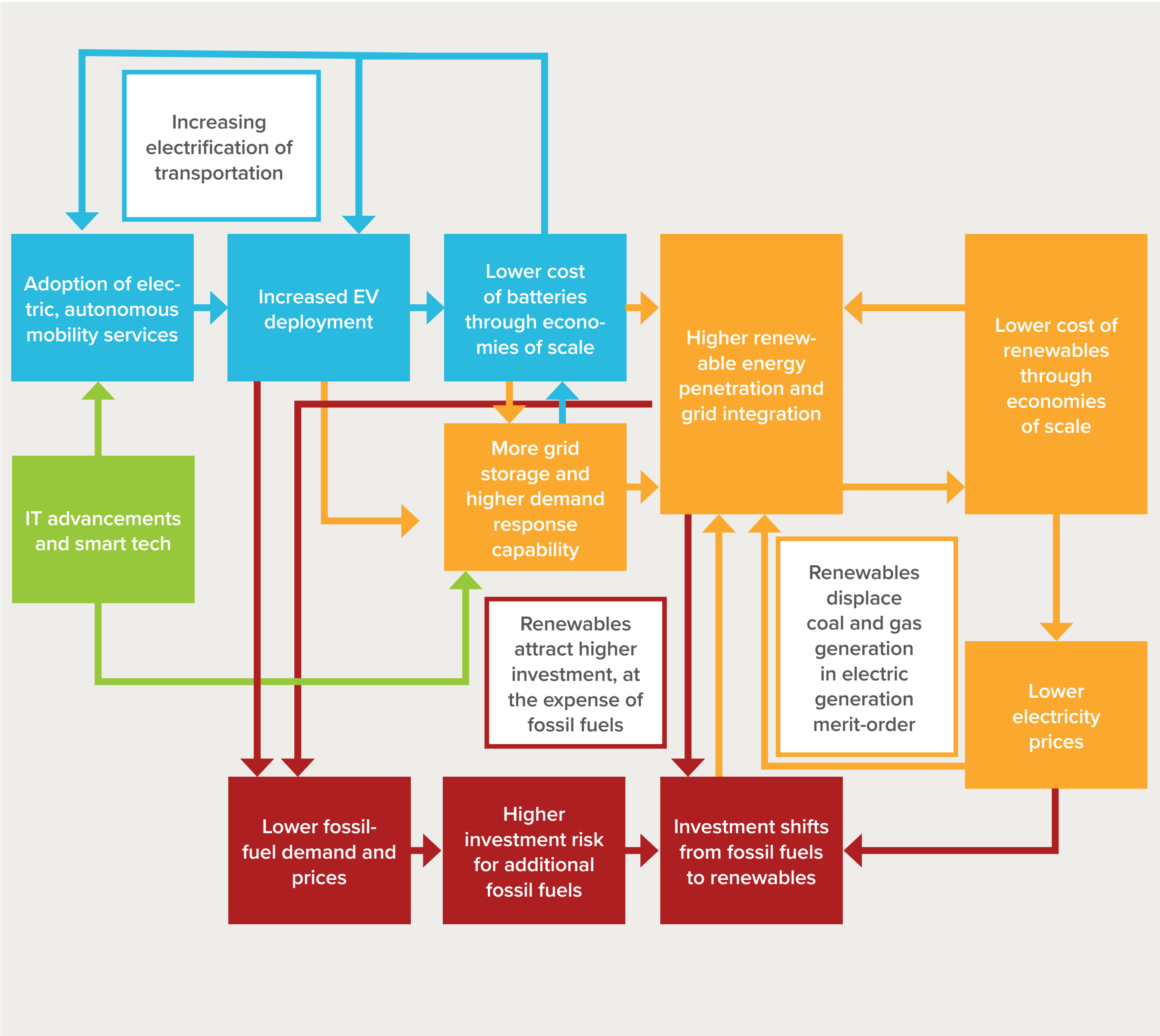


Photo courtesy U.S. Department of Energy

FIGURE 8

REINFORCING FEEDBACK LOOPS IN TECHNOLOGY AND DEPLOYMENT SUPPORT A RAPID ENERGY TRANSITION. THIS FIGURE ILLUSTRATES SOME OF THE MOST IMPORTANT OF THESE FEEDBACKS.



4. LEAPFROG OPPORTUNITY REPRESENTED BY NEW INFRASTRUCTURE STILL TO BE INSTALLED IN DEVELOPING COUNTRIES

Even with significantly higher energy productivity, the economic growth in emerging and developing markets will drive energy demand growth well above the demand in developed economies. This growth presents not only the challenge to ensure affordable access to energy for all, but also the opportunity to create the sustainable energy infrastructure of the future. With far less lock-in of existing capital assets, emerging economies can build their energy systems on the basis of more cost-effective and clean technologies.

An example in point is India, where even in the run up to the Paris climate discussions, much of the government's emphasis was on expanding coal infrastructure and power generation. But now that renewables, particularly solar PV, have become the lowest-cost options for electricity in the country, investments and new capacity additions are rapidly shifting in that direction. In 2016–17, India added 11.2 GW of renewable capacity—at par with thermal capacity addition[33]—and in 2016 for the first time, IEA found that electricity assets worldwide had won more investment than all fossil-fuel supplies did. Similarly, work by the Energy Transitions Commission has shown that energy consumption for new buildings can be reduced by two to six times, dramatically reducing the forecast for increased energy demand.[34]

In mobility, India recently released a blueprint for transformative change that would leapfrog the traditional development pathways in favor of shared, electric, and connected mobility services. This vision, developed with support from RMI, describes a fast-track transition to a cleaner, energy-secure, and more cost-effective future transportation system.[35]

Photo courtesy Joerg Boethling

03 FROM BUSINESS AS USUAL TO THE TRANSFORMATION OF THE ECONOMY

A business-as-usual emissions scenario leads to a steady increase in global average temperatures relative to preindustrial averages, with temperature increases of approximately 3.7 C° by 2100. In this scenario, the 1.5 C° threshold is breached in 2033 and 2 C° in 2049.

To describe an alternative pathway, we focus on a few key vectors with the potential to drive major shifts in energy demand and supply. These vectors were chosen based on market analyses, expert interviews, and technical potential to reduce emissions. In our alternative scenarios, efficiency measures reduce energy demand by approximately 60% and virtually all remaining energy demand is electrified. On the supply side, a rapid uptake in renewables provides clean energy supplies to meet remaining demand.

DEMAND: DIVERSE TECHNOLOGIES REDUCE AND ELECTRIFY ENERGY DEMAND

Efficiency technologies, combined with electrification of energy demand, offer the greatest potential for transforming the energy economy. This transformation relies on changes in four core areas: buildings, industry, transportation, and electrification of transportation and heating/cooling demand.[v] In general, the energy economy will move from a system based on large, centralized infrastructure to one based on efficient, data-driven distributed systems.

Buildings. In the buildings sector (both residential and commercial), technological improvements include end-use efficiency improvements, fuel switching, smart controls, and integrative design.[36]

Industry. The transformation in industry would come about through the implementation of energy efficiency and waste heat technologies.

Transportation systems design. The transportation sector would be transformed through end-use efficiency caused by demand reduction and vehicular design changes. Better urban planning and route optimization would reduce total driving needs while advanced materials would produce lighter vehicles needing smaller engines.

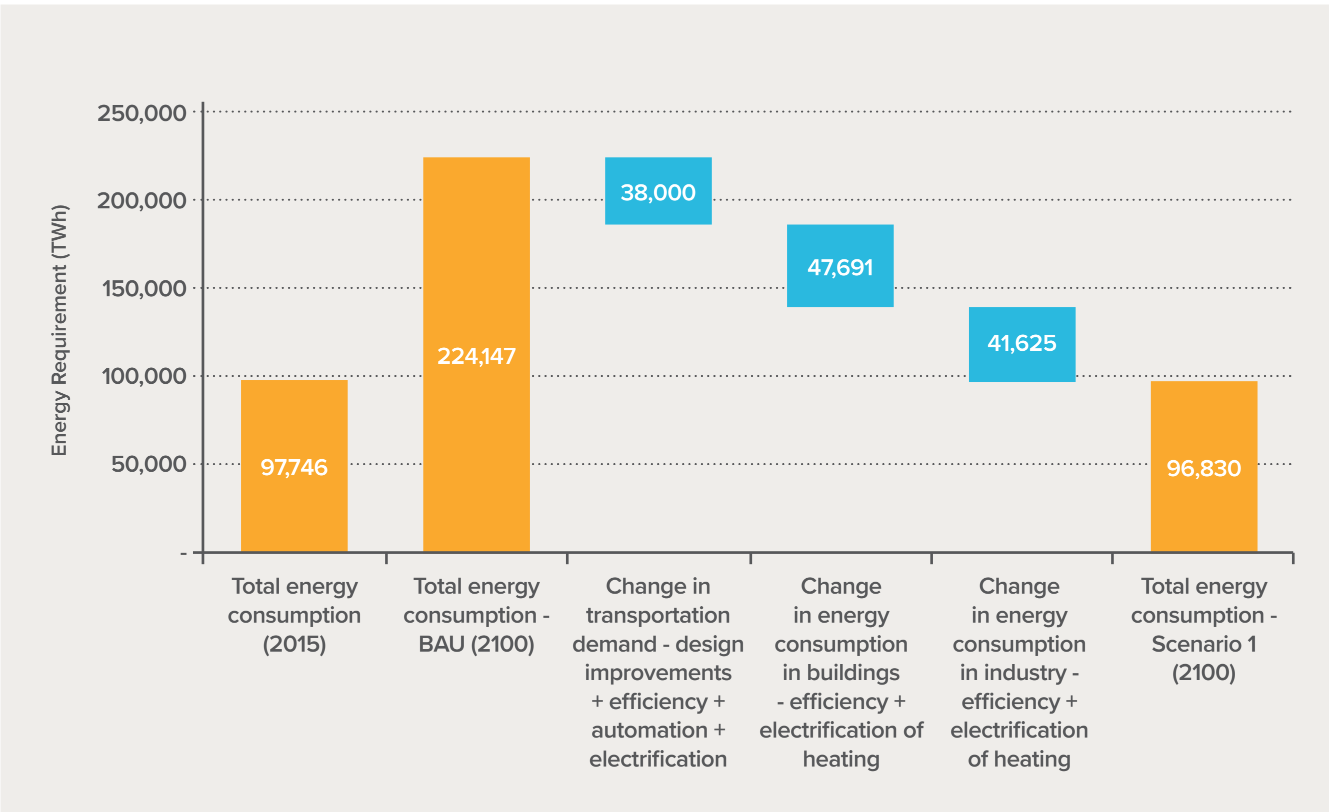
Electrification. Heat pumps and electric vehicles drive the transition to a more electrified energy system, with increased electricity demand being met by renewable energy sources.

When combined, new demand-side technologies and better use practices result in a 56% decrease in total energy required in 2100 compared with business as usual. Figure 9 summarizes the contribution of various sectors in reducing the business-as-usual energy demand in our most aggressive scenario.

[v] The measures are an aggregate of numerous design improvements and use practices derived from *Reinventing Fire* and *Reinventing Fire: China.*

FIGURE 9

CHANGE IN ENERGY CONSUMPTION RELATIVE TO BUSINESS AS USUAL, 2015–2100



SUPPLY: MARKET DIFFUSION DYNAMICS CONTINUE THE RAPID UPTAKE OF RENEWABLES

International public policy is promoting the adoption of renewable energy, while the private sector continues to drive innovation in the energy sector. Both solar and wind have exhibited exponential growth in the past decade. In 2016, for example, renewables met more than half of global growth in electricity demand,[37] and in that year alone, prices fell 37% for the lowest Mexican solar-power bids and 43% for Europe's best offshore wind bids.

About 26% of the world's 2016 generation came from renewables (including hydro). Reinforcing these market trends, renewable costs will continue to decline. By 2040, global utility-scale solar levelized cost of electricity (LCOE) is projected to drop by 66% and onshore wind LCOE by 47%, with estimates placing new solar and wind as cheaper than existing coal and gas generators well before 2030.[38]

Building on such trends, in the most aggressive scenario, solar and wind could constitute over 90% of the world's electricity supply portfolio by 2040, with other renewables and nuclear energy contributing to the remainder.

AGRICULTURE, FORESTRY, AND OTHER LAND-USE TRANSFORMATION

A rapid transition in energy production and demand alone is unlikely to keep warming well below 2 C°. The world will also need to address the balance of greenhouse gas emissions and sequestration associated with agriculture, forestry, and other land use (AFOLU).

Today we recognize a limit to traditional approaches to agricultural intensification at the expense of soil systems and an increasing demand for food as global populations continue to rise. To meet these demands, new forms of land management will be required that will decrease emissions related to land use, increase natural carbon sequestration, and improve ecosystem health. Such practices include, for example, increasing forest cover and avoiding conversion of forests to other land uses, integrating trees into farming, farming without disturbing the soil through tillage, adopting permaculture principles, managing wetlands, and using rotational grazing techniques that amplify soil carbon sequestration. A number of studies indicate bioenergy paired with carbon capture and storage (BECCS) could provide a scalable opportunity for "negative emissions" energy, though the net carbon effects depend on the source of biomass and sustainable land management.[39] Additionally, biomass pyrolysis, the heating of biomass in the absence of oxygen, can generate energy (offsetting fossil-fuel use) from agricultural or forestry residues (no competition with food-producing crops), sequester carbon,[vi] and improve soil health when the byproduct, biochar, is applied to soils.[40] The 2016 United States Mid-Century Strategy for Deep Carbonization found that U.S. ecosystems could sequester 30% to 50% of remaining economy-wide GHG emissions by 2050, under a scenario in which economy-wide emissions are reduced by 80% or more.[41]

Because there is a scarcity of potential data on carbon sequestration at the proper scale for our analysis, we interviewed experts and conducted our own research in order to identify four major mitigation vectors. We found that these vectors alone could mitigate almost 8.5 gigatonnes of CO_2 equivalents (CO_2e) per year by 2050 and almost 16 gigatonnes of CO_2e per year by 2100. At this rate, by the mid-2040s, the agriculture, forestry, and land-use sector would be a net-neutral contributor to CO_2e emissions because it would be sequestering enough atmospheric carbon to offset all of its emissions. Beyond 2046, this sector could be a net sink of atmospheric carbon emissions.

[vi] This process produces biochar, a form of carbon that decays at a slower rate than the natural decay of the initial fuel source, thereby sequestering carbon. The total life-cycle carbon emissions or sequestration from biochar depends on the source of the biomass, potential alternative uses of the biomass, and soil management following biochar application.

VECTOR	EMISSIONS MITIGATED (Gt CO_2e/y)[vii]		
	2030	2050	2100
Reduced consumption of beef (reduced methane from livestock and avoided conversion of forest to pasture)[viii]	0.4	0.7	1.5
Conservation agriculture, grazing management, and land restoration that provide a sink for carbon emissions	0.3	1.1	3.6
Biomass pyrolysis that increases carbon retention in soil and replaces fossil fuels for heat and power generation	1.5	4.2	4.8
Land conversion to forest (underutilized pasture and agricultural land is converted to forest) that provides a natural sink for carbon emissions	1.2	2.5	5.9
TOTAL	**3.4**	**8.5**	**15.8**

These numbers reflect a set of stylized scenarios and should be interpreted in the context of substantial future uncertainty around population growth, dietary preferences and trends, diverse soils and ecological zones types paired with variable land management strategies, the business-as-usual case, and other factors. Global projections for potential AFOLU mitigation range from 12.5 Gt CO_2e by 2030 as forecasted by McKinsey & Company, and up to 87 Gt CO_2e by 2050 as IPCC predicts.[42] Paustian et al. estimates enhanced soil management practices could sequester 8 Gt CO_2e/year globally.[43] These estimates reflect maximum technical and/or economic potential, and likely mitigation activity could be much lower.

Ambitious policy frameworks will be key to incentivize land management strategies that have positive carbon impacts. Although the energy sector has the potential to exhibit virtuous cycles of technology deployment and cost reduction, this dynamic could be suppressed in the land-use sector without a substantial change in market forces and consumption patterns influencing land management. Carbon-based incentives can support the large amounts of capital that will be needed for conservation easements, organic certification program and carbon protocol implementation, and the purchase and installation of advanced field equipment, precision agriculture software, and sensors. Preservation of high-carbon landscapes like natural grasslands, old-growth forests, and wetlands will be critical to avoiding carbon loss.

The good news is that signs indicate this transition is already starting to take shape. Reforestation is gaining ground, and global deforestation rates are slowing.

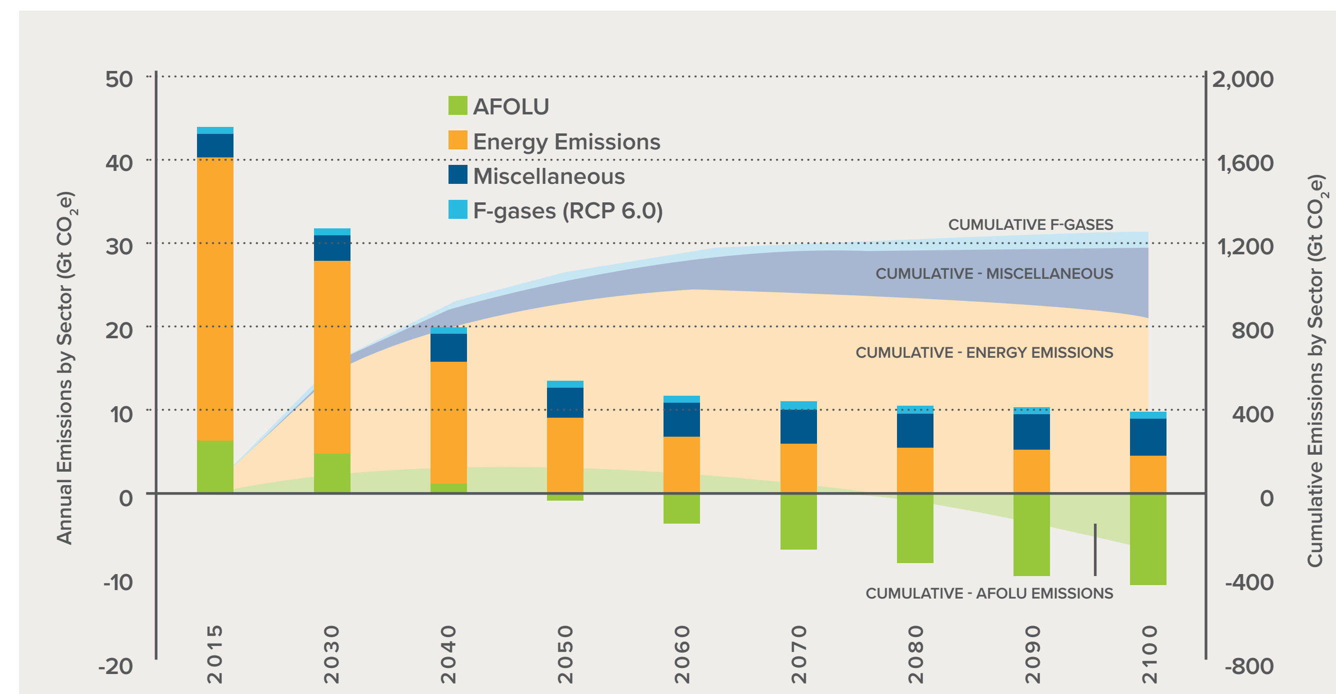
The increase in consumption of organic foods over the past decade is one example of how changes in standard farming practices and consumer behavior have driven changes in land-management practices. Increasing adoption of organic agriculture vis-à-vis conventional agriculture could not only reduce global greenhouse emissions[ix] but also improve soil-based sequestration of carbon.[44] At a global scale, growth in the organic food market is expected to continue at a compound annual growth rate (CAGR) of approximately 16% through 2020, reaching a market size of roughly $211 billion.[45]

Likewise, continued growth of the plant-based meat industry as a substitute for red meat could also help reduce growth in direct emissions from the agricultural sector and avoid additional emissions from deforestation for new pastures and for soy production as cattle feed. Recent trends estimate that the plant-based meat industry could grow at roughly 6.6% annually to reach $6 billion by 2022.[46] This growth again is driven largely by changing consumer preferences coupled with educational and marketing campaigns.

History provides hope that with education, government policy, and market incentives, new practices can be adopted. After World War II, for example, in response to the exponential growth in population, the training of farmers in new methods through global extension programs drove agricultural productivity while new seed varieties revolutionized agriculture. Such success can be replicated in the future through a better understanding of the carbon sequestration opportunity in the AFOLU sector and by adoption of new and innovative business and implementation models to realize that opportunity.

FIGURE 10

IN SCENARIO 1, EVEN THOUGH THE AFOLU SECTOR PROVIDES A NET SINK OF GHG EMISSIONS BY 2050, CUMULATIVE EMISSIONS WILL BE ON AN UPWARD TREND UNTIL THE 2070s. GLOBAL ANNUAL EMISSIONS ARE NET-POSITIVE UNTIL THE LATE 2090s, WITH THE ENERGY SECTOR BEING THE SINGLE LARGEST CONTRIBUTOR.



[vii] A detailed explanation of the AFOLU modeling approach can be found in the supplementary technical materials for the paper.

[viii] While this may sound like a radical shift from today's dietary preferences, such a future could reflect the potential for plant-based alternatives to prodvide a much lower cost and tastier substitute for real meat, allowing for this transition to be enabled entirely through consumer choice.

[ix] Emission reduction and sequestration benefits of organic agriculture are highly variable and uncertain. Though the U.S. Food and Agricultural Organization has initiated work relating to these areas, further research is needed to estimate their full potential. For this reason, we have not included organic agriculture as a vector.

AGAINST CLIMATE DESPAIR: A CALL TO ACTION

An energy transformation big enough and fast enough to hold the global average temperature rise to well below 2 C°, although daunting, is both practical and possible. Such a conclusion against despair relies not simply on mandates or hoped-for inventions but on current capabilities implemented by business-led, market-driven, and often highly profitable solutions.

Despite the shift in U.S. federal policies, new subnational coalitions are starting to emerge. Nine states including New York, Washington, and California; 218 cities; 310 universities; and more than 1,500 businesses are preparing a plan to fill the void left in the wake of U.S. withdrawal from the Paris Agreement.[47] Elsewhere, multiple nations, including China, India, Germany, France, and Italy, have reaffirmed their commitment to the Paris Agreement.[48]

Similarly, reforms in farming, forests, grazing, and other land-use practices can move enough carbon from air to soil to achieve a world well below a 2 C° temperature rise. Business leadership and engaged consumers can together deliver a world with the same or better energy services and food production at a cost trillions of dollars lower than business as usual while providing significant non-energy benefits for health, development, prosperity, equity, and security.

Trends indicate that this transition is not only profitable but can generate millions of new jobs. Making this future happen will be an enormous challenge—but not an impossible one. And although the power of markets to drive such a radical transformation is potentially great, both the energy sector transition and the AFOLU transformation will require robust market and policy frameworks to succeed at the necessary scale and speed.

In order to arrest global climate change with urgency and efficiency, we need all hands on deck and above all, *applied hope* in the face of the most challenging task humanity has ever undertaken.

Top photo courtesy Power Africa; bottom photo courtesy U.S. Department of Energy

04 APPENDIX

SCENARIO COMPARISON TABLE

	ENERGY SUPPLY[*]		ENERGY DEMAND[*]		AGRICULTURE, FORESTRY, AND LAND USE	F-GASES AND OTHER FORCINGS
	Solar PV	Wind	Buildings Efficiency (% reduction below BAU)	Light-Duty Vehicle		
Business as Usual	Based on IEA Current Policies Scenario to 2040. GCAM 3.0 Baseline Limited Technology Scenario is used to extend projections from 2040 to 2100.				GHG emissions data from the Food and Agriculture Organization of the United Nations (FAO) FAOSTAT database used for projections to 2040. Values extrapolated to 2100 using curve-fitting population growth estimates.	RCP 8.5 trajectory (same trajectory for BAU and scenarios 2, 3, 4, 5)
Scenario 1: Most Aggressive	**High** S-curve growth anticipated for solar PV. Penetration of solar in global supply portfolio eventually saturates at 60%.[Δ]	**High** S-curve growth anticipated for wind. Extrapolating from *Reinventing Fire* and *Reinventing Fire: China* 2050 values, penetration of wind in supply portfolio saturates at 39% for OECD countries and at 25% for non-OECD countries.*	**High** For OECD, based on *Reinventing Fire*'s Scenario 3 Electricity 2050 – 51% 2100 – 73% Heat 2050 – 53% 2100 – 77% For non-OECD, based on *Reinventing Fire: China* Electricity 2050 – 30% 2100 – 48% Heat 2050 – 33% 2100 – 54%	**High** For OECD, based on IEA *Global EV Outlook* 2016: 2030 – 10%, 2050 – 40%* For non-OECD, based on UNEP EV scenarios and road map for India, and recent plans to target 100% EV sales for India by 2030: 2030 – 35% *	Modeled emission-reduction vectors: • Reduced consumption of beef • Conservation agriculture, grazing management, and land restoration • Biomass pyrolysis • Land conversion to forest In all scenarios, the rate of emission reduction was the same. For more details, please read the technical appendix.	RCP 6.0 trajectory

[*] This table includes only those variables that change across the four scenarios. To know about the methodology employed to calculate other variables, please read the supplementary technical materials.

* 2100 or 2050 values in these cases were determined by curve-fitting methods. For details, please read the supplementary technical materials.

[Δ] These values represent a hypothetical what-if scenario for global solar growth. The year in which saturation of penetration levels of solar or wind occurs are not specified in this formulation but are implicitly calculated in the log-linear functions used. For details, please read the supplementary technical materials.

	ENERGY SUPPLY†		ENERGY DEMAND†		AGRICULTURE, FORESTRY, AND LAND USE	F-GASES AND OTHER FORCINGS
	Solar PV	Wind	Buildings Efficiency (% reduction below BAU)	Light-Duty Vehicle		
Scenario 2: Aggressive	**High** S-curve growth anticipated for solar PV. Penetration of solar in global supply portfolio eventually saturates at 60%.[Δ]	**High** S-curve growth anticipated for wind. Extrapolating from *Reinventing Fire* and *Reinventing Fire: China* 2050 values, penetration of wind in supply portfolio saturates at 39% for OECD countries and at 25% for non-OECD countries.*	**High** For OECD, based on *Reinventing Fire's* Scenario 3 Electricity 2050 – 51% 2100 – 73% Heat 2050 – 53% 2100 – 77% For non-OECD, based on *Reinventing Fire: China* Electricity 2050 – 30% 2100 – 48% Heat 2050 – 33% 2100 – 54%	**High** For OECD, based on IEA *Global EV Outlook* 2016: 2030 – 10%, 2050 – 40%* For non-OECD, based on UNEP EV scenarios and road map for India, and recent plans to target 100% EV sales for India by 2030: 2030 – 35% *	Modeled emission-reduction vectors: • Reduced consumption of beef • Conservation agriculture, grazing management, and land restoration • Biomass pyrolysis • Land conversion to forest In all scenarios, the rate of emission reduction was the same. For more details, please read the technical appendix.	RCP 8.5 trajectory (same trajectory for BAU and scenarios 2, 3, 4, 5)
Scenario 3: Aggressive	**High** S-curve growth anticipated for solar PV. Penetration of solar in global supply portfolio eventually saturates at 60%.[Δ]	**High** S-curve growth anticipated for wind. Extrapolating from *Reinventing Fire* and *Reinventing Fire: China* 2050 values, penetration of wind in supply portfolio saturates at 39% for OECD countries and at 25% for non-OECD countries.*	**Low** For OECD, percent reduction below BAU based on *Reinventing Fire's* Scenario 2 Electricity 2050 – 36% 2100 – 52% Heat 2050 – 37% 2100 – 53% For non-OECD, based on *Reinventing Fire: China* Electricity 2050 – 30% 2100 – 48% Heat 2050 – 33% 2100 – 54%	**High** For OECD, based on IEA *Global EV Outlook* 2016: 2030 – 10%, 2050 – 40% * For non-OECD, based on UNEP EV scenarios and road map for India, and recent plans to target 100% EV sales for India by 2030: 2030 – 35% *	Modeled emission-reduction vectors: • Reduced consumption of beef • Conservation agriculture, grazing management, and land restoration • Biomass pyrolysis • Land conversion to forest In all scenarios, the rate of emission reduction was the same. For more details, please read the technical appendix.	RCP 8.5 trajectory (same trajectory for BAU and scenarios 2, 3, 4, 5)

	ENERGY SUPPLY†		ENERGY DEMAND†		AGRICULTURE, FORESTRY, AND LAND USE	F-GASES AND OTHER FORCINGS
	Solar PV	Wind	Buildings Efficiency (% reduction below BAU)	Light-Duty Vehicle		
Scenario 4: Most Conservative	**Low** S-curve growth anticipated for solar PV. Extrapolating from *Reinventing Fire* and *Reinventing Fire: China* 2050 values, penetration of solar in supply portfolio saturates at 39% for OECD countries and at 35% for non-OECD countries.*	**Low** S-curve growth anticipated for wind. Extrapolating from *Reinventing Fire* and *Reinventing Fire: China* 2050 values, penetration of wind in supply portfolio saturates at 39% for OECD countries and at 25% for non-OECD countries. Near-term growth follows forecasts from Bloomberg New Energy Finance.*	**Low** For OECD, percent reduction below BAU based on *Reinventing Fire's* Scenario 2 Electricity 2050 – 36% 2100 – 52% Heat 2050 – 37% 2100 – 53% For non-OECD, based on *Reinventing Fire China* Electricity 2050 – 30% 2100 – 48% Heat 2050 – 33% 2100 – 54%	**Low** OECD and non-OECD, based on IEA *Global EV Outlook* 2016: 2030 – 10%, 2050 – 40%*	Modeled emission-reduction vectors: • Reduced consumption of beef • Conservation agriculture, grazing management, and land restoration • Biomass pyrolysis • Land conversion to forest In all scenarios, the rate of emission reduction was the same. For more details, please read the technical appendix.	RCP 8.5 trajectory (same trajectory for BAU and scenarios 2, 3, 4, 5)
Scenario 5: Conservative	**Mod/High** S-curve growth anticipated for solar PV. Penetration of solar in global supply portfolio eventually saturates at 60%. Near-term growth follows forecasts from Bloomberg New Energy Finance.	**Low** S-curve growth anticipated for wind. Extrapolating from *Reinventing Fire* and *Reinventing Fire: China* 2050 values, penetration of wind in supply portfolio saturates at 39% for OECD countries and at 25% for non-OECD countries. Near-term growth follows forecasts from Bloomberg New Energy Finance.*	**Low** For OECD, percent reduction below BAU based on *Reinventing Fire's* Scenario 2 Electricity 2050 – 36% 2100 – 52% Heat 2050 – 37% 2100 – 53% For non-OECD, based on *Reinventing Fire: China* Electricity 2050 – 30% 2100 – 48% Heat 2050 – 33% 2100 – 54%	**High** For OECD, based on IEA *Global EV Outlook* 2016: 2030 – 10%, 2050 – 40%* For non-OECD, based on UNEP EV scenarios and road map for India, and recent plans to target 100% EV sales for India by 2030: 2030 – 35%*	Modeled emission-reduction vectors: • Reduced consumption of beef • Conservation agriculture, grazing management, and land restoration • Biomass pyrolysis • Land conversion to forest In all scenarios, the rate of emission reduction was the same. For more details, please read the technical appendix.	RCP 8.5 trajectory (same trajectory for BAU and scenarios 2, 3, 4, 5)

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