



Seven Challenges for Energy Transformation



Our Challenge to Transform

Friends and Colleagues:

Many of us, working in our own ways on energy and climate issues, are asking: ***How can we rise to meet the urgency of the climate challenge in the next 10 years?***

Whether we are 60 years old or 16, we share the reality that the decade immediately ahead is a pivotal time in the history of life on earth. It is a time when many possibilities are still open, but the window of opportunity to avoid the most severe consequences of climate change is closing quickly.

Climate scientists are telling us, plainly and clearly, that if we reduce greenhouse gas (GHG) emissions 40%–50% by 2030, a world with only 1.5°C of average global temperature increase is still possible. The scientific evidence also shows that the difference between 1.5°C and 2.0°C of warming, although seemingly small, would be tremendously consequential not just for our lives but for those of all future generations of living beings. The consequences of a world with 3°C–4°C of warming, which we are currently tracking toward, are almost unimaginable.

So, how can we respond?

Putting 500% more effort against the climate challenge while still using the same approach is not enough to achieve the breakthroughs we need.

At Rocky Mountain Institute, this realization is challenging us to think more creatively about how we can be more effective and to fundamentally adjust how we work. Doing this requires a willingness to change what we work on, to experiment, and to take risks.

We know we have a better chance of creating positive changes that are disproportionate to our efforts if we take a systemic view of the energy transition and intervene in opportunities that have the highest leverage. Taking a systems view allows us and everyone working on the climate crisis to work more effectively because we can see, with clear focus, how our work fits within the context of the whole. At RMI, we see that investing in learning together at this level is critically important.

We know that to achieve our goals, we will need to work together more effectively within the large and diverse global community of actors and allies engaged in this work. This is not a time when institutional or personal pride of ownership is helpful. Achieving breakthroughs will require challenging our own assumptions about who we are and how we can best contribute. It will require radical, global collaboration across organizations with different roles in society to achieve a wholesale economic transformation.

In this spirit, we are inviting members of our network and beyond to join us during the next 12 months to identify and pursue the real breakthroughs that can make a difference at this critical time. No doubt, many of these opportunities are beyond us individually but within our reach collectively.

To facilitate this dialogue, and to support the work that we hope will emerge from it, we are engaging with other energy and climate leaders to discuss opportunities for global energy transformation and how our respective activities and capabilities relate to the whole. In 2020, RMI will launch a new Global Energy Solutions Lab to help to carry this collaborative work forward in pragmatic and actionable ways.

We offer this report, *Seven Challenges for Energy Transformation*, as a starting point for these conversations. These challenges are framed as invitations to explore solutions together rather than proclamations about the steps needed to get to a particular outcome because we know full well that they, too, will likely need to be expanded, reorganized, or reinvented as we go forward.

In view of the urgency of current circumstances, RMI has committed itself to an organization-wide process of reevaluation and reinvention over the year ahead. ***We stand ready to reconsider and change any aspect of what we do and how we do it to achieve breakthrough outcomes.***

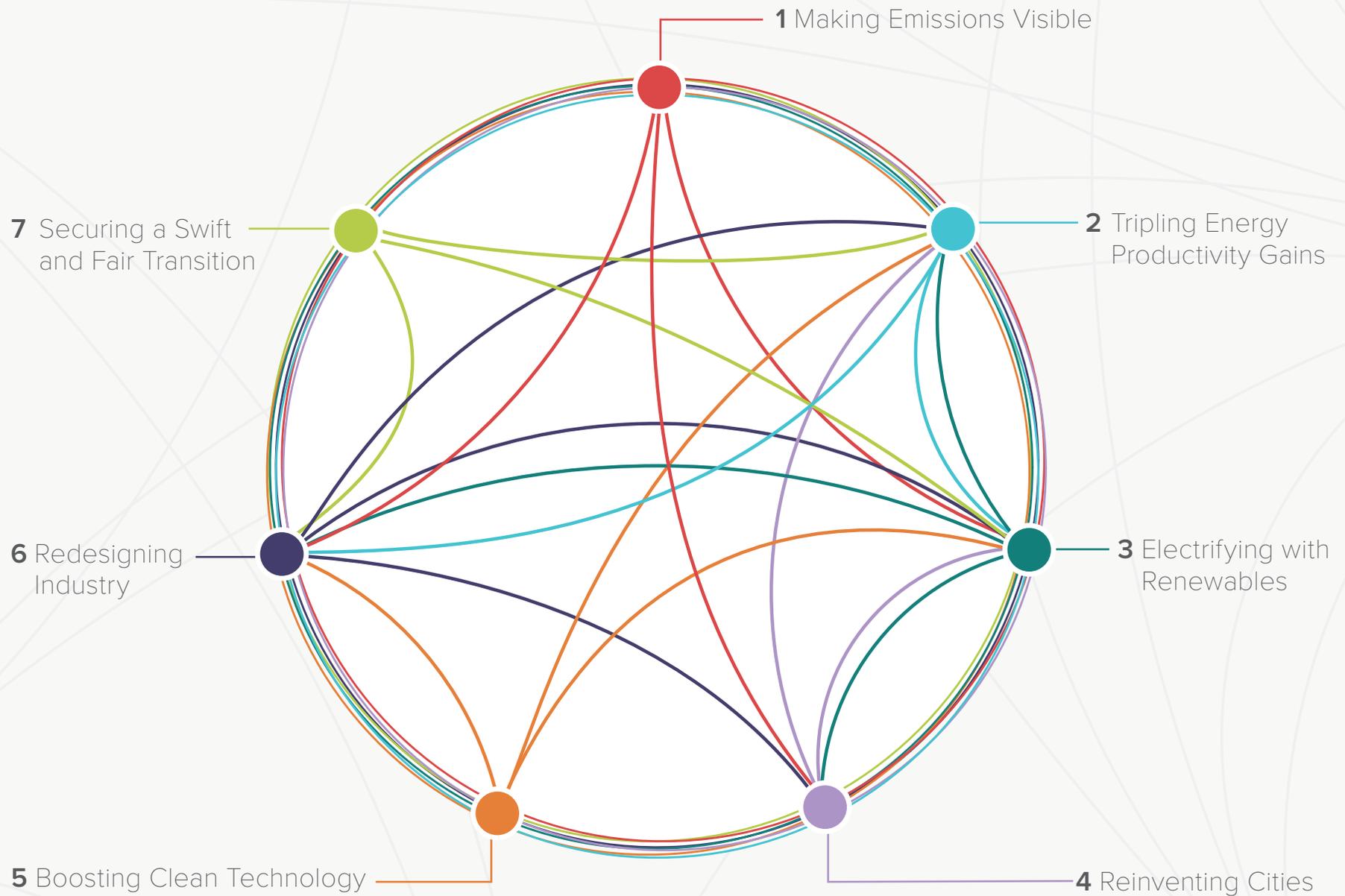
In this commitment, we know that we do not stand alone, but in a widening community of institutions rising to meet the urgent challenge at hand. Together, we have the capacity to raise awareness, transform markets, and design new solutions. We look forward to continuing to evolve our work together with the full force of our energy, creativity, and perseverance.

With steadfast and hopeful intention,

A handwritten signature in black ink that reads "Jules Kortenhorst". The signature is written in a cursive style with a large, sweeping initial "J" and a horizontal line extending from the end of the name.

Jules Kortenhorst, on behalf of the RMI team

Seven Challenges for Energy Transformation



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Suggested Citation

Rocky Mountain Institute, *Seven Challenges for Energy Transformation*, Rocky Mountain Institute, 2019,
<https://rmi.org/seven-challenges-report>.

Acknowledgments

Key contributions and insights were gathered from RMI leaders and experts, especially Josh Agenbroad, Paul Bodnar, Thomas Koch Blank, Koben Calhoun, Cara Carmichael, Jacob Corvidae, Jon Creyts, Mark Dyson, Garrett Fitzgerald, Carla Frisch, Leia Guccione, Lena Hansen, Mike Henchen, Taku Ide, Richenda van Leeuwen, Jamie Mandel, James Mitchell, Tyeler Matsuo, Patrick Molloy, Rushad Nanavatty, Paolo Natali, Victor Olgyay, Samhita Shiledar, Clay Stranger, Cyril Yee, and Eric Wanless.

This report was developed and authored by RMI's Emerging Solutions group, led by James Newcomb and managed by Kieran Coleman, with critical research, analysis, and support from Amory Lovins, Charlie Bloch, Josh Brooks, Jake Glassman, Joseph Goodman, Krutarth Jhaveri, Katie Mulvaney, Madeleine Tyson, Ethan Wampler, and Guy Wohl. Important external research, analysis, and expertise was provided by Jeffery Greenblatt and Emily McGlynn.

External insights and guidance were gathered from W. Brian Arthur and Arnulf Grübler, as well as the excellent work of organizations including Bloomberg New Energy Finance, the Coalition for Urban Transitions, Carbon Tracker, DNV GL, the Energy Transitions Commission (ETC), the International Institute for Applied Systems Analysis, the International Renewable Energy Agency, Material Economics, McKinsey & Co, and the Ellen MacArthur Foundation.



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; the San Francisco Bay Area; Washington, D.C.; and Beijing.



**Innovation Fund
for Energy Solutions**

This report was made possible by financial support from development partners and by RMI's Innovation Fund for Energy Solutions.

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Executive Summary



Now is the time for action.

While some parts of the energy system are changing rapidly toward reducing GHG emissions, the world is badly off track from what is needed to achieve the Paris Agreement goal of limiting global average temperature increase to well below 2°C. Top-down government policy actions cannot be expected to deliver the changes needed in time to avert the most severe consequences of global climate change. Many nations are struggling to address issues of security, trade, and economic stability; only a few have the focus and the will now necessary to make the major changes in energy policy that are required to put energy systems on a path to real change in the time frame needed.

Our analysis and experience suggest that there is another way to get to the goal. This is a path of emergence, sparked by bold and decisive actions on the part of citizens, corporations, philanthropic institutions, subnational leaders, regulators, and policymakers. **Meaningful progress to address the climate crisis can emerge quickly from an upwelling of actions taken by leading institutions in the next two to three years—provided these institutions have the will and the capacity to work together in new ways.**

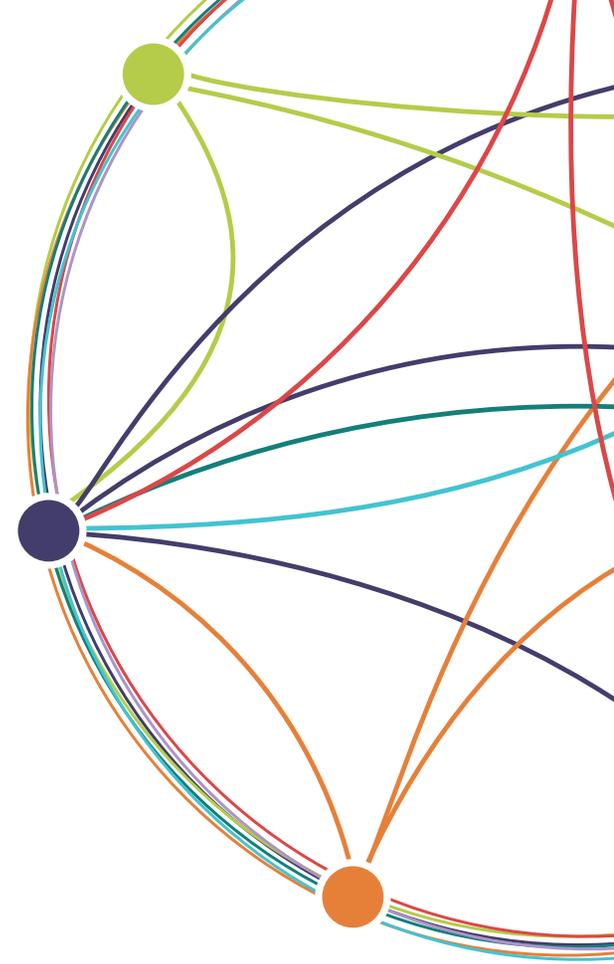
Taking a systems view, we identify seven key places in the global energy system where solutions are within our reach but not yet at hand. This framing is a starting point, not a definitive set of answers, to catalyze better understanding, alignment, cooperation, and faster action. Perhaps most importantly, this work will help us think more clearly about how the different parts of the system are linked, and therefore how our actions can be more strategic and focused. Because action on these challenges will be strongly synergistic, having a view of the whole can ensure we work more effectively.

Seven Challenges for Energy Transformation

1. Making emissions visible
2. Tripling energy productivity gains
3. Electrifying with renewables
4. Reinventing cities
5. Boosting clean technology
6. Redesigning industry
7. Securing a swift and fair transition

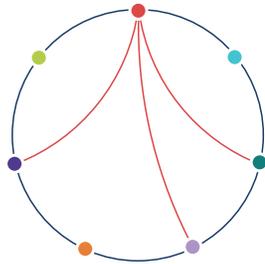
These challenges are not meant to provide a comprehensive taxonomy of the energy system. They are **places to intervene** in that system. As such, they are defined by cross-cutting systems of actors rather than by a sectoral view.

For each, we describe why the challenge is important from a global energy and climate perspective and why it might be an area where we can make significant and rapid change within the next decade. We conclude each challenge with a set of key questions as a starting point for further exploration of collaborative action on the part of industry, government, civil society, and philanthropy to catalyze change.



1

Making Emissions Visible



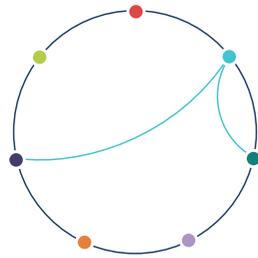
How can we improve the transparency, accountability, and actionability of climate and energy data to drive faster greenhouse gas emissions reductions?

Current climate and energy data systems fall far short of what is both needed and possible to meet the urgency of the climate challenge. Bringing state-of-the-art data collection and analysis systems to bear on this problem could trigger a truly revolutionary “big bang” of innovations by putting powerful information in the hands of key actors. It is within our reach to create an integrated, open-source system capable of generating emissions maps of the world with continuously improved granularity, smaller uncertainty bands, and reduced time lags. A three-step process could support building this global, integrated system:

1. Converting today’s fragmented initiatives into a diverse information ecosystem
2. Facilitating the development of platforms that apply data and analytics to specific opportunities
3. Integrating the resulting capabilities and resources into an independent global system for climate and energy data tracking and communication

2

Tripling Energy Productivity Gains



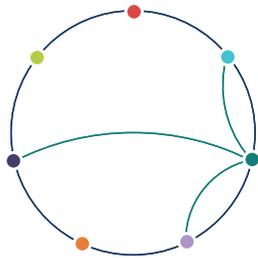
How can we replicate what's working at scale, improve design of new buildings and infrastructure, and increase turnover of inefficient assets?

To achieve well below 2°C in the most cost-effective way, we need to globally triple the pace of improving energy productivity in the next decade relative to the last few years. Energy productivity advances health, development, and security, and can save trillions of dollars' worth of supply-side and carbon-removal investments. But achieving this goal will require bold actions to:

1. Get incentives right, especially through better integrated resource planning and utility regulation
2. Quickly scale efficiency programs and regulations that are working today
3. Rapidly electrify energy use in buildings, transportation, and parts of industry, where electricity brings an efficiency benefit
4. Improve design practices to achieve leapfrog efficiency gains
5. Accelerate asset turnover with retrofits and scrapping

3

Electrifying with Renewables



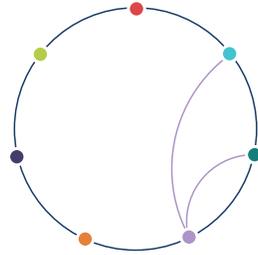
How can we rapidly expand renewables and increase electricity's share of global energy use?

Electrification with renewable power is among the most important leverage points to rapidly transform the global energy system. We can limit global average temperature rise to well below 2°C if we can electrify 40%–50% of energy end use by 2040 while increasing the share of electricity generation from renewables to 75%–85%. Limiting warming to 1.5°C would require hitting these ambitious marks plus creating a more efficient, less materials-intensive economy. With known technologies deployed at conservatively expected costs, this could be achieved while generating net benefits between now and 2050 of \$65–\$160 trillion.¹

On the supply side, electricity systems are experiencing a momentous transition: clean sources of electricity have become the lowest-cost sources of supply throughout much of the world. But changes are still needed to harvest this potential through reforming utility business models, expanding competitive energy markets, and retiring uneconomic assets. In buildings and transportation, electrification options are at or near the economic tipping points that could trigger rapid growth but need additional push from policymakers and regulators to achieve the necessary market transformations in these sectors.

4

Reinventing Cities

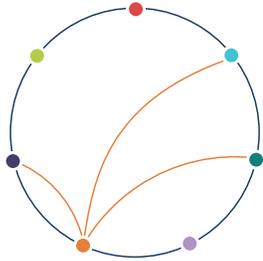


How can leapfrog improvements in urban systems and infrastructure be harnessed to deliver secure, resilient, and clean energy services for all?

Cities are hubs of rapid learning, knowledge sharing, and experimentation, with the potential to reshape global energy. Cities also face public health and other growth-related challenges associated with carbon-intensive fuels and lifestyles. The value created from a transition to low-carbon solutions could be immense: \$2 trillion in annual investments could yield \$2.8 trillion in returns by 2030 and \$7 trillion by 2050, annually, while reducing emissions by 90% over the same time frame.² Greater electrification of efficient buildings and transportation systems will be primary pathways for cities to reach these goals. This can be enabled and accelerated by stronger global networks of cities for supporting innovation and sharing best practices. In addition, leapfrog opportunities exist, especially in rapidly urbanizing areas, to implement better urban design and fundamentally transform urban mobility systems.

5

Boosting Clean Technology

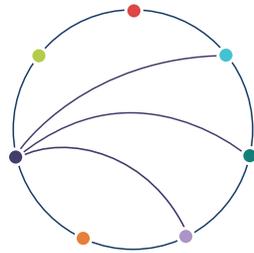


How can we speed the development and rapid adoption of high-impact clean energy technologies?

The transition to a low-carbon energy system is now advancing faster than expected in areas where globally scaled manufacturing has unleashed steep declines in the cost of clean energy technology. Technologies like wind, solar, and batteries have achieved dramatic cost reductions and crossed tipping points for wide adoption, but critical technology gaps exist in other areas, especially in industry and transport. Coordinated actions by industry and government can pull forward the timetable for crossing these critical thresholds, sometimes by a decade or more, through targeted research, development, and deployment in areas like hydrogen production, long-term energy storage, insulation materials, and industrial processes. Institutions involved in cleantech innovation could develop a better integrated systems-level commercialization ecosystem like that found in the pharmaceutical and biotech industries to address barriers to technology commercialization.

6

Redesigning Industry



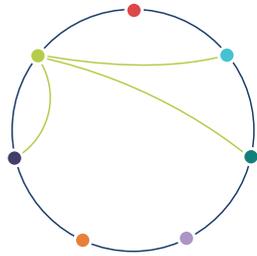
How can we shift the way we produce, transport, and use energy and materials in global products and infrastructure?

We urgently need to accelerate emissions reductions in heavy industry, long-haul transportation, and aviation to set these sectors on decarbonization pathways comparable to those in electricity supply. We need new technology and better design coupled with fast-action, near-term steps to reduce carbon intensity and transformative long-term solutions to lessen the use of the most carbon-intensive materials. The complete decarbonization of global goods and services will require sweeping action across sectors to reduce the use of carbon-intensive materials through better design and improved processes. Four cross-cutting and cross-sectoral levers can realign incentives to drive industry decarbonization:

1. Climate-aligned financial sector commitments
2. Top-down and bottom-up policy incentives
3. Market evolution to create greater transparency and reward low-carbon solutions
4. Catalytic multistakeholder collaboration focused on pragmatic solutions

7

Securing a Swift and Fair Transition



How can we manage financial, institutional, and human aspects of the energy transition to transform all economies?

The transition to a clean energy economy can mitigate the worst consequences of climate change while simultaneously delivering large net benefits to our economies and communities. Progress toward supplanting carbon-intensive assets with zero-carbon alternatives entails disruption and dislocations that must be predicted and managed. It is essential to adopt new tools and methods to speed investment and capital stock turnover, manage risk, ensure access to energy, reduce transition costs, and mitigate negative impacts on affected industries and communities in order to maximize net value creation from global clean energy transformation. Four main financial levers will help to transform global energy use:

1. Building new low-carbon assets
2. Halting the build-out of high-carbon assets
3. Accelerating the retirement of existing carbon-intensive assets
4. Improving the productivity of existing and new capital stock

At the same time, anticipating and managing the impacts of energy system changes on workers and communities through better planning, workforce training, and transition support can help to ensure broad access to the benefits of the transition.

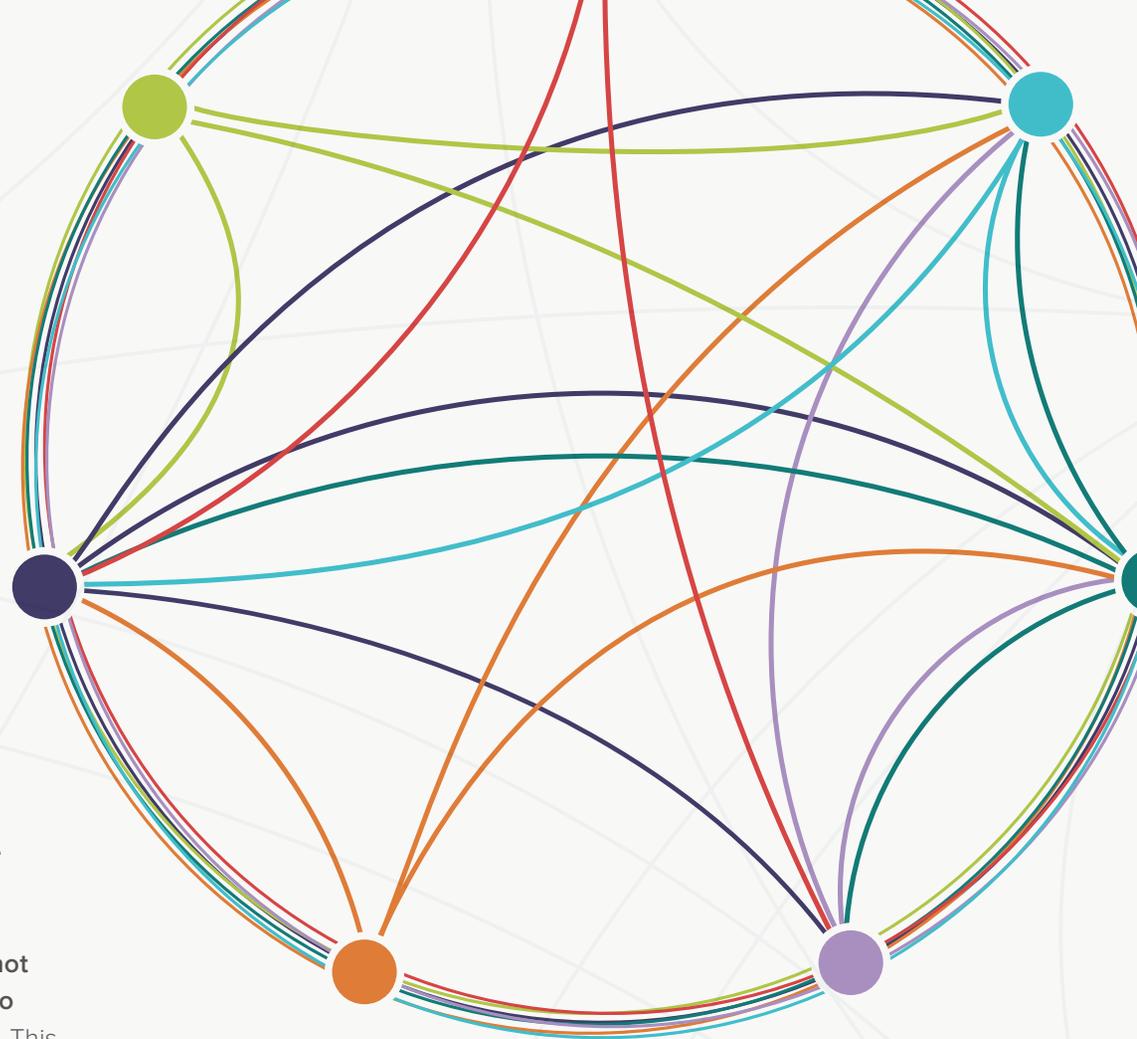
Introduction

How can we be hopeful about the speed of the energy transition in the face of the quickening pace of climate change and the urgent need for far-reaching changes to our energy systems in the next decade? If we imagine the global energy system as a supertanker and put ourselves at the helm, we might see that even as we turn the wheel toward a sustainable path now, we are still likely to overrun the goal of limiting average global temperature increases to well below 2°C, and we could well exceed 3°C–4°C.

But if we instead recognize that this seemingly unalterable energy system is built from billions of parts acting in parallel, we can see that it is possible to break these apart and reconfigure the system in ways that could easily achieve our goals. This is the nature of the transformation needed.

Transformation requires that we have the vision and courage to not just turn the wheel on the existing technoeconomic system, but to take it apart and rebuild it, even as we continue to move forward. This deeper change starts from our willingness to reconsider what is possible in our own lives, communities, and organizations as we explore climate solutions.

Real solutions are not abstract; they are pragmatic and close to home. Former United Nations Executive Secretary Christiana Figueres suggests that we should begin this inquiry not by asking the question, “What can be done?” but rather by asking, “What must be done?”



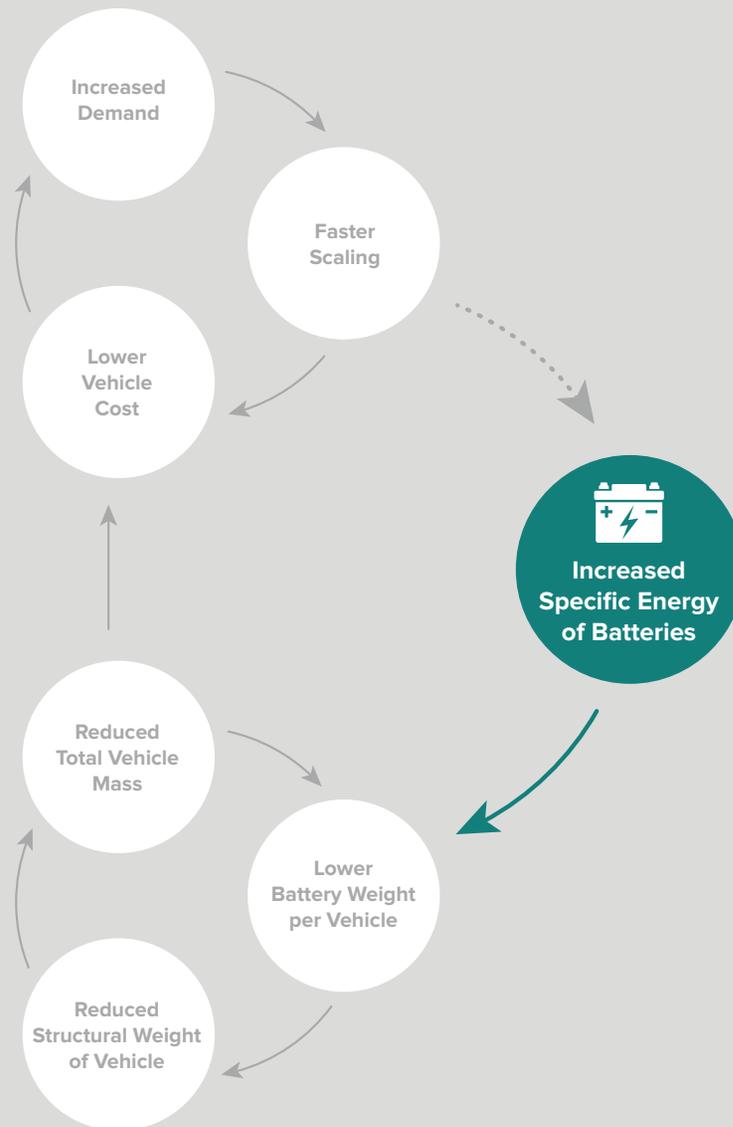
Systems Thinking for Speed and Scale

We know that to achieve transformation, **we must find opportunities where relatively small changes can deliver disproportionate results in reducing GHG emissions.** To identify these sensitive, high-leverage points in the energy landscape, we have to take a systems view.

This is challenging work because no formulaic approach can give us the insights we are looking for. We have to look at problems from different perspectives and study different levels of the system. But the recent disruptions in the energy system caused by greatly improved technologies and economics offer clues as to likely places to find answers.

The energy system is composed of many, many layers of technology, woven into the fabric of our societies and our economy. Economist Brian Arthur, one of the pioneers of complexity theory, emphasizes that systems of technology are subject to *discontinuities, tipping points, and increasing returns to scale.*³

EXHIBIT 1
Positive Feedbacks in Markets and Technology: The Case of Electric Buses



Source: RMI

Structural Transformations Are within Reach

When new technologies begin to interact in ways that have cascading or compounding effects, as is the case today with the accelerating electrification of energy systems across transportation, buildings, and industry, these changes begin to cause structural shifts in the economy and in the technology system that are beyond the scope of conventional economic theory. The economy, in Arthur's words, "exists always in a perpetual openness of change"; its evolution is "continual, fractal, and inexorable."⁴

Deep structural changes, of the kind we see beginning today in the energy system, are studied more by historians than by economists. Novel technologies call forth novel arrangements and organizational forms, occasionally leading to systemic shifts like the industrial revolution or today's clean energy revolution.

A recent World Economic Forum white paper, authored by Kingsmill Bond, Angus McCrone, and Jules Kortenhorst, *The Speed of the Energy Transition*, suggests pathways by which the energy transition could arrive faster than most experts today expect.⁵ The authors explain that we are approaching critical tipping points where widespread changes in energy markets, technology, and policymaking are possible.

Add to this the potent possibilities for emerging market countries to leapfrog past conventional development paths, and we can begin to see a picture in which the energy landscape could shift in ways that are rapid and disruptive.

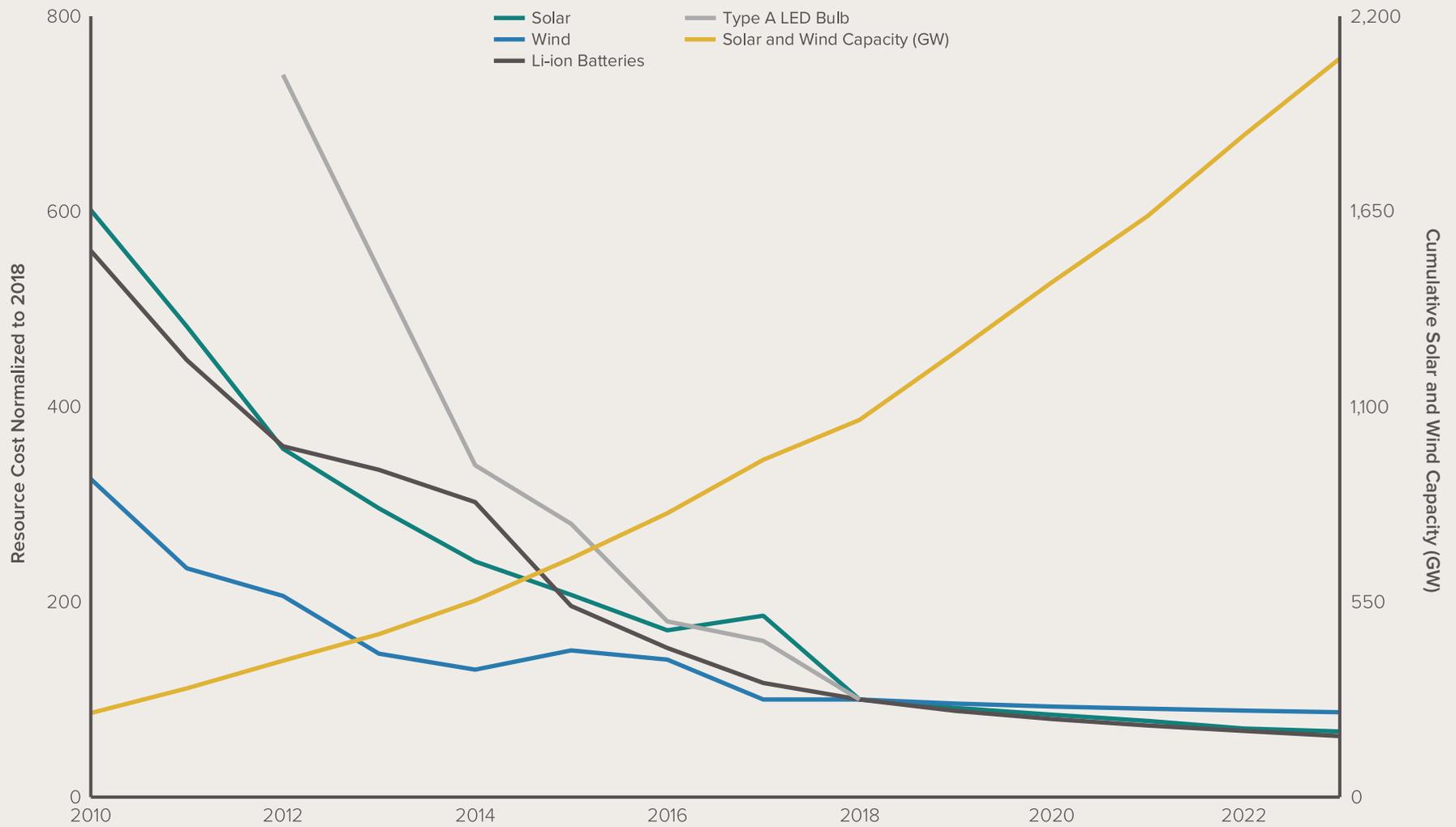
Harnessing systems dynamics, such as reinforcing feedback loops, can help us cost-effectively leapfrog carbon-intensive technologies. Reinforcing feedback loops amplify initial causes and effects to generate self-propagating change.

For example, electric buses can soon adopt higher energy density batteries that require 50% less space for the same energy, reducing bus weight and enabling buses to double storage capacity at 25% less weight. This efficiency can improve trip duration, enabling more passengers to ride the bus on the same battery charge, reducing cost per passenger. As a result, demand for electric buses will grow, and they will earn increasing economic returns, justifying larger-scale manufacturing and further reducing the cost of these energy dense batteries. This can spur further demand both from bus manufacturers and other sectors, further reducing cost and improving performance.

Identifying and harnessing these dynamics intentionally can bring transformative new solutions like next-generation batteries to cost advantage and scale on a time frame required to meet pressing needs like urban mobility.

EXHIBIT 2

Real Cost Declines for Key Clean Energy Technologies: 2010-2023



Source: RMI, BNEF, Cadmus⁶

Our Challenge

At RMI, we have framed the opportunities for global energy transformation in a short list of key challenges that require the world's collaborative efforts to solve. These challenges are framed through the lens of the technical, economic, and business realities that have been the foundation for RMI's work for nearly 40 years. We hope that this formulation will be informative and complementary to other analyses that are more focused on applying national policy levers to drive the energy transition.

This is not to say that the social, political, and human dimensions of climate change are any less important. But our perspective focuses on unlocking opportunities for value creation through market-based solutions, voluntary actions, and accelerated implementation of new technology. We know that to deliver real change we will need other actors with different perspectives and domain expertise at our side. The solutions we pursue address not only climate but also economic development and growth, public health, security, equity, and justice. These considerations are both local and global.

Although we can see areas where solutions are needed, none of us have complete answers. Nor can any of us achieve them without new and more effective ways of collaborating globally. How we approach the work is critically important, and we seek to learn as we go, by developing solutions together and increasing our capacity to collaborate locally and globally.

Finally, we note that our focus here is on the energy system, not on the wider set of climate change mitigation actions, including nature-based solutions such as agriculture, forestry, and land use changes, that could be significant contributors to limiting global climate change. In the end, changes in both these domains will no doubt be needed to achieve our goals.

The Role for and Limitations of Integrated Assessment Models

Although taking a complex-systems view of the energy transition may help us to identify sensitive points for intervention, conventional Integrated Assessment Models (IAMs), which are the backbone of most analyses of global climate scenarios, do not capture complex system dynamics or even basic learning curves for technology. IAMs aim to explore future trajectories of socioeconomic and physical Earth systems while considering whether and how we might limit global climate change over the decades ahead.⁷ But these models have performed poorly over the past 5–10 years in predicting the rapid and dynamic changes associated with the rise of renewable power generation and the pace of technology change in this area.

This is a problem. IAMs are used as a source of guidance on national policies intended to mitigate climate change. Because the research groups that maintain IAMs are primarily responsible to national policymakers, the only agents of change represented in the model are homogenous social planners able to take centralized action at an international level.⁸

Thus, these models narrow the solution space and disempower billions of actors with a collective role to play.

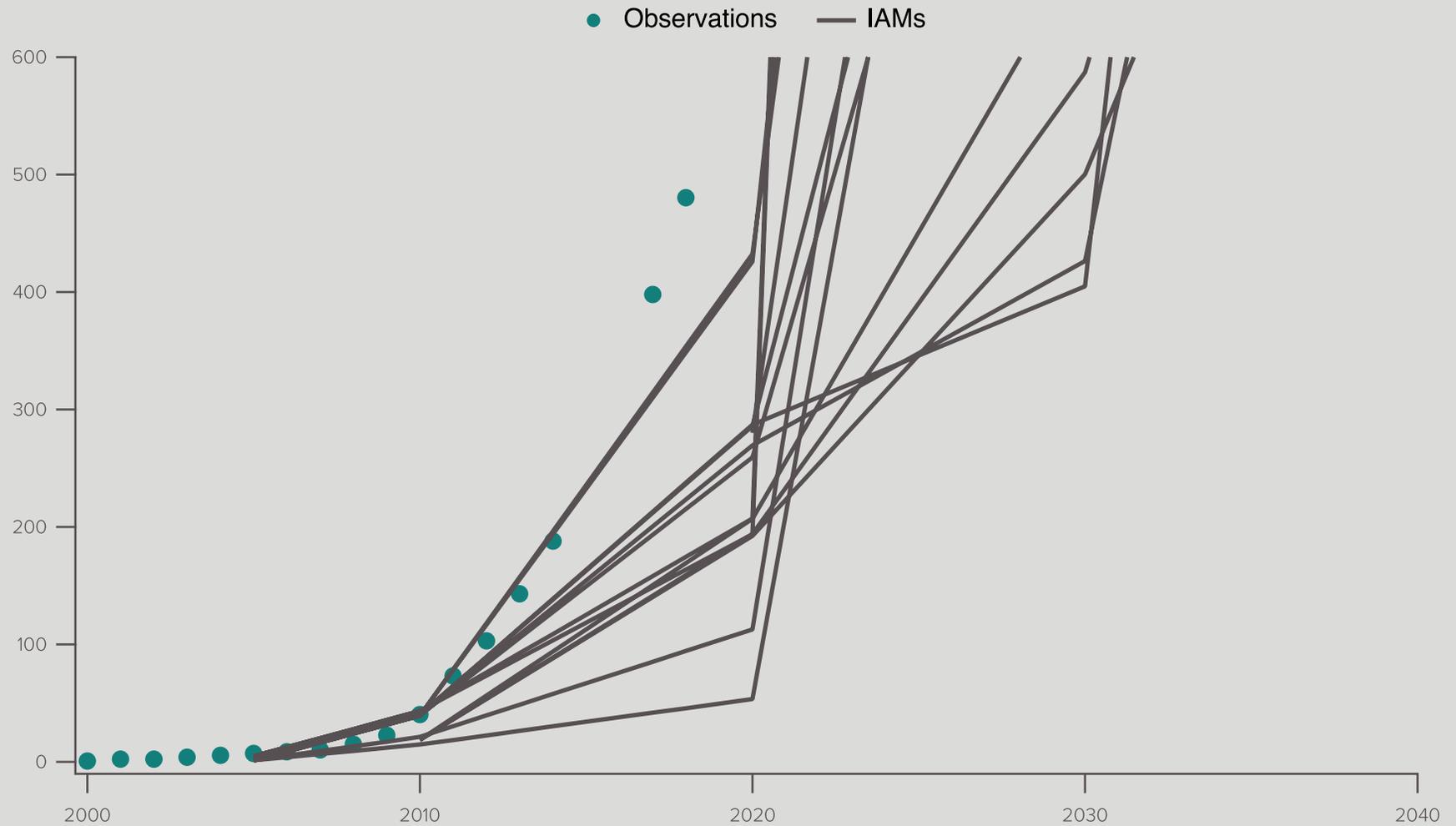
An important limitation of the existing models is that they fail to capture complex system dynamics, such as increasing returns to scale. This may help explain why they have missed emergent trends in technology, such as how fast rapidly scaling global manufacturing drives costs down through learning and scaling by industry. For example, observed data for global installed solar capacity in 2018⁹ is higher than all of the most ambitious IAM projections for 2020¹⁰ *meant to limit temperature rise to 1.5°C over the next century* (see Exhibit 3).¹ Given these limitations, we should not let today's IAMs limit our thinking about what changes in the energy system are possible nor what the costs and value of such changes will be.

¹ These projections will serve as a foundation for the upcoming IPCC Sixth Assessment Report.

EXHIBIT 3

Actual Solar Generation Capacity Has Exceeded the Most Optimistic Integrated Assessment Model Scenarios

Installed Global Solar Generation Capacity (GW)

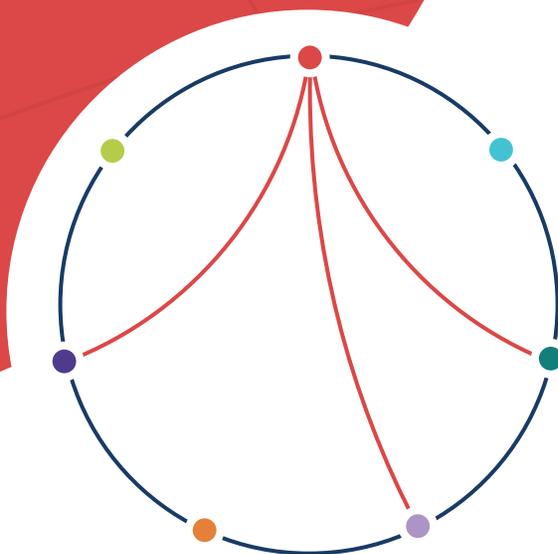


Source: RMI, Nature Climate Change, Nature Energy, MIT¹¹

1

Making Emissions Visible

How can we improve the transparency, accountability, and actionability of climate and energy data to drive new ideas and faster greenhouse gas emissions reductions?



Making Emissions Visible

Current climate and energy data systems fall far short of both what is needed and what is possible to meet the urgency of the climate challenge. Decision makers at all levels of the energy system are reliant on hopelessly outdated government-reported emissions data to make decisions. Bringing state-of-the-art data collection and analysis systems to bear on this problem could trigger a truly revolutionary “big bang” of innovations by putting powerful information in the hands of policymakers, advocates, and consumers. Better access to data has already revolutionized several of the world’s largest industries. The return on investment from radically improving transparency could be among the highest available to speed the energy transition.

The ultimate and urgent prize is an integrated, open-source system capable of generating emissions maps of the world with continuously improved granularity, smaller uncertainty bands, and reduced time lags. Such a system would fundamentally disrupt the nonstandard corporate reporting methods and United Nations Framework Convention on Climate Change (UNFCCC) approach to monitoring, reporting, and verification (MRV). It would equip political leaders, citizen activists, businesses, and researchers with a powerful tool worthy of a global campaign to control GHG emissions.

Achieving this revolution will require unprecedented—but feasible—coordination among those technologists, data scientists, product designers, and philanthropists leading current and future initiatives in this space. A three-step process could support building this global, integrated system:

1. Converting today’s fragmented initiatives into a diverse information ecosystem
2. Facilitating the development of platforms that apply data and analytics to specific opportunities
3. Integrating the resulting capabilities and resources into an independent global system for climate and energy data tracking and communication

Why Information Matters

Accurate, precise, and timely information about GHG emissions seems like an obvious prerequisite for managing the climate crisis. Yet the sobering reality is that policymakers, corporations, advocates, and citizens lack access to this data today. Improving the transparency, accountability, and actionability of climate and energy data is a sine qua non for rapidly enabling actions that reduce emissions at the individual, corporate, subnational, and national levels. New systems can be put in place in just a few years that would radically improve the timeliness and usefulness of climate and energy data. This, in turn, could set off a revolutionary big bang of innovations in policymaking and voluntary action by corporations and customers to accelerate climate change action.

From seafood to wood products and from textiles to produce, supply chain data and product labels that identify environmentally significant product attributes have driven far-reaching changes in markets, business practices, and societal choices. Yet current climate and energy data systems fall far short of both what is needed and what is possible to meet the urgency of the climate challenge.

EXHIBIT 4

Data-Led Transformation Dashboard

Increasing Transparency of Environmental Attributes

**Investment**

Environmental, social, and governance (ESG) criteria have become the main framework for measuring the sustainability and ethics of investments.

\$31 Trillion
Global sustainable investments
as of April 2019

**Consumer Products**

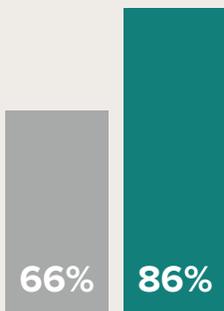
Independent verification of sustainability claims has promoted transparency, consumer confidence, and supplier accountability.

463
Eco-labels

**New Media**

Data and smart devices have transformed the scale of information sharing to connect users in a web of global influence across all facets of society.

4.1 Billion
Global internet users



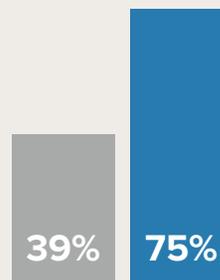
2010 2018

Percentage of asset owners who consider ESG criteria in management decisions



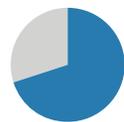
25%

of assets under management are related to ESG.



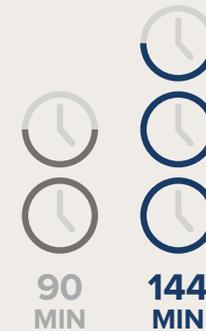
2016 2018

Percentage of consumers who are likely to switch to brands that provide more product information



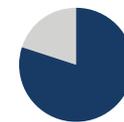
70%

of seafood consumers want more transparency from companies.



2012 2018

Minutes spent daily on social media by the average user



80%

of consumers believe social media has increased accountability for businesses.

Source: Bloomberg, UNPRI, Forbes, Ecolabel Index, Food Marketing Index, Globescan, Smart Insights, GlobalWebIndex, Sprout Social¹²

Gaps and Lags Inhibit Meaningful Action

At the **national and regional levels**, the current system of emissions monitoring, reporting, and verification that underpins the Paris Agreement relies on self-reported national emissions inventories that lag by more than two years. When policymakers, businesses, advocates, and citizens around the world seek data on GHG emissions, they must often rely on outdated, self-reported, government-issued spreadsheets based on negotiated, rudimentary calculation methodologies, leading to sometimes-erroneous conclusions and suboptimal results.

Moreover, transparency can inform decisive **regulatory action**. Bringing greater visibility to emissions could enable dispatchers to design for renewables participation; in China alone, the shift to a marginal cost wholesale market that selects wind and solar could reduce emissions by 0.4 Gt CO₂ per year. In the United States, WattTime has unveiled the carbon intensity of electricity generation at every location and moment on the grid, allowing intelligent end-use applications and storage technologies to optimize their use of grid power.

Among **corporations**, substantial progress is being made to improve the quality and timeliness of goal setting and reporting for GHG emissions. According to CDP, approximately half of the 250 largest emitters, responsible for one-

third of total annual emissions worldwide, have complete GHG emissions reporting. Yet current reporting methods and data remain insufficiently granular and timely to support corporate goal setting and accountability for achieving them. For example, data limitations have slowed progress toward implementing science-based decarbonization targets linked with ambitious corporate goal setting, and toward independent MRV of corporate action aligned with global carbon-mitigation needs.

Experiences with disclosure and reporting in specific countries confirm that this challenge is a common one. Since 2008, at the direction of the government, China's state-owned firms and more than 3,000 nonstate-owned companies have begun reporting sustainability performance. But the accuracy and usefulness of these reports is questionable: according to a 2017 study,¹³ less than 10% of listed companies in China have their sustainability reports externally assured. In India, sustainability issues are also accounted for in corporate reporting. Yet there is a wide gap between requirement and reality: research by the World Business Council for Sustainable Development indicates that 94% of corporate reporting requirements are mandated by regulatory authorities, yet another source suggests that 49% of companies do not provide sustainability reports using internationally recognized benchmarks.¹⁴

Finally, at the level of **consumer products**, the challenges are even greater. Climate-aligned consumer decisions will require detailed information about both the emissions that have already been incurred to produce and transport a product, and the emissions associated with its ongoing use. For example, the accumulated carbon footprint of materials in a newly bought gasoline-fueled car is of the same order of magnitude as the carbon footprint of its lifetime fuel consumption. Moreover, the embodied carbon and the use-related carbon footprints for many products are location-specific. With access to better data, apps on smartphones could read QR codes, determine location-specific GHG footprints for products, and support customer choices.

Data Enables Transformation

Throughout history, leaps in data access have presaged revolutionary changes in social and economic systems. Johannes Gutenberg's invention of the printing press in 1448 sparked a lasting reorientation in European society and religion through the mass production

of books and, consequently, the Protestant reformation. The rise of the internet and online shopping not only revolutionized retailing but fundamentally changed global supply chains and logistics as well. Detailed street maps developed by Google and others around the

world allowed Uber and other transportation network companies to disrupt an entire industry, creating and destroying hundreds of billions of dollars in market value globally. Today, targeted investments in improving the availability and usefulness of climate-related data could

EXHIBIT 5

GHG Emissions Data Leads to Reductions at Each Level of the System

	CURRENT STATE	FUTURE STATE
National Action and Multinational Agreements	<ul style="list-style-type: none"> - Multiyear delays in emission data reporting - Inconsistencies in reporting and disaggregation 	<ul style="list-style-type: none"> - Close to real-time data - Improved accountability
Subnational Action	<ul style="list-style-type: none"> - Limited data to support subnational goals 	<ul style="list-style-type: none"> - Positive rivalry as cities, states, and provinces track progress
Corporate Action	<ul style="list-style-type: none"> - Voluntary standards for reporting are evolving rapidly but not all corporations report - Supply chain issues remain challenging 	<ul style="list-style-type: none"> - Corporate actions and footprints are extremely transparent and timely - "Pull through" from low-carbon supply chains is visible
Consumer Action	<ul style="list-style-type: none"> - Detailed data to support consumer choices is scant - Carbon footprint estimates are largely based on averages 	<ul style="list-style-type: none"> - Carbon footprints of consumer products are transparent - Impact of consumer choices and behavior changes are measurable
Legal Action/Climate Liability	<ul style="list-style-type: none"> - Climate-related legal actions are proliferating, although legal questions persist - Detailed emissions data underpins lawsuits 	<ul style="list-style-type: none"> - Corporations mitigate risks of future liabilities
Device-Level Management	<ul style="list-style-type: none"> - Data sets and control capabilities are emerging to enable device-level management 	<ul style="list-style-type: none"> - Devices manage energy in real time to reduce emissions

fundamentally change awareness and action to mitigate climate change.

Already, the pace of data creation and new modes of access are reshaping societal values, politics, and markets. Whereas Gutenberg first printed the equivalent of 2.34 megabytes in his first 1,300 Bibles, by 2020 the world will produce 463 exabytes per day, a difference of 14 orders of magnitude, with 60% annual growth projected to 2025.¹⁵ From wearable devices to smart automobiles and blockchain platforms for information sharing, the infrastructure that is accelerating the digitalization of the economy can be harnessed to measure and manage GHG emissions. Closing the data loop and learning from successful initiatives can empower actors at all levels to shift the energy system onto a low-carbon trajectory.ⁱⁱ

ⁱⁱ The democratization of data provides transparency and decentralizes the process of value creation across sectors and the world. Better data leads to more robust analysis, better-informed decision-making, more widespread deployment, and ultimately, value creation. Several large-scale sustainability data initiatives, including data.gov, IUDX, and the Global Reporting Initiative, are already underway.

CASE STUDY

Data + People = Action

An app created by the Institute of Public and Environmental Affairs (IPE) in China put location-specific air and water-quality information in the hands of everyday citizens together with information from a real-time database of emissions from 40,000 factories and other sources. Users turned to the social media platform Weibo to call problems to the attention of companies and agencies responsible for enforcing environmental standards. In the first five months of the app's use, citizen complaints led to hundreds of inquiries by environmental protection bureaus and dozens of corrective actions by companies. Now, IPE has activated more than 70 of the largest local and multinational brands to engage with its Green Supply Chain program, in which companies compare their list of suppliers with IPE's list of violators to identify the gaps and make improvements (see Challenge 6).¹⁶

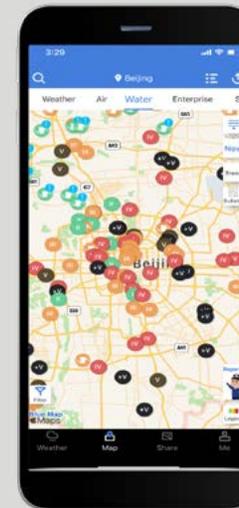
EXHIBIT 6

BlueMap App Empowers Chinese Citizens and Agencies to Hold Businesses Accountable

Localized weather forecasts



Comprehensive map system



Source: RMI, Institute of Public and Environmental Affairs¹⁷

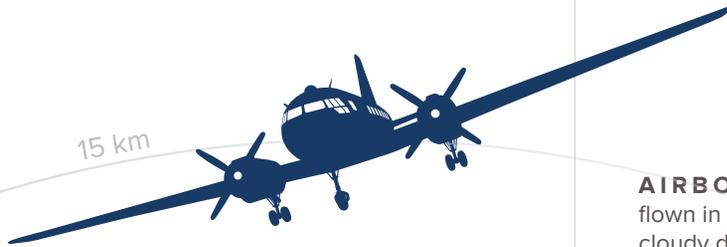
How to Measure Carbon

800 km



SATELLITES can be a powerful and scalable tool that can eventually provide daily global regional GHG emissions data at the facility level; land access permissions are not needed, and airspace restrictions do not apply.

15 km



AIRBORNE SURVEYS can pinpoint GHG emissions sources and can be flown in conditions that are not ideal for satellite missions, such as at night or on cloudy days; land access permissions are not needed.

100 m



STATIONARY MONITORING STATIONS can provide regional GHG atmospheric concentration data and wind speeds to help verify satellite and aerial surveys.

ground level



INTERNET OF THINGS SENSORS can take advantage of existing infrastructure and provide continuous emissions monitoring.



PEDESTRIAN SURVEYS provide highly sensitive and accurate emissions data; these surveys may be added to existing and routine field inspections.



RADIOISOTOPES can be used to track and verify the pedigree of commodity materials and their utilization in final products.

Source: RMI

An Integrated System for GHG Data

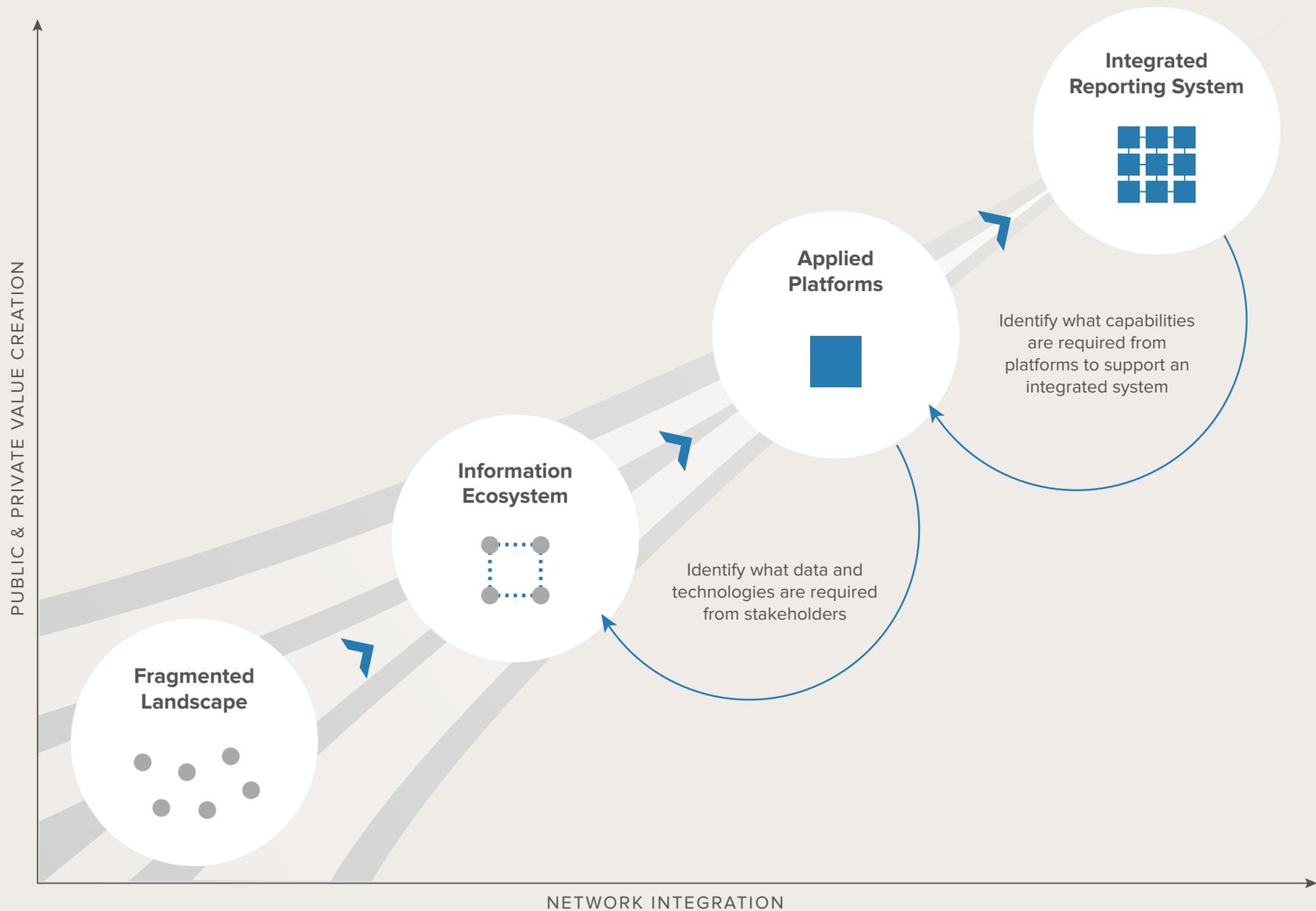
We have the tools today to construct an independent, real-time global GHG monitoring and estimation system that does not depend on government or corporate reporting alone. The combination of satellite and other remote sensing sources has enabled a revolution in measuring and managing carbon emissions that can leapfrog many of today's challenges, such as inaccurate, overly aggregated, and untimely reporting. Satellites are not the only 21st century tool to bring to bear. Ground-based data, atmospheric modeling, and pollution control monitors in some countries can be combined with emerging big data on energy, industry, transportation, and agriculture to produce increasingly accurate and precise information about GHG emissions at each level of the energy system around the world.

The ultimate and urgent prize is an integrated, open-source system capable of generating emissions maps of the world with continuously improved granularity, smaller uncertainty bands, and reduced time lags. Such a system would fundamentally disrupt the nonstandard corporate reporting methods and UNFCCC approach to MRV. It would equip political leaders, citizen activists, businesses, and researchers with a powerful tool worthy of a global campaign to control GHG emissions.

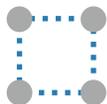
Achieving this revolution will require unprecedented, but feasible, coordination among those technologists, data scientists, product designers, and philanthropists leading current and future initiatives in this space. A three-step process could support building this global, integrated system:

1. Converting today's fragmented initiatives into a diverse information ecosystem
2. Facilitating the development of applied platforms from that ecosystem, and reinforcing it
3. Integrating the resulting capabilities and resources into an independent global system for climate and energy data tracking and communication

Toward a Fully Integrated Ecosystem of Climate and Energy Data



Source: RMI



1. Information Ecosystem:

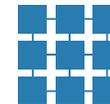
The building blocks of this global system are already in the works, from data sources to databases and data application areas. Connecting their outputs into an information ecosystem can ensure that proliferating data is accessible and applied to new and exciting applications, rather than facing bottlenecks like nonstandard data, rival coders, and special interests. The value of such an information ecosystem resides in its ability to:

- Ensure open access by means of an interoperable database system.
- Spur positive rivalry by ensuring that data is comparable across sectors and national borders.
- Scale utilization by drawing on the diverse expertise of independent software developers to build new applications, some of which might be platforms described in #2, Platform Development.
- Unlock human and financial resources to build mutually reinforcing computing and analytic capabilities.



2. Platform Development:

The ecosystem's multiplicity of data sources and technical capabilities can be channeled to build sector-specific platforms—for example, to track methane produced with near-zero leakage rates, enabling a “clean” natural gas market (see Challenge 6)—for application globally. These platforms draw on varied technologies, data pools, and capabilities (such as blockchain-enabled supply chain tracking), with the potential for platforms to share data. Platforms can address unique needs and opportunities in each sector with different value models while sharing access to data and building capabilities to facilitate integration.



3. Integrated System:

These platforms will enable independent tracking, verification, and analysis of climate and energy data in specific sectors and locations. A global system for corporate and national accountability of climate goals can draw on information generated by these platforms. Individually and in combination, these and other applications can generate global increasing returns to scale from point-source and regional emissions tracking and preferential treatment of low-carbon energy sources and processes. Key questions of value sharing, combining trust with independent data verification, and international coordination will have to be addressed for full systems integration to achieve globally standardized and scalable emissions reporting across public and private sectors.

Global Greenhouse Gas Data Initiatives: Blooming, But Fragmented

FOCUS

□ CH₄

△ CO₂

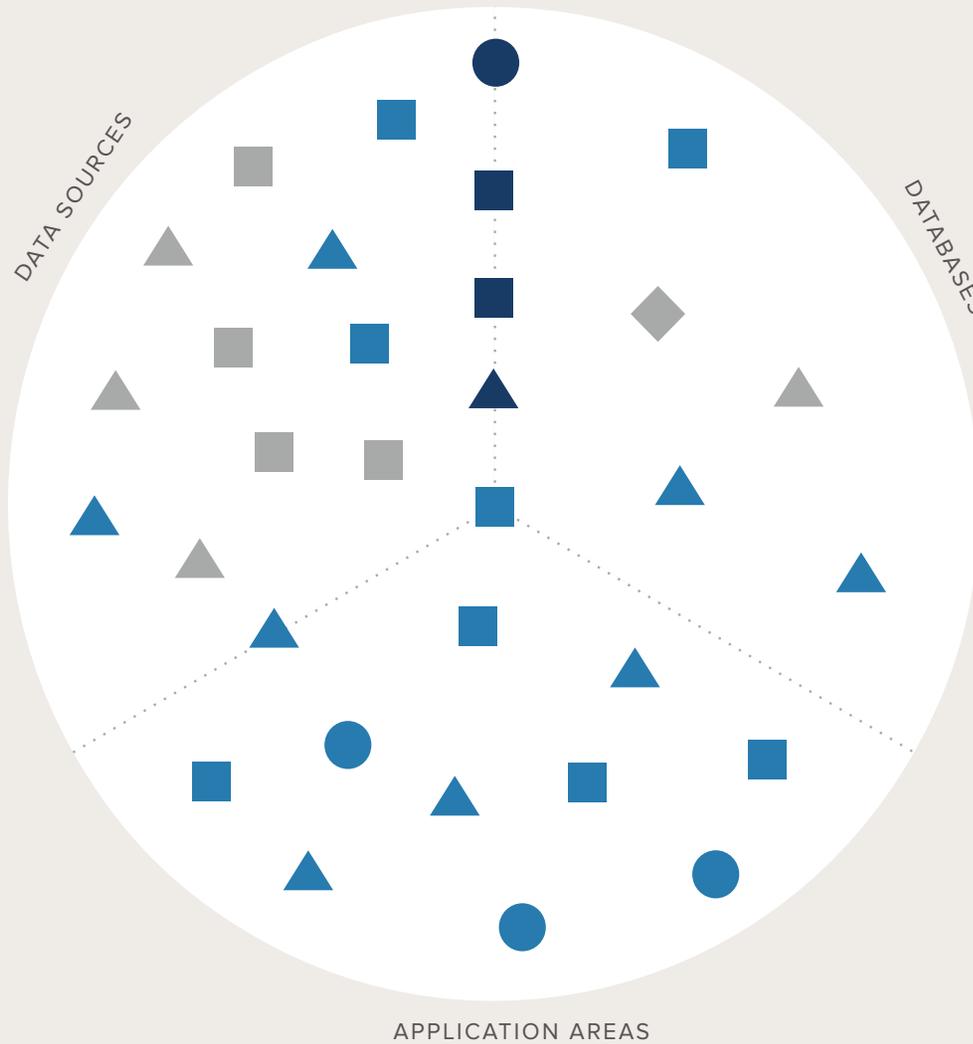
○ Other GHG

SECTOR

● Public

● Private

● Regional



PUBLIC

- ESA Tropomi
- JAXA GOSAT/GOSAT-2
- NASA OCO-2/OCO-3
- China CarbonSAT
- EDF MethaneSAT
- WattTime/CarbonTracker
- Global Forest Watch
- World Bank GGFR
- UN Global Climate Action
- Carbon Disclosure Project
- JPL MegaCities

PRIVATE

- TerraPulse
- GHGSat
- Scientific Aviation
- Planet
- Bluefield Technologies

REGIONAL

- CARB Methane HotSpot + Inventory
- CARB GHG Monitoring Network

Source: RMI

Fit-for-Purpose Platforms Draw on Common Data and Technologies

Technology

Satellite Systems

Terrestrial Monitoring Systems

User-Facing Apps for Integration

Internet of Things

Data

Facility-level Emissions Data

Resource Inventory Data

Weather Forecast Data

Real-time Market Data

Consumer User Trends Data

Application

Clean Gas Certification

- Supply chain tracking
- Gas leak tracking
- Reduced flaring

Low-Carbon Material Procurement

- Supply chain tracking
- Certificate of origin
- Material impact index

Resilient Low-Carbon Urban Grids

- Managing demand/supply of electricity
- Optimizing grid energy supply
- Predictive weather management

Potential

6 GtCO₂e/yr (using 20y GWP of 84)

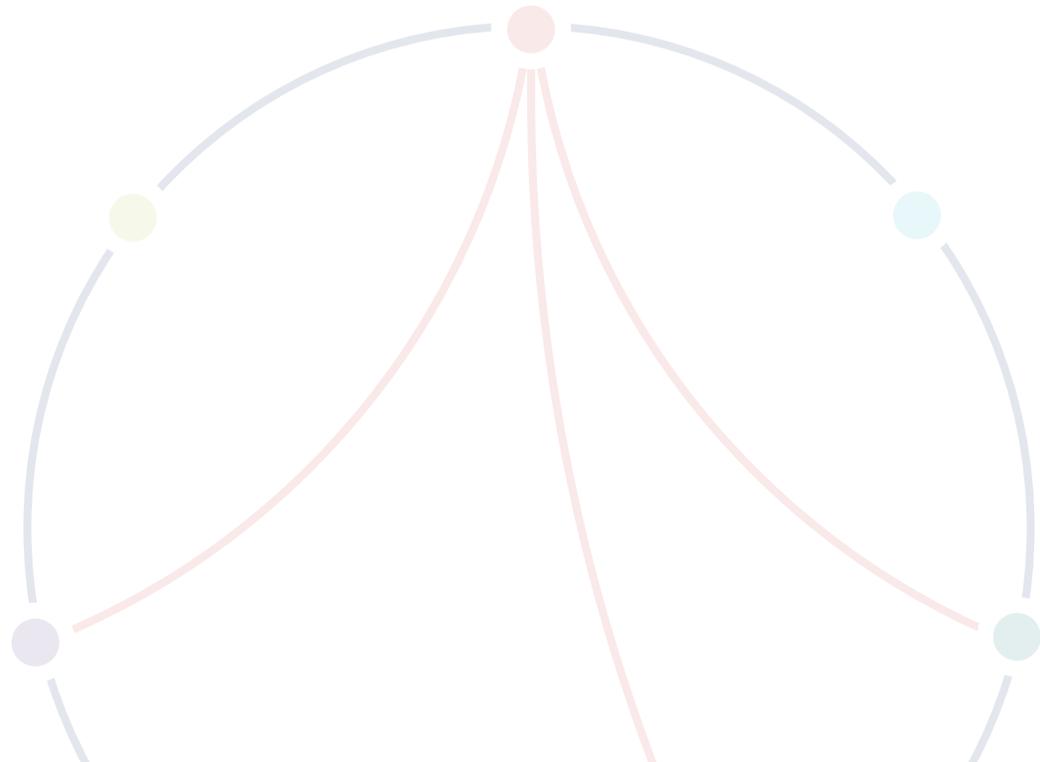
20%–40% steel emissions abatement by tracking “green circular” steel

\$20–\$70 billion in annual avoided costs in the United States

Source: RMI, Wall Street Journal, DOE¹⁸

Opportunities to Make Emissions Visible

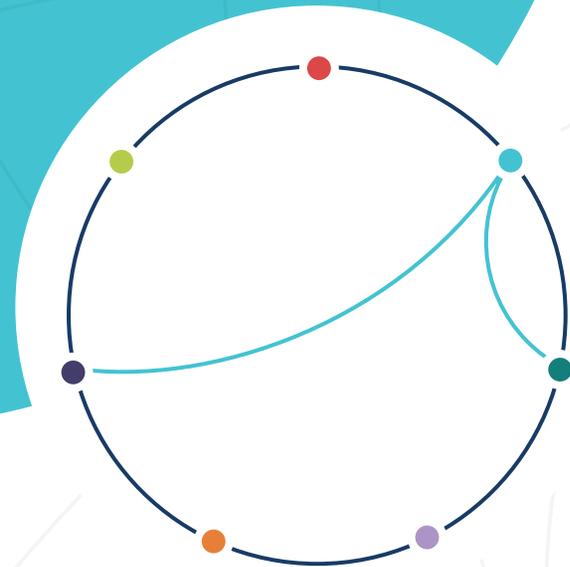
- What are the implications of dramatic advances in transparency around the operation and construction of carbon-intensive assets for corporate behavior in the context of rapidly growing consumer and investor awareness?
- What must be true for the current landscape of reporting efforts to monitor, verify, and amplify corporate climate commitments to leverage data from other measurement sources?
- How can technical, policy, and energy technoeconomic experts collaborate to identify leverage points for transparent data in energy and climate decision-making?
- What opportunities exist to coordinate development efforts and integrate underlying technology systems for mutual benefit of different data applications?



2

Tripling Energy Productivity Gains

How can we replicate what's working at scale, improve design of new buildings and infrastructure, and increase turnover of inefficient assets?



Tripling Energy Productivity Gains

To meet the most cost-effective scenarios to achieve well below 2°C in global average temperature rise, we need to at least triple the pace of energy productivity improvement globally in the next decade compared to the average 2011–2018 pace. Improving energy productivity is the most powerful climate solution we have and the only reason we are still below a 2°C average temperature increase today. Energy productivity advances health, development, and security and can save trillions of dollars' worth of supply and carbon-removal investments.

Wringing more work from less energy is a bigger energy “source” than oil. **It delivered three-fourths of the decarbonization of global energy from 2010 to 2016.** Yet it is also the least visible of our clean energy resources and therefore is sometimes overlooked. We see five main avenues to leapfrog energy productivity gains to new levels in the next decade:

1. **Buy the cheapest resource.** Rigorous energy system analyses for China and the United States—the two biggest CO₂-emitting economies—reveal multitrillion dollar net savings from more than tripling efficiency gains to 2050. The savings accrue to businesses, residents, and even to utility companies if incentives are put in place to level the playing field for competing resource options.
2. **Rapidly scale what works today.** A huge portfolio of established and emerging methods can harvest this resource across all sectors, building on proven policy instruments, business models, financing mechanisms, and advancing technology. Most methods can be market winners if allowed to compete fairly.
3. **Electrify end uses in transport, buildings, and industry.** Electrification presents a major opportunity to gain momentum; electrified solutions often are inherently more efficient, and the redesign required creates an opportunity to build more efficiency in at the beginning. Technologies to support electrification are at or near critical tipping points in several critical areas, including transportation.
4. **Design for efficiency.** “Integrative design” of buildings, vehicles, equipment, and factories as whole systems for multiple benefits can make energy savings severalfold bigger and less costly. It is starting to be adopted in passive and zero energy buildings but is rarely applied in vehicles and industry, is seldom taught, and is scarcely recognized. Some major opportunities are missing altogether from standard textbooks, models, studies, forecasts, and business plans.
5. **Accelerate asset turnover with retrofits and scrapping.** Fixing or scrapping inefficient devices is as important as adding new, efficient ones. Combining both methods can dramatically speed savings. Coordinate deep retrofits with major improvements that are already being made, and focus design leapfrogs on developing countries that are building massive infrastructure now, to avoid retrofits later.

Energy Productivity Is Critical to a Successful Energy Transition

Energy productivity is the single most important variable in models of climate consequences and choices—even more important than economic growth. Energy intensity improvements have nearly doubled from 1.3% per year during the previous three decades to 2.1% per year in this decade, and 2.9% per year in 2015. This means that **energy savings have more than doubled the world's gross domestic product (GDP) per unit of energy since 1984**. Cumulatively, US energy savings since 1975 account for 30 times the additions of renewables (see Exhibit 11), making efficiency the most prevalent, cost-effective, and underrated resource at our disposal.

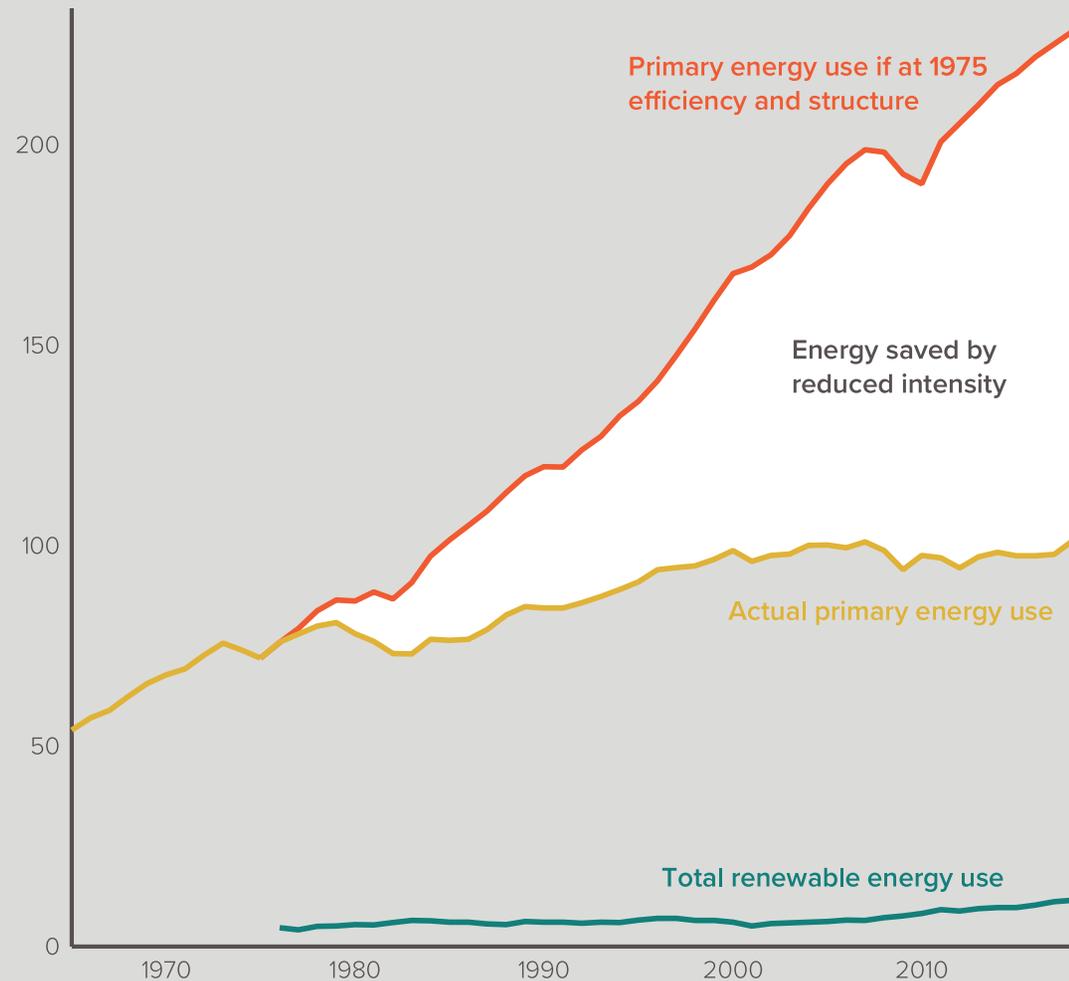
Energy Productivity vs. Energy Intensity

Energy productivity is a simple, intuitive measure of global efficiency performance calculated as GDP per unit of energy input. Energy intensity (total primary energy per unit GDP), the inverse of energy productivity, has historically been the metric of choice and has been used here to align with historical trends. Given the fixed energy and carbon budget we have across different climate change scenarios, the question should not be how much energy is required for a unit of economic development (intensity metric), but rather how can we maximize the productivity of every unit of energy put into the system. Hence, the framing of this challenge in terms of productivity.

EXHIBIT 11

Relative Importance of US Energy Savings and Renewables, 1975–2018

US Primary energy use (Quadrillion BTU/y)



1975–2018 cumulative savings from intensity reduction: 2,589 qBTU

1975–2018 cumulative growth in total renewable output: 87 qBTU

Source: RMI, EIA¹⁹

The power of increasing productivity is illustrated by scenarios in the Intergovernmental Panel on Climate Change's November 2018 1.5°C report (see Exhibit 12). The Low Energy Demand Scenario (LED) shows the impact of doubled energy productivity in the period from now until 2050. Its supply-side costs drop approximately two to three times relative to Pathway 4, which assumes smaller increases in energy productivity. Moreover, it avoids costly investments in carbon capture and sequestration (CCS) that are required in the other scenarios to meet the 1.5°C goal.

EXHIBIT 12

Global Energy Scenarios to Achieve 1.5°CCO₂ emissions and capture (Gt CO₂)

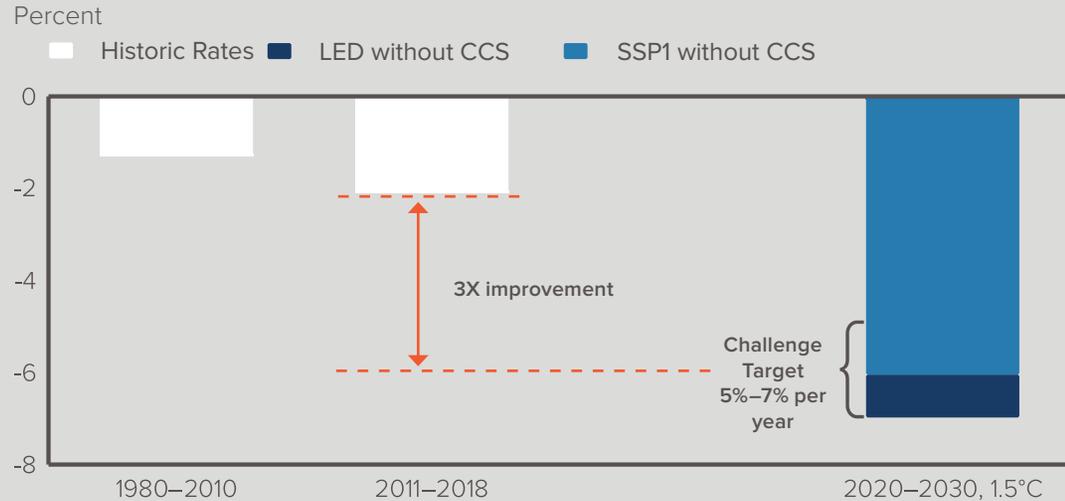
CO₂ emissions from fossil fuel-burning and industrial processes are in white. Emissions or reabsorption by agriculture, forestry, and land use (AFOLU) are orange. Carbon removal by growing and burning biomass to generate electricity while capturing and sequestering the carbon (BECCS) is yellow. The Shared Socioeconomic Pathways (SSPs) are scenarios that will be used in analyses for the next Intergovernmental Panel on Climate Change (IPCC) Assessment Report, scheduled to be released in 2021. SSP5 is characterized by energy-intensive economic development that relies heavily on fossil fuels, whereas SSP2 follows historic patterns of growth, and SSP1 achieves comparatively lower energy intensity and a more sustainable pathway for growth. The Low Energy Demand (LED) scenario is driven by changes in end-use technologies and user behavior that achieve half the energy demand of SSP5, without relying on engineered negative emissions technologies.

Source: RMI, IPCC²⁰

But is such fast and sustained growth in energy productivity achievable? **The sustained rate of productivity improvement needed to achieve the Low Energy Demand scenario is approximately three times the 2011–2018 average pace.** Exhibit 13 shows historic rates of intensity improvement and what is needed to stay well below 2°C of warming. Although tripling the rate of productivity improvement in the next decade is ambitious, waiting until later would make it nearly impossible to achieve the well below 2°C goal without heavy use of costly carbon capture and storage. Exhibit 14 illustrates the underlying reality that the later we start, the steeper the required increases in the rate of energy productivity gain needed. Because the grid is more carbon intensive in the early years, productivity gains now are worth more than those that come later in terms of avoided carbon emissions.

EXHIBIT 13

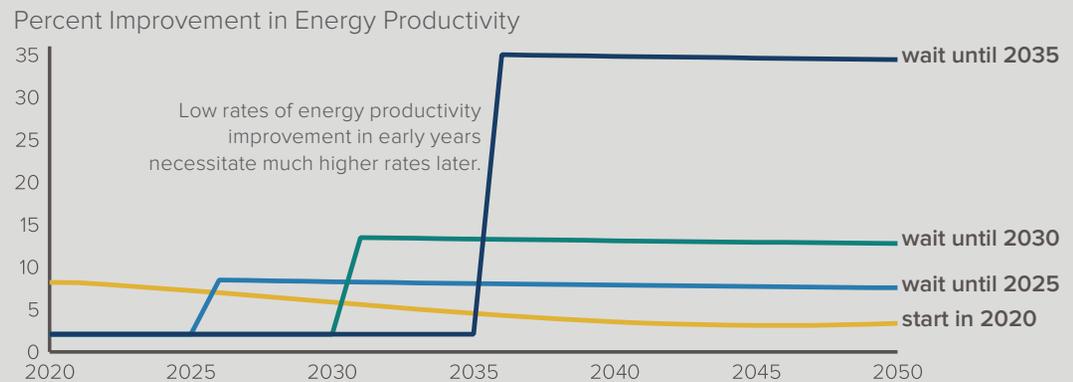
Challenge 2 Target: Triple Intensity Improvements to Achieve Well Below 2°C
Historical, Modeled, and Target Energy Intensity Improvements



Source: RMI, Nature Climate Change, Nature Energy²¹

EXHIBIT 14

Save Now or Pay Later: Productivity Gains in the Next Decade Are Critical



RMI, Nature Energy²²

Achieving the Productivity Potential

Although this goal may seem dauntingly ambitious, a combination of approaches can be used to achieve it, taking advantage of favorable global trends in technology, public awareness, access to finance, and energy policy tools. We see five high-leverage points to intervene to boost productivity gains that cut across multiple sectors or energy use.

1. Buy the cheapest resource.

Careful studies at the level of households, businesses, cities, and entire energy systems show that the energy productivity resource is often the most abundant and cost-effective energy resource based on life-cycle costs of operation. Removing obstacles can unlock these savings.

Clear and consistent incentives. California's strong and consistent energy policies and regulatory incentives created an ecosystem of service providers delivering efficiency services and saved residents and businesses more than \$65 billion over the past several decades.²³ In China, strong leadership, clear objectives, and a dynamic market for energy service companies (ESCOs) have helped to deliver energy intensity reductions. From 2010 to 2016, China's GDP grew by 8.1% per year, and energy intensity fell by 25%.

Integrated resource plans (IRPs). IRPs give regulators and policymakers visibility into the value of energy efficiency investments and the trade-offs with supply-side investments. They are increasingly widely applied globally, and where they are used, they help advance planning and procurement for energy productivity investment.

Electric utilities. Creating a level playing field for competition between supply and demand-side resources through regulatory incentives and utility business model reforms can yield large energy and cost savings. Efficiency and demand response can often outcompete new supply and grid investments, whether on a stand-alone basis or integrated into clean energy portfolios (see Challenge 3). In the United States, utility energy efficiency programs delivered 30 million megawatt hours of energy savings in 2017 at a cost of just 2 cents per kilowatt hour and saved 12,000 megawatts in peak demand.

Transportation. Electric vehicles (EVs) can outcompete internal combustion drivetrains for some applications today and many more in the near future. Shifting to a mobility services model will speed the uptake of electric vehicles because companies providing mobility services can see the total cost of operation advantage of EVs more immediately.

Performance standards and labels.

Efficiency standards, ratings, and labels for everything from buildings and motors to refrigerators and computers support decision makers at all levels to opt for low-carbon choices (see Challenge 1).

2. Rapidly scale what works today.

A deep and diverse set of proven tools exists for increasing energy productivity, especially in the buildings sector.

Improving buildings at scale. Buildings consume 40% of the world's energy and 70% of its electricity. Looking ahead, with at least 2 billion people expected to move to cities by 2050, mostly in emerging market countries, the efficiency opportunity in new building construction is massive, both in terms of embodied energy (steel, concrete, and other carbon-intensive materials) and future energy use.²⁴ Net-zero energy designs are cost-effective today with existing technologies in many areas and can become the standard for new buildings and entire districts. Retrofitting existing buildings for deep energy savings and electrifying end uses can be cost-effective with well-timed investments in the building's life cycle. Innovations like the Energiesprong model pioneered in the Netherlands (and now applied in the United States under the

REALIZE program) are critical to achieve the pace and scale we need. Moreover, advanced tools for assessing building energy retrofit opportunities in large portfolios of buildings, such as RMI's Portfolio Energy Optimization tool, allow rapid and efficient scaling of retrofit investments.

Performance prizes and demand aggregation. Performance prizes and demand aggregation can help to pull new technologies into the market faster and drive down costs with large-scale manufacturing (see Challenge 5). The Global Cooling Prize and India's Energy Efficiency Services Limited (EESL) are examples of these approaches.

Performance standards. Performance standards for products ranging from lightbulbs to appliances to vehicles have been demonstrated to deliver billions of dollars in savings for customers in addition to local and global environmental benefits.

Financing and ESCOs. New financing methods to help homeowners and small businesses manage the up-front costs are helping boost adoption rates for energy efficient technology globally. In China, ESCOs have gained market acceptance and financial support in alignment with government policies and goals and are providing services to a widening range of customer types.

CASE STUDY

Performance Prizes and Demand Aggregation: Leveraging Efficient Technology

The **Global Cooling Prize** (GCP) has the potential to mitigate 0.5°C in global warming by 2100 by bringing to mass markets a residential cooling technology that has five times less climate impact and uses four to five times less energy than today's equipment. GCP is led by a coalition of global partners (including RMI) that engage industry and markets to identify and scale a solution and will award at least \$3 million in prize money to the top-performing technologies from among 139 applicants from 31 countries. About 4.5 billion room air conditioner units will be in use globally by 2050, compared to 1.2 billion today.

Energy Efficiency Services Limited (EESL) is a public-sector joint venture created by India's government to enable consumers, industries, and governments to effectively manage their energy needs through access to energy efficient technologies. EESL is implementing the world's largest nonsubsidized energy efficiency portfolio across lighting, buildings, e-mobility, smart metering, and agriculture at a scale that no organization has been able to achieve. EESL focuses on solution-driven innovation with no subsidy or capital expenditure. It uses its Pay-As-You-Save model to obviate the need for any up-front capital investment by the consumer. EESL has distributed over 360 million LED lightbulbs as part of its lighting efficiency offerings.



Credit: iStock

3. Electrify end uses in transport, buildings, and industry.

The switch to electricity use typically entails significant gains in efficiency because conversion losses associated with coal, oil, and gas are avoided altogether. Some examples prove the point:

- For passenger cars, electric motors require less than one-quarter the energy used by internal combustion engine vehicles for every kilometer driven.
- In buildings, air- and ground-source heat pumps require between one-fifth and one-half as much energy as that used by on-site gas boilers.
- In some industrial systems, replacing long, thin, crooked pipes and ducts with fat, short, straight ones can cut pump and fan energy (together about half of motor energy) by approximately 80%–90%.

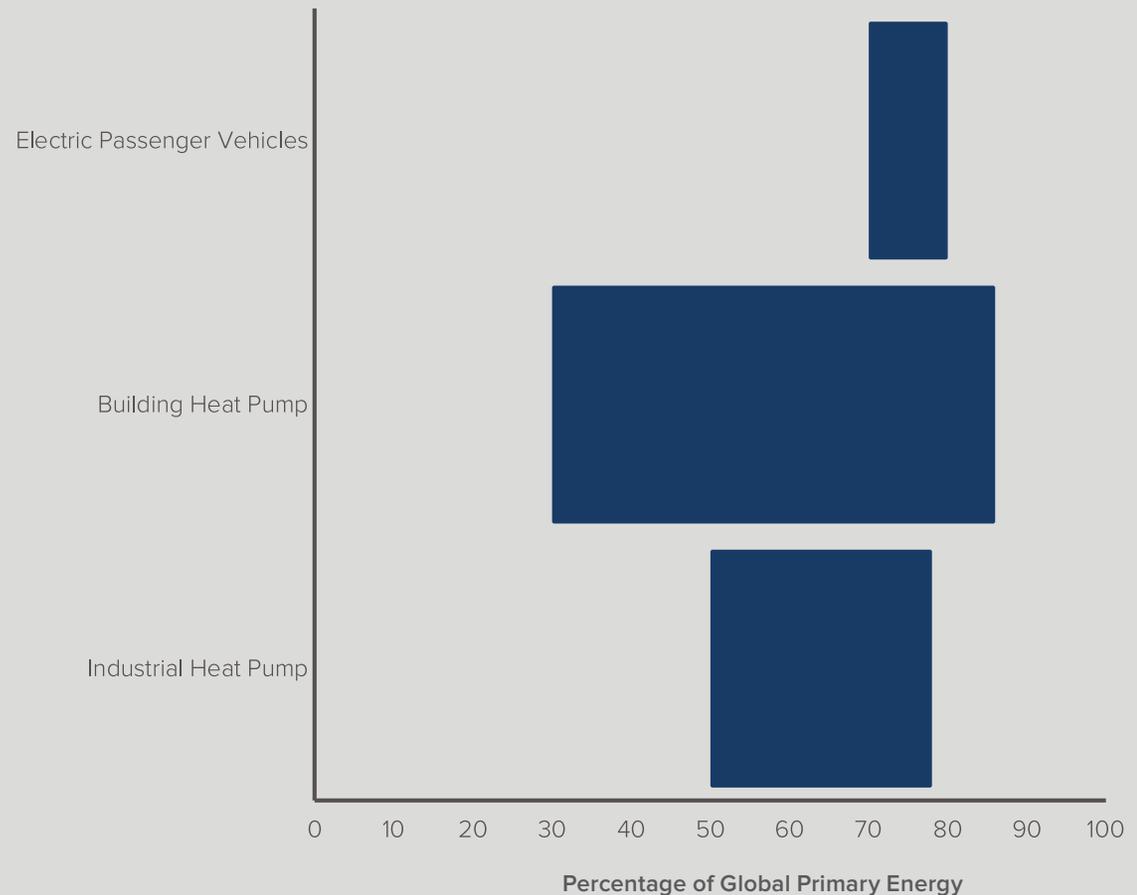
4. Design for efficiency.

“Integrative design” of buildings, vehicles, equipment, and factories as whole systems for multiple benefits can increase energy savings and reduce costs. It is a starting point for designing passive and net zero buildings, but it is rarely applied in vehicles and industry, seldom taught, and scarcely recognized. Exhibit 16 illustrates efficiency gains that have been demonstrated in dozens of projects

EXHIBIT 15

Efficiency Gains from Electrification

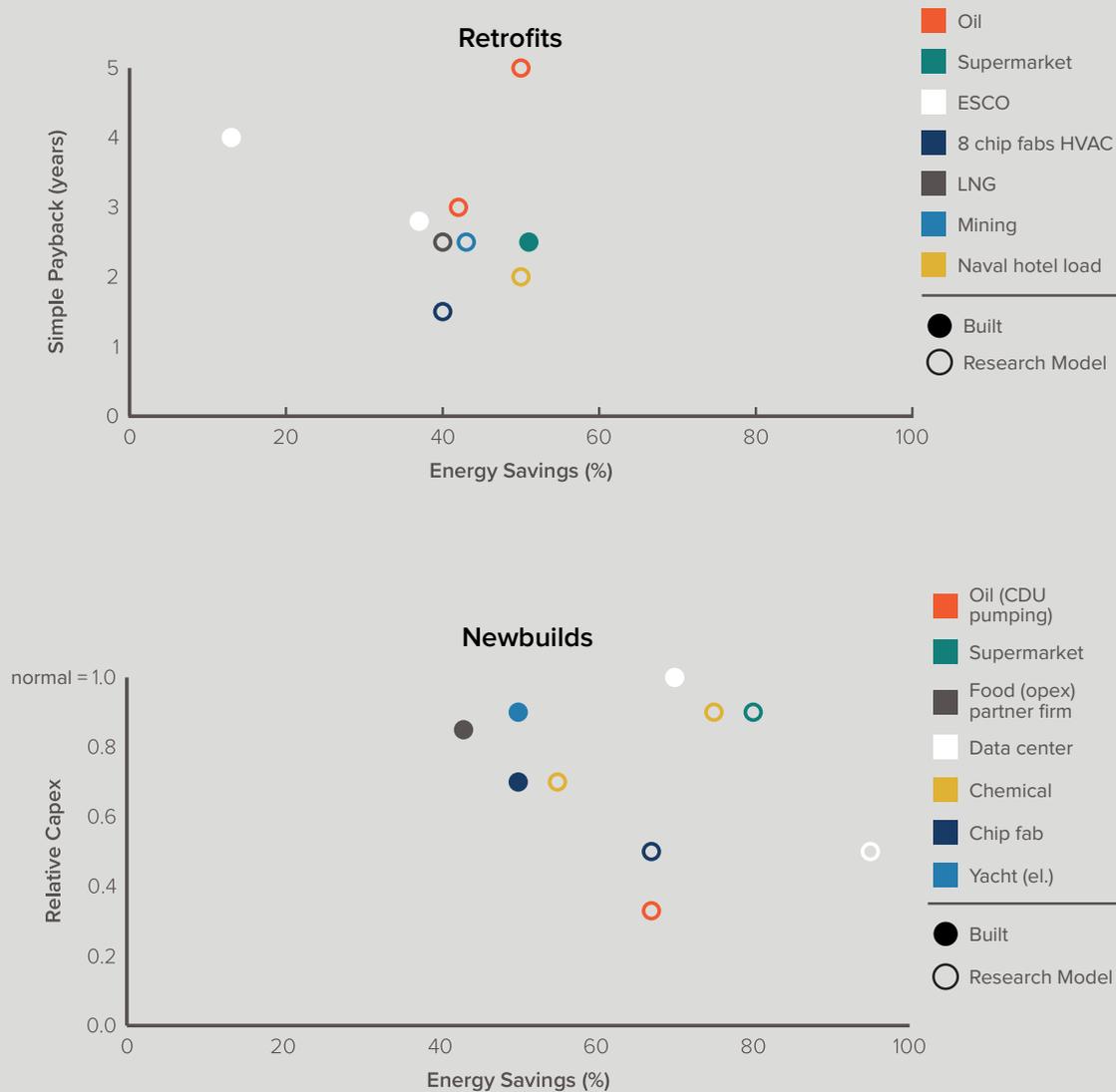
Energy savings potential from electrification by end use



Source: RMI

EXHIBIT 16

Leapfrog Efficiency Gains from Integrative Design



Source: RMI

across diverse sectors from integrative design approaches. Bringing integrative design principles into more widespread use in the next decade is a formidable challenge, but perhaps one comparable to the rapid expansion of Six Sigma techniques and tools in the 1990s.

Applying integrative design to new infrastructure and building construction in rapidly urbanizing countries, could significantly reduce the use of carbon-intensive materials such as steel and concrete (see Challenge 7).

5. Accelerate asset turnover with retrofits and scrapping.

Another strong accelerator is to retrofit, idle, or scrap inefficient devices that drag down the average efficiency of the fleet of equipment in service in various sectors. This is important everywhere, but especially in wealthy countries where there are large pools of inefficient equipment (see Challenge 6). For example, in Organisation for Economic Co-operation and Development (OECD) countries, average gains of 5% in new energy equipment raise the fleet average efficiency by only about 2% per year because of the pool of old, inefficient equipment lingering in service.²⁵ Incentives to retire or replace old, inefficient equipment—like the famous Cash for Clunkers program in the United States that provided incentives to retire older cars during the financial crisis—can help to reduce the long-term carbon shadow of inefficient assets.

Opportunities to Triple Energy Productivity Gains

- How can diverse actors speed and expand energy efficiency by making it as vivid and tangible as clean energy supply, even though energy is invisible and the energy you don't use is almost unimaginable?
 - How can analysts and policymakers ensure that the efficiency resource is assessed with the same level of detail and rigor applied to supply resources so that efficiency's now-obscured contributions to climate protection and other goals become clear and available?
 - What misconceptions and mythologies that keep efficiency suppressed or neglected must be reexamined and challenged?
 - What must happen for accelerated scrappage and deep retrofit of major energy efficient capital stocks to become as routine as their slow turnover and replacement?
 - How can developing countries leapfrog over conventionally inefficient design in building new cities and infrastructure?
 - What would it take to shift integrative design in all sectors from rare to common?
- 

3

Electrifying with Renewables

How can we more rapidly expand renewable power supply and increase electricity's share of global energy use?



Electrifying with Renewables

Electrification with renewable power is one of the most important leverage points to rapidly transform the global energy system. We can limit global average temperature rise to well below 2°C if we can **electrify 40%–50% of energy end use by 2040 while increasing the share of electricity generation from renewables to 75%–85%**. With known technologies deployed at conservative expected costs, this could be achieved while generating net benefits of \$65 trillion to \$160 trillion until 2050.²⁶

Replacing proposed fossil fuel-based generation with **clean energy portfolios** that combine wind, solar, storage, and demand management is already emerging as a cost-saving option, and the economic advantage for clean energy will continue to improve. But market, regulatory, and other challenges present obstacles to rapid renewables development in many markets globally.

Regulators and policymakers can ensure cost-effective renewables are implemented by:

- Taking advantage of **competitive wholesale power market mechanisms**.
- Employing **transparent, all-source procurement practices** that include demand-side resources to meet resource adequacy and flexibility needs.
- Looking ahead to the future need for **long-duration, low-carbon flexibility resources** and prioritizing market development of and research into storage, demand, or clean fuels that can mitigate day- to seasonal-scale renewables variability.ⁱⁱⁱ

Electrification of greater shares of energy end use can be achieved by electrifying mobility, buildings, and some industrial applications. In almost all these cases, electrification yields significant efficiency gains. In buildings and transportation, electrification options are at or near the economic tipping points that could trigger rapid growth but need an additional push from policymakers and regulators to achieve the necessary market transformations in these sectors.

How Far and How Fast?

Keeping global average temperature increase to well below 2°C depends critically on:

- Making a fast transition to increased use of electricity in overall energy use.
- Increasing the share of renewable power in electricity supply.

How far and how fast these transitions need to take place varies under alternative energy scenario assumptions, as illustrated in Exhibit 17. Based on the results of RMI's integrated energy system modeling at the national level and modeling of global energy system pathways to achieve less than 2°C, RMI has set **2040 challenge target ranges for electricity generation from renewables and electricity as a share of final energy at 75%–85% and 40%–50%, respectively²⁷ (see Exhibit 17)**. This requires an annual compound growth of 4% in electrification, compared with 1.2% growth historically, and it requires 7% of growth in renewables generation, compared with 4.8% growth historically.^{iv}

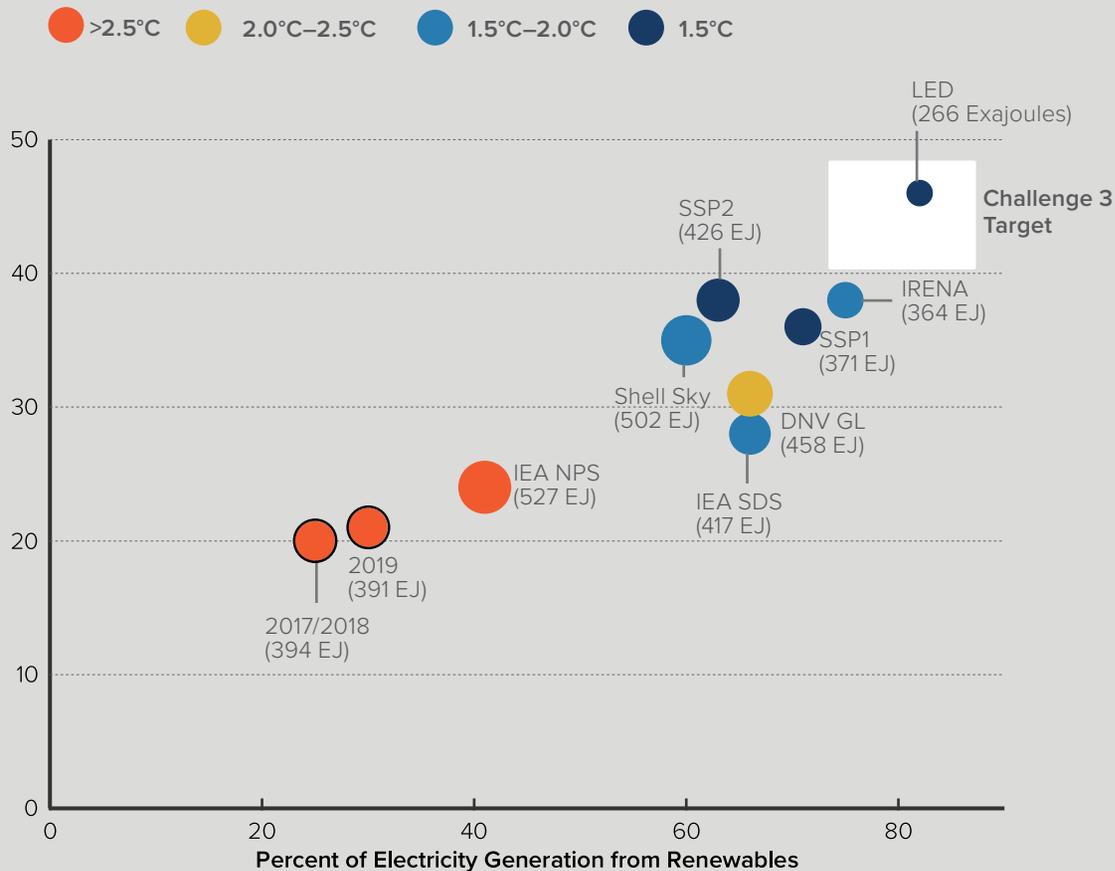
ⁱⁱⁱ Policy-mandated renewable requirements have been proven to be effective and should be extended and expanded. This paper focuses on market-based interventions that are complementary to such actions.

^{iv} Historical estimates are based on the International Energy Agency's *World Energy Outlook 2018* compound annual growth rates from 2000 to 2017. Required future rates are calculated from the challenge targets.

EXHIBIT 17

Electrification with Renewable Power: How Far and How Fast to Stay Below 2°C?[∨]

Percent Electrification of Final Energy Demand

Source: RMI, Nature Climate Change, Nature Energy, DNV GL, Shell, IEA²⁸

[∨] All scenarios are for the year 2040; the 2017–2018 data point represents actual data. The size of each circle is proportional to final energy demand, real or projected.

Recent progress toward these benchmarks is uneven across different geographies. In general, however, **renewable electricity supply** is rapidly gaining momentum globally, because of its competitiveness relative to conventional generation. Achieving 2040 targets would require a much more rapid pace of renewable deployment, but the economics at the margin and projected renewable cost reductions are largely working in favor of such an increase in many geographies.

The rate of **electrification** across buildings, transportation, and industry, however, is badly off the pace needed to achieve 2030 or 2040 goals on a pathway to less than 2°C, and the challenges of getting on track to reach the target are formidable. Coordinated efforts are needed to accelerate the pace of electrification in buildings and transportation.

Renewable Electricity Supply: Running Downhill, But Not Fast Enough

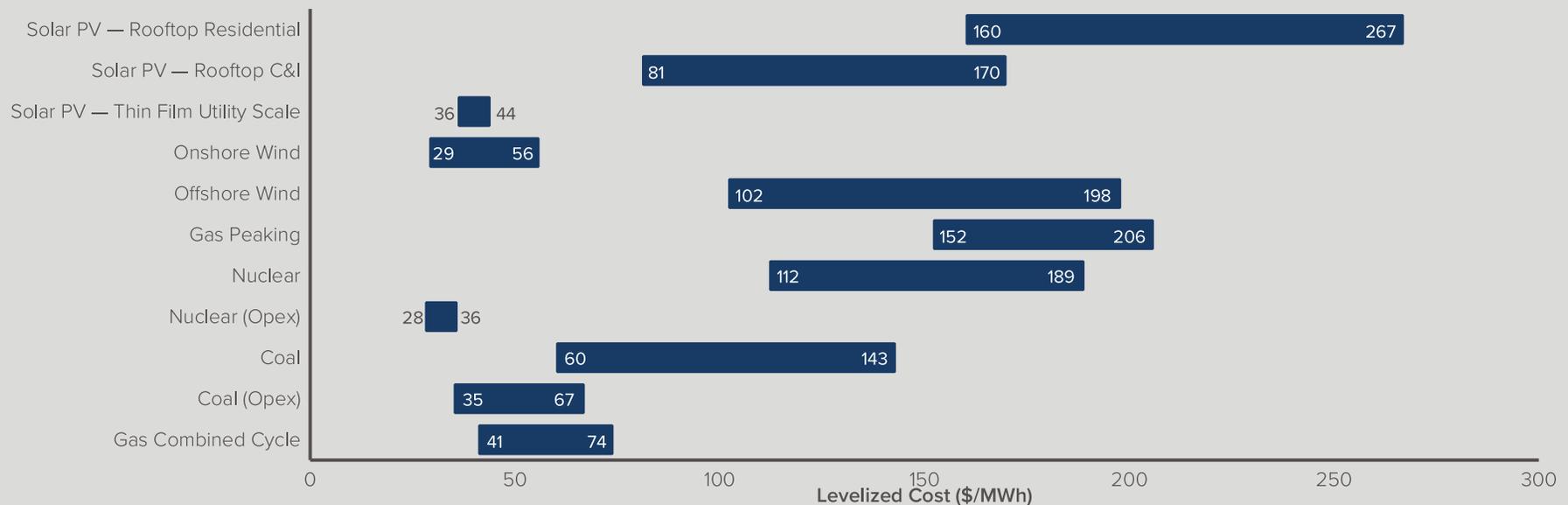
With the precipitous declines in the cost of renewable energy technologies over the past 10 years, new wind and solar projects can be built for less than the cost of operating existing fossil-fired power plants throughout much of the world (see Exhibit 18). From 2008 to 2019, benchmark prices for unsubsidized wind and

utility-scale solar photovoltaic (PV) fell by 69% and 88% respectively.²⁹ Further cost declines are anticipated for these resources, as well as for flexibility resources, including demand management and battery storage that support renewables integration.

EXHIBIT 18

Renewable Energy Project Costs Undercut New-Build and Existing Fossil Generation Costs at US Average Prices

2018 Levelized Cost (\$/MWh)



Note: Recent bid prices for renewables are significantly lower than these 2018 average benchmarks in many markets. It's important to note that nonrenewable costs are subsidized, while the renewable costs shown are unsubsidized.

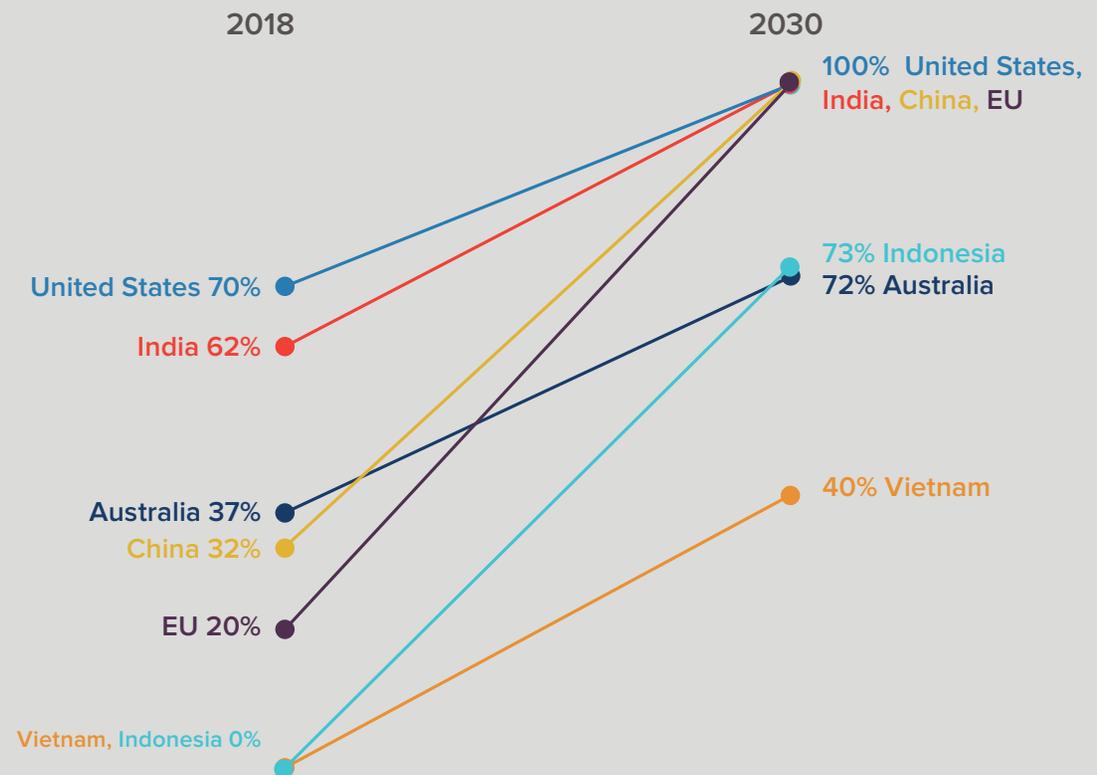
Source: RMI, Lazard³⁰

Given the price declines for wind and solar, a significant share of existing coal-fired plants in countries around the world are increasingly uncompetitive against renewables, even on a marginal operating cost basis. In the **United States**, an estimated 74% of coal-fired generating capacity costs more to operate than building new wind or solar projects nearby, based on 2019 benchmark pricing inclusive of tax credits.³¹ US solar PV costs are expected to decline further, by 24%–46%, between now and 2030.³² We estimate that 85% of operating US coal capacity could be outcompeted by unsubsidized renewables by 2025. From a global perspective, the United States is only one of many countries that have over 80% of coal capacity that is expected to cost more than renewables projects by 2030 (Exhibit 19). That said, in some countries, such as **China**, renewables today remain more expensive than fossil fuels and are more expensive than they should be, given global benchmarks. A sustained focus on identifying country-specific cost drivers and reduction strategies, similar to the US Department of Energy’s SunShot Initiative, is critical.

EXHIBIT 19

Renewables Make Coal-Fired Generation Uneconomic in Most of the World by 2030

Percentage of operating and under-construction coal capacity with higher long-run operating cost than renewables in 2018 and 2030



Note: Based on country averages

Source: Carbon Tracker³³

The Challenge to Natural Gas in the Power Sector

Can an increasingly renewable electricity system deliver the same standard of reliability, resilience, and flexibility that the current grid does? Experience is proving that *clean energy portfolios* consisting of renewables, batteries, energy efficiency investments, and intelligent demand-side resources can deliver the

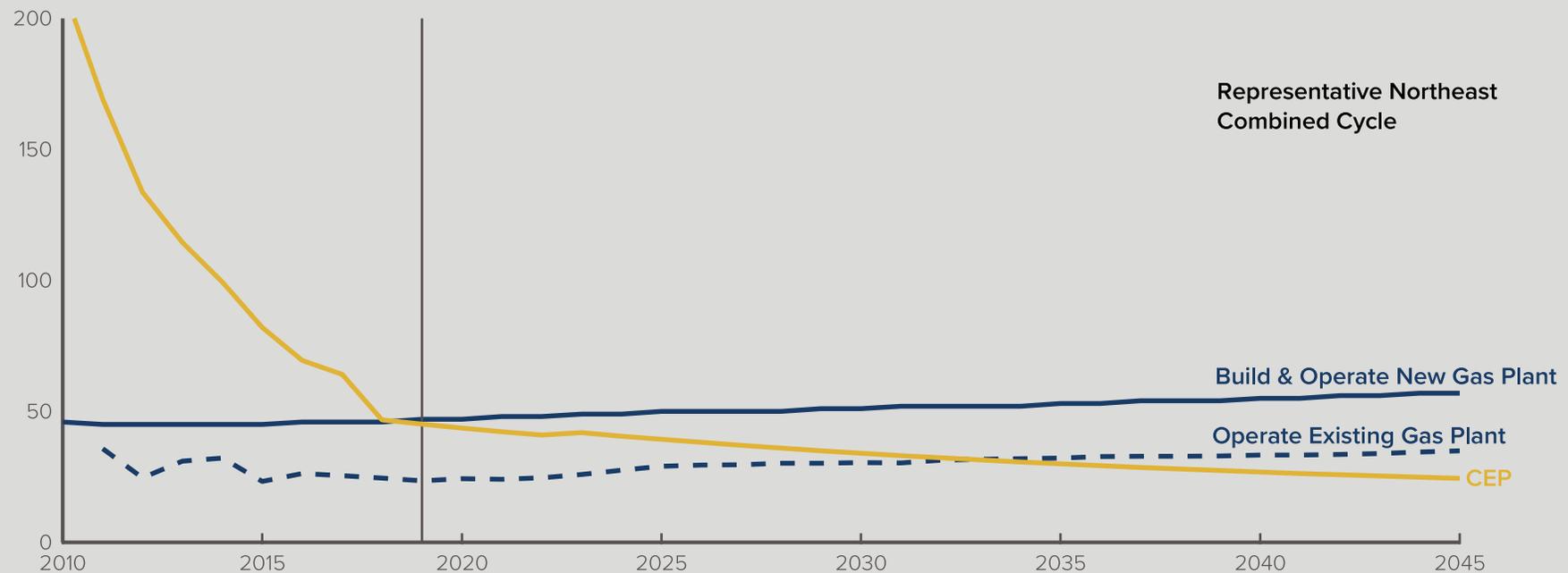
flexibility needed to match the performance of conventional power plants. In a 2019 study, RMI found that 90% of new gas-fired power plants proposed for construction in the United States could be cost-effectively replaced with clean energy portfolios capable of delivering the same levels of energy, peak supply, and

ramping that the gas plants would deliver.³⁴ If some of these plants are constructed anyway, clean energy portfolios could undercut the go-forward operating costs of 90% of them by 2035 (Exhibit 20).

EXHIBIT 20

Clean Energy Portfolios Outcompete Gas-Fired Generation (US Example)

Cost of Electricity, \$/MWh (2019 real \$)



Source: RMI³⁵

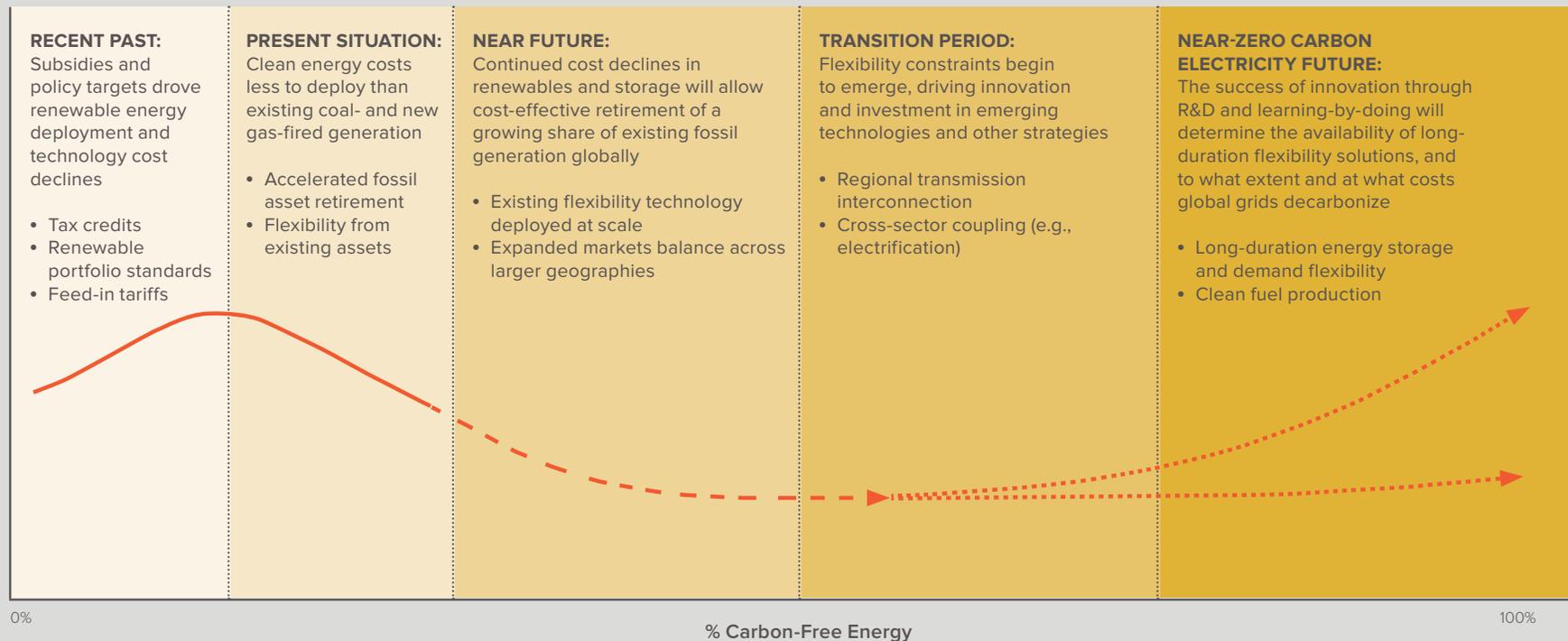
Although the competitiveness of renewables and the readiness of grid operators to integrate these resources into electricity systems vary widely around the world, many countries and regions will be able to cost-effectively increase the share of renewables over the next decade by avoiding new and/or displacing existing fossil fuel-based generation. Broadly speaking, by adding renewables, these systems can

“run downhill” toward lower costs, even when considering transition costs. Eventually, as renewable shares rise toward 80%–100%, needs for long-duration energy storage and other solutions to meet seasonal fluctuations and unusual weather conditions will likely lead to rising costs so that variability can be managed (Exhibit 21).

EXHIBIT 21

Investment Required to Increase Renewables' Share in Power Systems en Route to a Zero-Carbon Electricity Future

Cost



0%

% Carbon-Free Energy

100%

Source: RMI

From a global perspective, we see three pathways for action to drive renewables' share of electricity supply in the next decade:

1. Implement competitive electricity markets more widely and improve their efficacy.
2. Shift utility business models and procurement practices.
3. Enhance planning and finance mechanisms (Exhibit 22).

These actions will support the ongoing evolution of markets and enable them to take full advantage of low-cost renewables while

ensuring that grid operators will be able to manage flexibility and integrate distributed energy resources. Today, countries that rely on competitive markets to maintain efficient system operations in the short term—through bilateral physical contracts, power exchanges, or coordinated spot markets—account for 54% of global electricity consumption. As China and India complete implementation of their power sector reforms, this share may increase to more than 80%. Right now, the application of least-cost dispatch principles in China could save 0.4 Gt CO₂ emissions per year by shifting supply from coal to solar and wind.

Global sharing of best practices in electricity market design can be an essential enabler of the clean and flexible electricity systems of the future. Existing markets were largely designed in a centralized-resource paradigm, so they are not yet fully effective at integrating cost-effective distributed and customer-sited resources such as energy efficiency, demand response, demand-side management, and clean energy portfolios. Further, markets can be modified and developed specifically to incentivize adequate capacity at peak times and innovation in long-duration flexibility resources, which lack revenue incentives in present-day markets.

EXHIBIT 22

How to Accelerate from 5% to 7% Annual Growth in Renewables Supply

		LEVERS		
		<i>How do these support progress toward higher levels of renewables penetration?</i>		
		Competitive markets: efficient and integrated operations	Utility business models and procurement: large-scale investments	Planning and finance: investment and turnover
PATHWAYS	Increase renewable supply	Widen the use of competitive markets and integrate among them Integrate externality prices into markets Enable voluntary renewables purchasing	Require transparent all-source procurements for energy supply	Improve integrated resource planning for distributed resources and emerging technologies Provide government and multilateral support to renewables in emerging markets
	Improve system flexibility and resilience	Allow all-source bidding to provide flexibility resources	Create a level playing field for nonutility investment in flexibility resources	Look ahead to long-term needs for seasonal storage and resilience
	Manage asset transition	Expose all resources to market-based competition	Facilitate retirement of uncompetitive assets	Smooth capital and labor transitions with securitization of retiring assets and support to affected communities

Although declining renewable power prices are influencing markets globally, differences in market and regulatory structures and other factors distinguish the opportunities and challenges for increasing shares of renewable power in different countries and regions. Exhibit 23 illustrates key opportunities for and challenges to increasing the share of renewables for select countries and regions.

EXHIBIT 23

Opportunities for and Obstacles to Electrification with Renewable Power in Select Areas

	Opportunities	Obstacles
India	<ul style="list-style-type: none"> -There are ambitious renewable power goals -Wholesale markets are being established -India is one of the world's lowest-cost solar power producers -Public-private partnership model has encouraged renewables development -Electrification of two- and three-wheelers is expected to increase rapidly -The Government of India has a storage mission to increase the availability of advanced batteries 	<ul style="list-style-type: none"> -Renewables development growth has been slowed by distribution company debt, tariff caps, and financing difficulties -Less than 5% of power is traded in markets today, and utilities are tied in expensive, long-term bilateral agreements -No existing market for ancillary services exists today -Domestic solar panel and battery manufacturing is limited -Rooftop solar is developing slowly -Development of EV charging infrastructure is slow
Southeast Asia	<ul style="list-style-type: none"> -Fast growth rates and urbanization have led to dynamic new opportunities, including conglomerate-led real estate development -Urban pollution and congestion drive public demands for clean mobility options -Auctions for clean energy are emerging in Vietnam and can provide competition in other parts of the region 	<ul style="list-style-type: none"> -Cheap Indonesian coal (and embedded politics around coal) supports growing usage in the region -Subsidized electricity rates dampen uptake for energy efficiency -Weak and politically compromised regulators inhibit cohesive planning

Continued on the next page

EXHIBIT 23 (CONTINUED)

Opportunities for and Obstacles to Electrification with Renewable Power in Select Areas

	Opportunities	Obstacles
Africa	<ul style="list-style-type: none"> -There are well-developed regulatory regimes for renewable energy across several North African countries, including those for grid-tied solar and residential solar hot water -There are favorable regulatory regimes for renewables in some sub-Saharan countries, but other challenges limit implementation -There are opportunities for regional market development through existing power pools -Fast growth and urbanization rates in some sub-Saharan countries have led to new opportunities for green mobility solutions to address urban air quality problems 	<ul style="list-style-type: none"> -Access to energy remains a challenge in many countries in sub-Saharan Africa (over 600 million people without power) -There is a lack of transmission and distribution infrastructure, as well as utility solvency issues -There is a lack of access to affordable capital; public finance is still critical to getting projects completed
China	<ul style="list-style-type: none"> -Renewable energy auctions are driving leveled costs of energy down for new wind and solar to levels comparable with new coal -The large market has huge potential to drive down the costs of renewables and energy storage -Wholesale electricity markets are being implemented and could improve renewable integration and identify uneconomic plants -Coal restrictions are becoming increasingly stringent to decrease on-site coal use and total coal consumption, and to improve air quality -Strong policy support—including subsidies for vehicles and chargers, road access privileges, and time-of-use preferential rates—is provided to EV owners and other stakeholders that could enhance electricity utilization and renewable power uptake. -High-speed train dominates intercity travel that is less than 1,000 kilometers 	<ul style="list-style-type: none"> -Provincial protectionism hinders a fully efficient power system through cross-border exchange -State-owned enterprises and local governments lack incentives to close unnneeded fossil fuel assets -Advanced technologies—such as smart charging and vehicle-to-grid, which is critical for effective EV grid integration and renewable consumption—are not fully viable from the grid side -Natural gas fuel switching could lock China into expensive fossil fuel use for heating -Coal-fired generating assets are relatively new and far from retirement -Heavy industry is extremely difficult to electrify
United States	<ul style="list-style-type: none"> -Clean energy portfolios are now cheaper than existing coal and new gas -Competitive wholesale markets encompass a large share of the US market -Leading states are developing new business models and operating systems to integrate distributed energy resources -New policies are emerging to drive electrification of buildings 	<ul style="list-style-type: none"> -Utility business models do not yet provide a level playing field to ensure least-cost resource procurement -Vehicle electrification is advancing without the benefit of supportive federal policy -Incentives for development of long-term energy storage or demand management do not exist

Finally, the transition to higher shares of renewable supply can be enabled and accelerated by the adoption and integration of **digital controls and information systems** to enhance electricity system flexibility and resilience. Securely managing a system with exponentially growing numbers of control points will be a challenge for many grid operators, especially with growing concerns about operational and cybersecurity. But the potential value of managing these distributed resources is high: one recent study found that if the last 5% of electricity system needs during critical periods could be served by smart, flexible demand, the cost of storage investments required to balance markets would fall by a factor of seven.³⁶

Digital solutions—such as the energy blockchain platform developed by **Energy Web Foundation**, an RMI subsidiary—could help to balance multiple levels of the grid simultaneously. Such solutions could create more value and choice for customers and allow effective integration of higher shares of distributed resources.

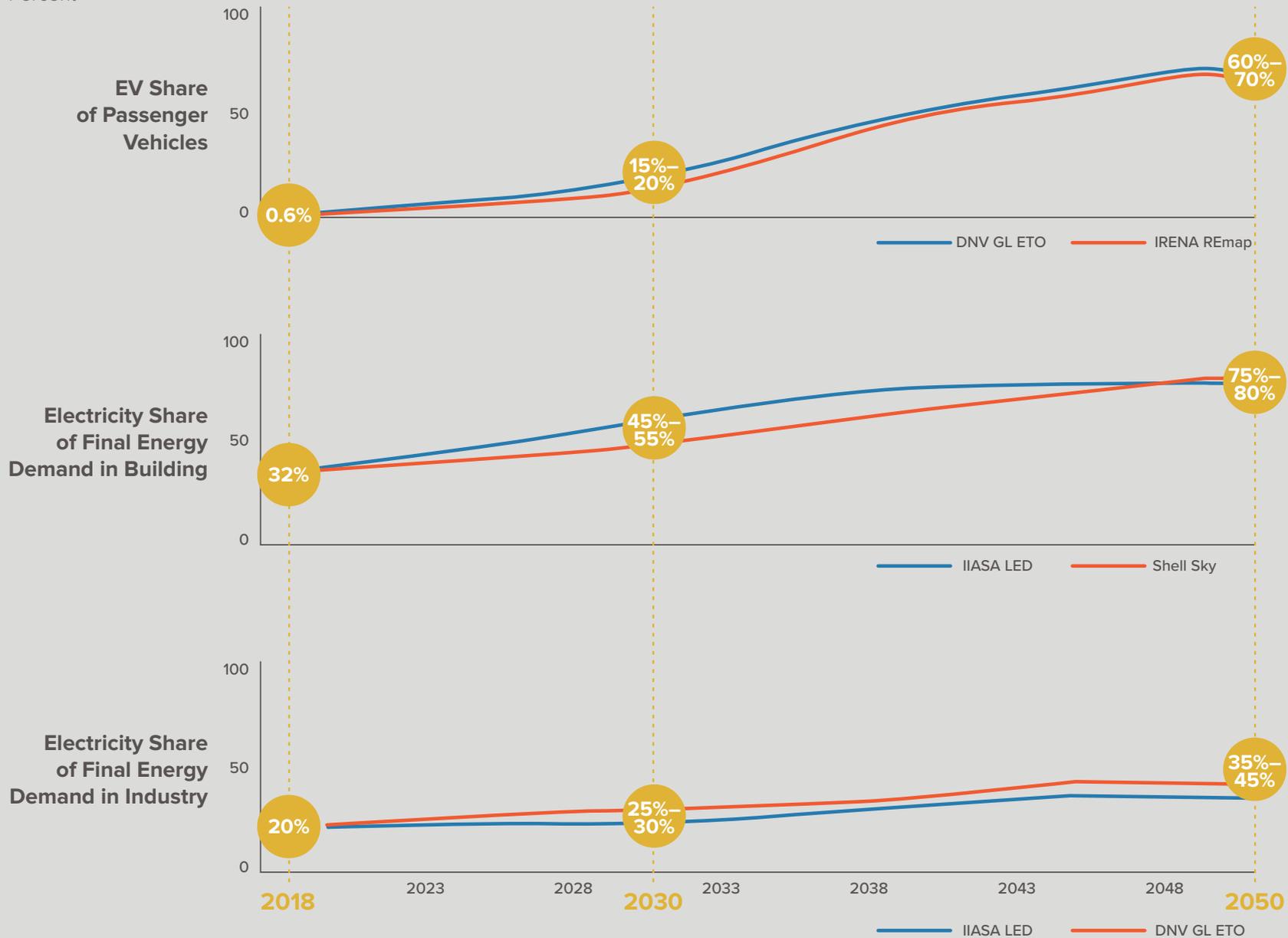
Electrification: Changing the Guard

Substituting electricity for fuel used in buildings, vehicles, and industry at the scale needed to limit global climate change to less than 2°C will require changes to hundreds of millions of pieces of equipment around the world and will involve billions of people. This fundamental reality defines the electrification challenge and distinguishes what is needed to overcome it from the measures needed to transform electricity supply. In the latter arena, the number of decision makers directly involved is much smaller.

Based on a review of studies that describe pathways to achieve less than 2°C, we frame the challenge targets for electrification by sectors, as shown in Exhibit 24.

Electrification Milestones to Keep Warming to Well Below 2°C

Percent



Source: Nature Climate Change, IRENA, DNV GL, Shell³⁷

In both end-use sectors and electricity markets, coordinated efforts across policy, markets, technology, and finance will be essential to **more than triple the annual**

growth rate of electrification. Exhibit 25 identifies key levers to accelerate electrification across different sectors.

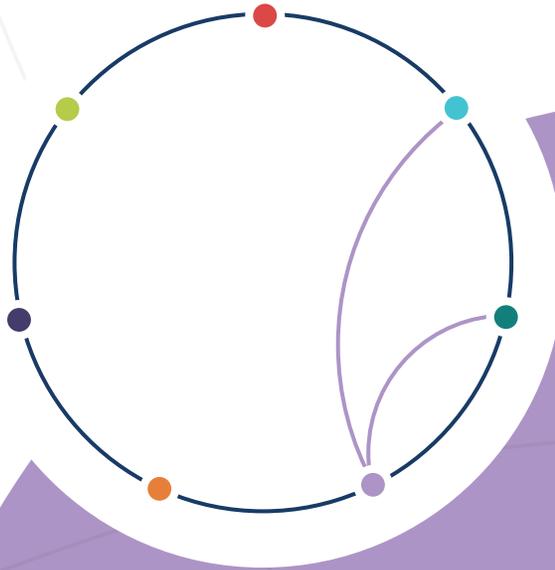
EXHIBIT 25

Key Leverage Points to Accelerate End-Use Electrification from 1.2% to 4% per Year

	POLICY	MARKETS & INDUSTRY	FINANCE
BUILDINGS	<ul style="list-style-type: none"> -Incentives for electrification upgrades -Halt the expansion of gas infrastructure to new buildings -Strengthen building performance standards 	<ul style="list-style-type: none"> -Bundling efficiency and electrification (i.e., retrofitting appliances and homes) -Heating-as-a-service business models -Deploy zero-carbon district heating with new business models 	<ul style="list-style-type: none"> -On-bill financing from utilities -Enable residential and commercial PACE financing -Coalitions pressure energy companies to halt gas build-out
TRANSPORTATION (Light Duty)	<ul style="list-style-type: none"> -Support the rapid build-out of charging infrastructure -Integrate energy, mobility, and infrastructure planning -Incentivize rapid adoption of EVs -Support shared mobility services business models 	<ul style="list-style-type: none"> -Replicate best practices in e-bus procurement -Coordinate industry R&D for batteries and smart charging -Implement market structures to allow charging to provide grid services 	<ul style="list-style-type: none"> -Financing mechanisms to address risk and first-cost premiums for EVs and batteries -Investment in new manufacturing capabilities for medium- and heavy-duty vehicles -Catalyze the used EV market
INDUSTRY	<ul style="list-style-type: none"> -Incentives for adoption of electric technologies (e.g., carbon pricing, industry demand-response programs) -Energy savings targets and supporting regulations -Differentiated carbon prices (i.e., border adjustments) 	<ul style="list-style-type: none"> -Creation of service-based offerings to eliminate capex-opex trade-offs, especially for process heat -Coordinated bulk procurement for cost reduction -Relocating industrial facilities to low-electricity-cost regions 	<ul style="list-style-type: none"> -Standardizing small capex finance models for off-taker fuel switch, including process heat -Trading of credits for low-carbon products/commodities (enables futures markets and securitization) -Investor pressure on carbon performance (e.g., Task Force on Climate-Related Financial Disclosures)

Opportunities to Electrify with Renewables

- How can we design competitive markets to support clean and efficient continued electrification in the developing world, where many people still live without basic electric service?
 - What can and should utilities look like as we create competitive markets in regions with low levels of electrification (extension of service)?
 - How do we rapidly evolve historically slow-to-change utility regulation to provide clear policy coupled with appropriate incentives for utilities to lead and accelerate the transformation of the power system?
 - How do we create regulations that encourage continued innovation from utilities as well as clean energy solution providers?
 - How can utilities and ESCOs deliver electrification of existing buildings at scale and speed?
- 



4

Reinventing Cities

How can leapfrog improvements in urban systems and infrastructure be harnessed to deliver secure, resilient, and clean energy services for all?

Reinventing Cities

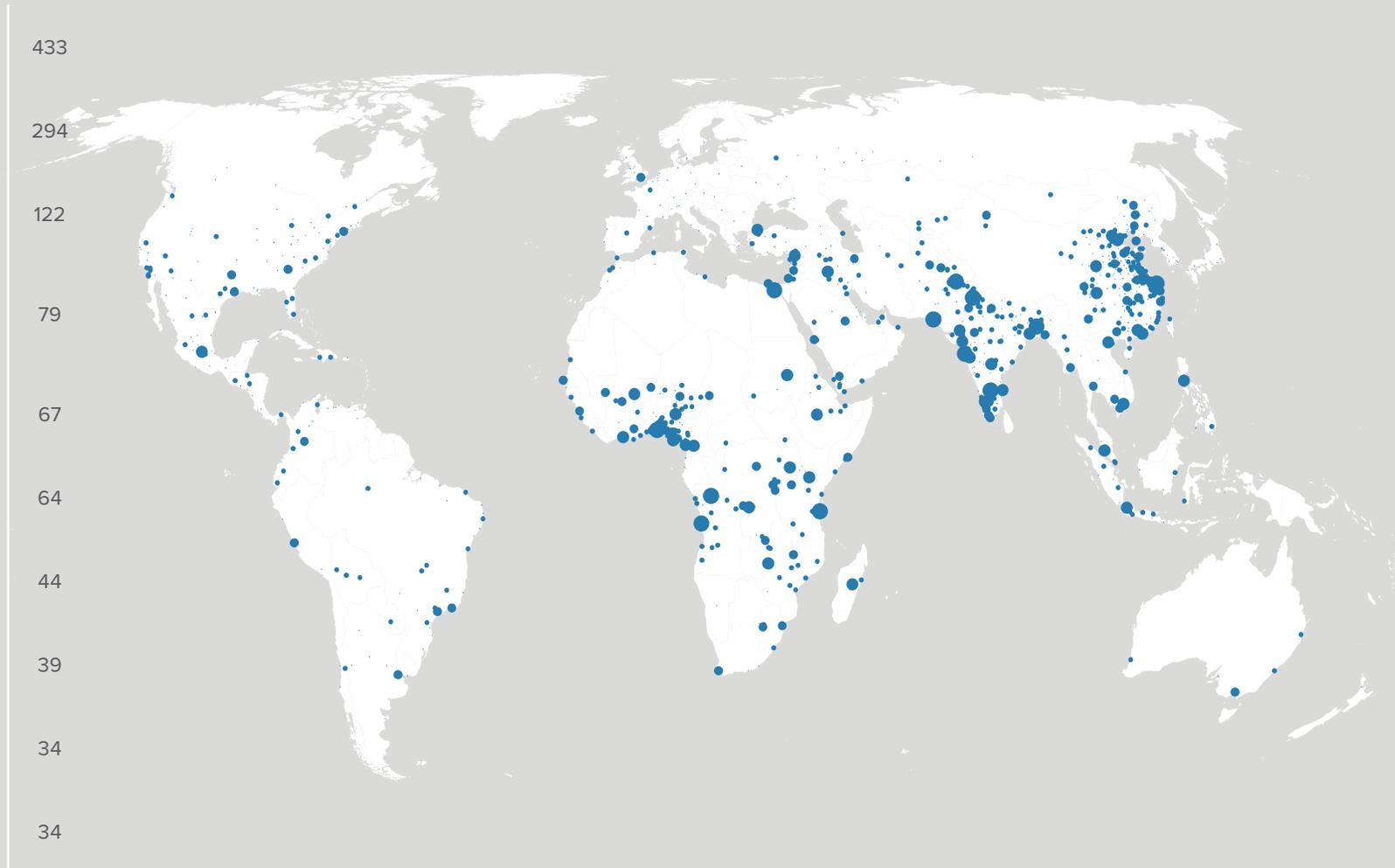
Cities are hubs of rapid learning, knowledge sharing, and experimentation with the potential to reshape global energy. The necessity is clear: cities face immense health and migratory challenges associated with carbon-intensive fuels and lifestyles. In particular, **high-growth cities are expected to add more than 2 billion new urban dwellers by 2050, presenting an opportunity to shift mobility and infrastructure systems worldwide onto a low-carbon trajectory.**³⁸ Moreover, the value created could be immense: \$2 trillion in annual investments in proven solutions could yield returns of \$2.8 trillion by 2030 and \$7 trillion by 2050, annually, while reducing emissions by 90% over the same time frame.³⁹ Timely global learning and coordination will be essential to grasp this opportunity.

- Specifically, by 2050, the 1,000 fastest-growing cities can avoid 3 Gt CO₂ from transport and 4 Gt CO₂ from buildings per year while bringing next-generation solutions to scale.
- These coordinated actions can help cities avoid up to 7 million deaths per year from worsening air pollution, 1.4 million deaths per year from traffic crashes, and 220 million migrants fleeing climate-related disasters and agricultural productivity losses.
- A key enabler of urban activity and dynamism, transport of goods and people can be provided with clean, high-utilization and software-enabled service models with supporting policy for radically lower cost to end consumers.
- Next-generation building design, materials, and operations can eliminate lifecycle carbon emissions and reshape urban landscapes in high-growth cities in a “leapfrog” co-determined by better urban mobility planning.
- Empowered and visionary urban planning can build efficient cities around people, to improve health outcomes, increase proximity to vital needs, and dramatically reduce emissions.
- High urban growth rates represent an opportunity to “boomerang” new solutions worldwide, leveraging network effects to scale low-carbon technologies and practices within and across cities, from developing to developed countries.

Projected Change in Global Cities' Population by Country 2015-2050

Millions

China	433
India	294
Nigeria	122
Democratic Republic of the Congo	79
United States	67
Pakistan	64
Bangladesh	44
Indonesia	39
Tanzania	34
Mexico	34



Source: RMI, United Nations⁴⁰

Why Cities Matter

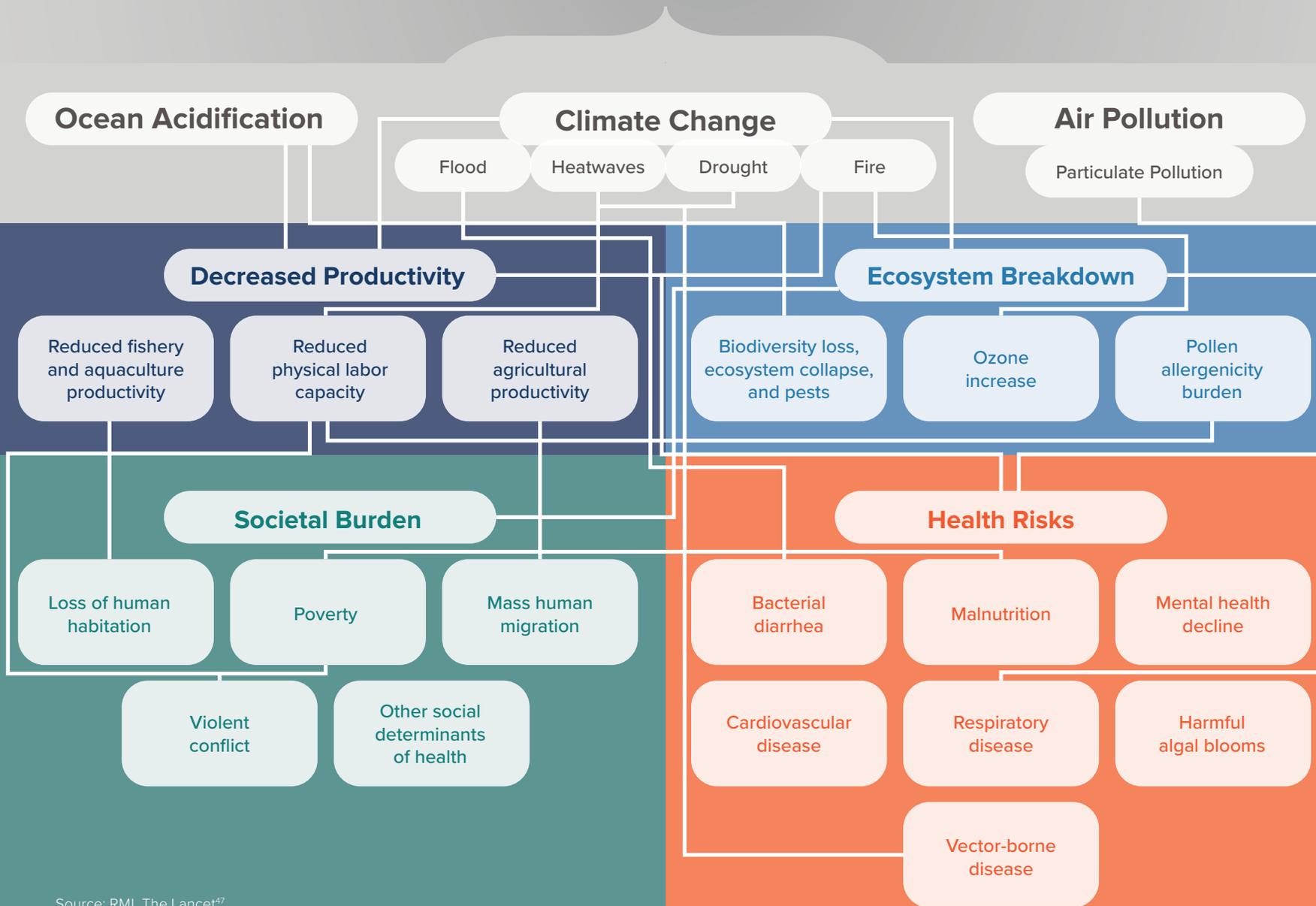
Urban areas account for nearly 70% of direct global energy consumption and more than 70% of global carbon emissions.⁴¹ And they are far from static. Driven by urbanization in developing economies, cities are home to an ever-increasing portion of the world's people and host to a rapidly increasing share of the world's economic output—from 4.2 billion people and more than 80% of global GDP in 2018 to nearly 7 billion and 90% by 2050.⁴²

By 2050, the number of cities in developing countries with at least 1 million people will have doubled, and the number with at least 5 million people will have tripled. Climate change will also accelerate urbanization. By the same date, **the World Bank estimates 220 million people will migrate within their own countries in response to diminishing agriculture yields, extreme weather events, and shifting disease burdens,** roughly equal to the total number of global immigrants today.⁴³ The associated rate of change and increase in demand for transportation services, residential and commercial space, electricity, water, food, and consumer goods we can expect is comparable only to the urban industrialization of the Western world we saw in the late 19th and early 20th centuries.

Meanwhile, cities acutely feel the consequences of fossil fuel-intensive development and climate change (see Exhibit 27). Between 2010 and 2016, air pollution concentrations worsened in 70% of the world's cities, and in 2015 alone, nearly 3 million people died as a direct result of fine particulates released by fuel combustion and tires,⁴⁴ out of a total of 7 million attributable to air pollution.⁴⁵ This compares with 1.4 million fatalities from road transport crashes per year.⁴⁶ All three trends were experienced predominantly in developing countries. Roughly 90% of the world's urban areas are on coastlines vulnerable to storms and sea level rise, as coastal residents around the world are already experiencing. Urban heat island effects can raise average city center temperatures by 3°C–5°C, creating potentially severe health consequences for the poorest and most vulnerable urban dwellers—people without air conditioning and access to quality healthcare.

The Pathways Between Climate Change, Energy Use, and Human Health

Greenhouse Gas Emissions



Source: RMI, The Lancet⁴⁷

Cities Are a Critical Leverage Point for Climate Action

Radical changes in the way cities use energy are critical to support human development and mitigate these effects in both developed and developing cities. Put simply, human economic activity is causing climate change, and because cities are where that economic activity is heavily and increasingly concentrated, cities need to be at the center of climate action, and incremental improvements will no longer suffice. The potential emissions abatement and value creation opportunity is immense; recent analysis by the Coalition for Urban Transitions suggests that 90% of emissions could be abated for compact, clean, and connected cities at a net present value of \$24 trillion (see Exhibit 28).⁴⁸

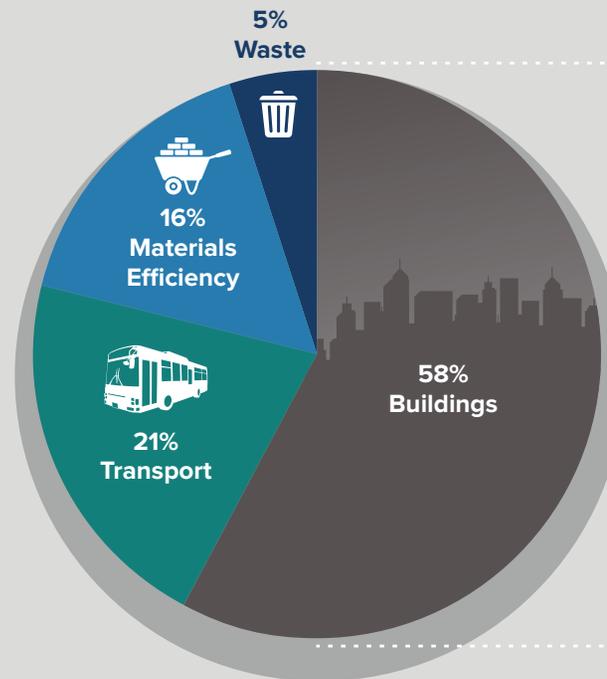
Fortunately, cities also have several unique characteristics that make them well situated to drive systemic leapfrog solutions to emissions.

Concentration of knowledge and talent.

Cities themselves represent a powerful locus of action that can reshape the future of energy use. Today, less than 100 cities account for 8% of the world's population but a full 25% of world economic output. That nonlinear dynamic is a result of the way cities pull in people, concentrating both knowledge and talent, and the beneficial innovation and network effects that result.

EXHIBIT 28

Urban Value Creation and Emissions Reduction Are the Same Opportunity



Urban emissions can be

Reduced 90%

for net present benefits of

\$24 Trillion

Source: Coalition for Urban Transitions⁴⁹

Rapid urbanization. The rapid pace of urbanization in emerging economies is one of the most dynamic forces of the 21st century. At least 2 billion people will move into 1,000 already crowded cities by 2050, mostly in developing countries. “Urbanization 2.0” is a critical opportunity to shift the trajectory of the global energy transition—and failing to act now, especially in developing economies, will lock us even more firmly into a catastrophic climate pathway. Although this rapid urbanization presents serious challenges, including adequate housing, transport, and trash management, the corresponding opportunity is that the absence of mature infrastructure and still-emergent patterns of behavior create a singular window in which to radically reduce the energy- and carbon-intensiveness of economic development.

Tendency toward interconnection. If even a small fraction of these rapidly growing cities can act quickly to design and test radical new solutions, these solutions could diffuse through cities around the world, scaling up and simultaneously adapting to different cities’ unique contexts and further improving their efficacy.

Emerging markets comprise 85% of the fastest growing cities, each home to more than 1 million residents by 2050. There, the absence of mature infrastructure combined with still-emergent patterns of behavior creates the opportunity to skip a generation of carbon-intensive technologies, production methods,

and development models—and move straight to energy-productive and climate-friendly urban solutions.

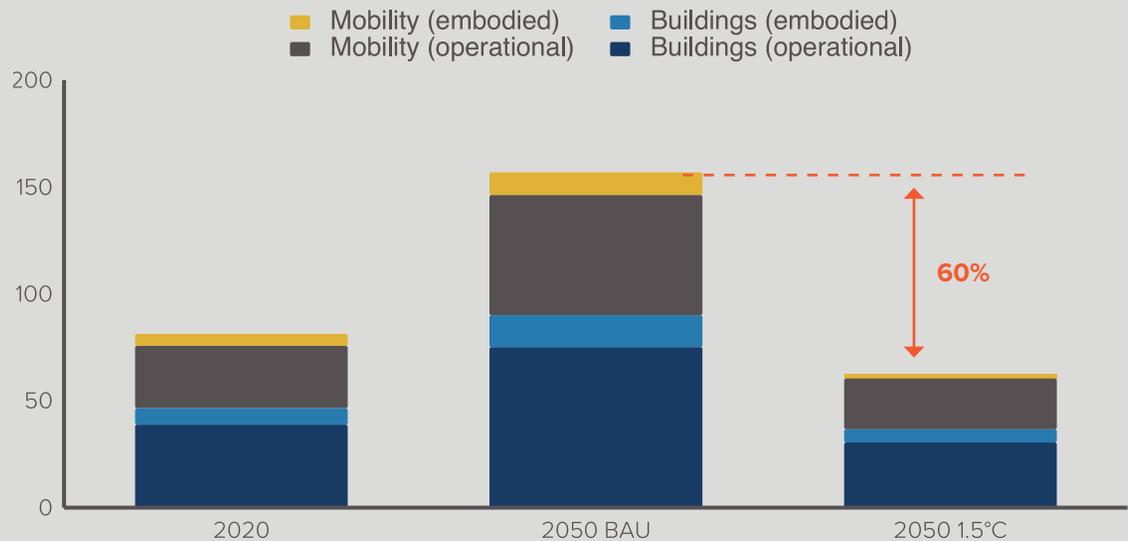
Low-cost, high-performing solutions that are brought to scale in developing countries can in many cases boomerang back through developed countries to maximize the value and speed of asset turnover (see Challenge 7). Thus, even in

developed cities worldwide, we have the potential to cost-effectively move past incremental gains in efficiency, end-use electrification, and electricity system reform to solutions that represent a step change. Several compelling possibilities are beginning to take shape to act on these leapfrog opportunities.

EXHIBIT 29

The Leapfrog Opportunity in the 1,000 Fastest Growing Cities Amounts to 60% Reduction in Energy Use by 2050

Exajoules



Source: RMI, Nature Energy⁵⁰

Unleashing Shared, Clean, Electric Multimodal Mobility

Channeling the flow of people and goods is a core function of cities, making mobility a key enabler of cities' dynamic growth and unlocking human interaction on a scale and speed to create networks of innovators and ideas that can be rapidly prototyped and spread. These network effects are important because continued gradual growth in EV penetration and slow turnover of existing capital stock is inadequate to limit warming to 1.5°C while meeting growing global demand for mobility services. Networked ideas should start with human-centered design to minimize the need for energy-intensive mobility services, and end with solutions for high capacity, high utilization clean transport market development.

The economic value of the fuel savings associated with the electric mobility transition is \$5.3 trillion per year in developed countries today and \$4.7 trillion per year in developing countries in 2050, according to RMI analysis. Better policies like congestion pricing can help realize that value, especially as those policies are tested and improved (in this case, to include dynamic pricing and predictive analytics). As a result, well-integrated urban mobility systems with high shares of public and nonmotorized transportation, coupled with all-electric first- and last-mile mobility services, all-electric urban freight delivery, and better physical and data integration to support multimodal transportation, can flip the transportation paradigm and create step changes in energy use and carbon emissions.

Achieving a Sustainable Future Mobility Paradigm Integrates Four Layers of Solutions

A New Paradigm	 Shared	 Connected	 Clean
Supporting Layers	<p>Highly shared utilization of cars, buses, and micromobility solutions</p> <p>Pedestrian mobility as an option and the first choice</p> <p>Mobility as a service</p>	<p>Open communication among vehicles to prevent accidents and optimize traffic flow</p> <p>Regular software updates to improve vehicle operations</p>	<p>Transportation sector ultimately emissions-free</p> <p>Distributed clean power supply and charging infrastructure</p> <p>Detailed, real-time information on power sources</p>
INFRASTRUCTURE	Cities designed to be pedestrian-centric	Infrastructure that can communicate with vehicles	Ample stations to serve vehicle fleets and grids
ROLLING STOCK	Shared vehicle fleets and extensive mass transit	These capabilities built in to all new vehicles	Fleets of zero-emission vehicles
DIGITAL ANALYTICS	Optimization needed to effectively share vehicles	Sensors and electronics (IT System) AI-enabled	Predictive congestion pricing
USER INTERFACE	Data-lite apps that enable vehicle sharing according to destination and human factors		Energy usage displays

Source: RMI, McKinsey & Company⁵¹

Reshaping the Urban Landscape for Productivity

Another leapfrog opportunity is to dramatically **reduce energy consumption and carbon emissions embodied in buildings and infrastructure**. In developed countries, 26% of projected emissions from buildings and infrastructure could be avoided by 2030 simply through more widespread implementation of incremental and whole-building efficiency measures.

But in developing countries, a new wave is emerging of innovations that are capable of reducing emissions embodied in buildings and infrastructure 70%–90%, thanks to construction innovations like topological optimization, modular design, and additive manufacturing.⁵² Substituting materials like cross-laminated timber and carbon fiber offer net-negative emissions profiles. For example, replacing steel rebar with carbon fiber could reduce emissions by nearly 1 Gt CO₂ because it would also require 80% thinner concrete slabs. These solutions do not presuppose but accompany improved code development, iteration, and enforcement to unleash the full potential of next-generation infrastructure (see Challenge 6).

More generally, when these innovations are combined with whole-system integrative design methods, technologies, and business models we have today, new buildings—and in some cases, entire brownfield urban districts and greenfield cities⁵³—can be built to net-zero carbon standards while providing positive financial value to developers, owners, tenants, and occupants. District- and city-scale developments can be served by integrated energy services providers (IESPs) who optimize heating and cooling, demand-side energy management, and electricity system operation across an entire community.

Coordinating Efforts for Speed and Scale

Beyond these types of technological and design leapfrog opportunities, cities also have an opportunity to scale innovative solutions nonlinearly, both within the city and across cities globally, by leveraging the network effects of collective action. These effects can drive both technology cost reduction and market expansion through increasing returns to individual cities and groups of cities while speeding the diffusion of lessons learned from new policies and urban planning practices.

To capture those network effects, cities must first respond to local needs by scaling up existing and testing new sector-specific market designs, stakeholder engagement models, and pricing signals and incentives. Looking across cities, city leaders can access shared leverage in building networks of cities performing testing and sharing lessons learned, and then speedily coordinating action on key solutions. Although many of these city networks already exist, there is significant opportunity to better coordinate and leverage those networks. To share in the medium- to long-term benefits of network effects, coalitions of active cities can coordinate to procure key technologies to accelerate cost reduction—faster than expected, at net positive additional long-term value to each city—thus enabling more cities to enjoy the resulting value creation sooner.

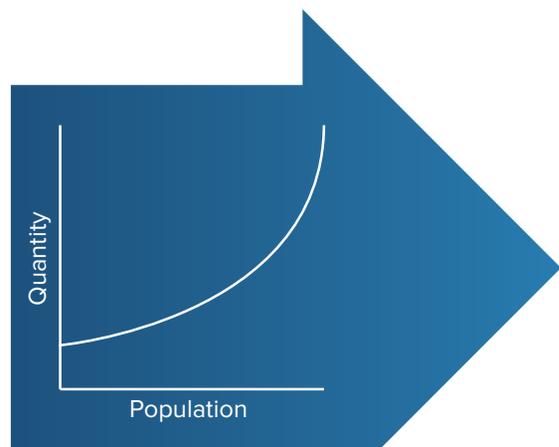
Innovation Scales Exponentially Within and Across Cities

It is crucial for cities to share knowledge and support one another to accelerate the rate at which solutions are transmitted and improved

between cities, and between cities and national governments. Access to the leading edge of best practices can help to increase the utilization of

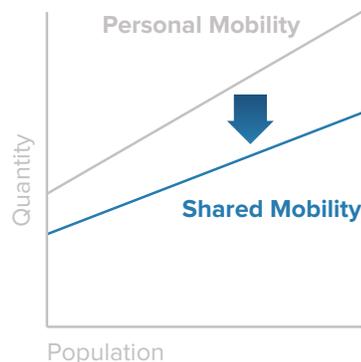
consumer goods and infrastructure for a given urban population, thus helping to achieve all of the United Nations' Sustainable Development Goals.

Innovation and Knowledge Outputs



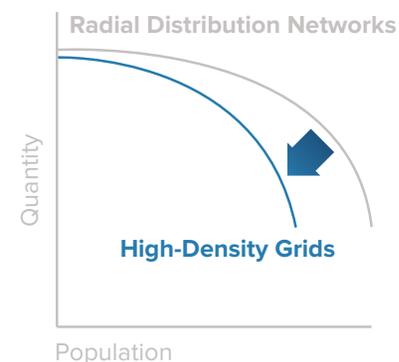
Innovation and knowledge economy outputs scale exponentially with city population.

Consumption Goods



Consumable goods scale proportionally with city population.

Infrastructure



Infrastructure quantity scales negatively with city population size.

America's Pledge and We Are Still In UNITED STATES

Cities, states, businesses, and universities that have committed to helping America reach its Paris climate goals are collecting data on non-national climate action, communicating the findings and results, and catalyzing climate action.

Source: PNAS⁵⁴

Alliance of Pioneer Peaking Cities CHINA

This is an alliance of Chinese cities that are committed to taking concrete actions to achieve emission peaks by 2030 with strategies such as industrial shift and energy savings and efficiency, green building, green transport, and reforming the energy system.

CASE STUDY

How Many Switzerlands Does It Take?

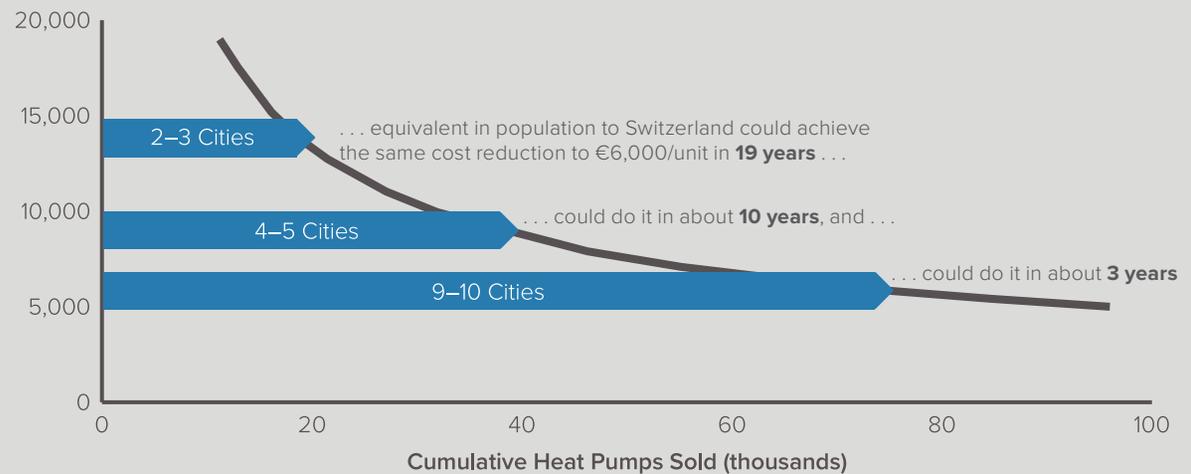
Collective action (in the form of demand aggregation) has been proven to drive critical cost reductions and market expansion. Switzerland installed about 700 MW of residential heat pumps between 1980 and 2004, with costs falling from approximately €20,000/unit to €5,000/unit.⁵⁵ Along the way, suppliers made technical advancements and scaled production to drive out cost. If four or five medium-to-large-sized cities signal their intentions to buy in bulk with adequate lead time, they could spur next-generation supplier manufacturing efforts to achieve the same cost reduction, together, in a fraction of the time.

The corporate sector has demonstrated this with renewables procurement—by entering into a joint virtual power purchase agreement with Apple and Akamai, Etsy (a much smaller company) was able to access much better deal terms than it would have been able to on its own.

EXHIBIT 32

Coordinated Urban Action Reduces the Time and Cost Required for Technology Cost Reduction

Heat pump cost, Euros per unit

Source: RMI, Utrecht University⁵⁶

Instigating Action

Cities are central to our climate and energy aspirations—both because of their influence on the system and because they are where most of humanity lives. They have the potential to **spur one another to action, learn from one another, and bring to bear enormous market power and policy influence at regional and national levels.** City leaders often like being the biggest or best, whereas city staff often learn most effectively from and place the most credibility on the experience of other city staff. Creating and working with cohorts of cities focused on the same topics, with a heavy emphasis on facilitated peer-learning, is one way to take advantage of this competitive–collaborative dynamic and speed the diffusion of lessons learned and best practices.

Accelerating the pace of solution design and scaling will require diverse experimentation within a shifting but continuous web of structured communication, coordination, and support among cities. Using enhanced digital platforms and approaches that support collective innovation, codes for success can be synthesized, transmitted, and translated to different local contexts, all while increasing awareness of and inviting stakeholders in other domains and geographic scopes into the problem solving and scaling process.

Acting together, cities can empower one another as the laboratories for solutions that will improve urban denizens' quality of life while mitigating the risk of irreversible climate change. By developing mechanisms to bandwagon together, transmitting learnings, and engaging global markets for next-generation mobility and infrastructure solutions, cities can act at a sweeping scale as conduits for transformative energy solutions.

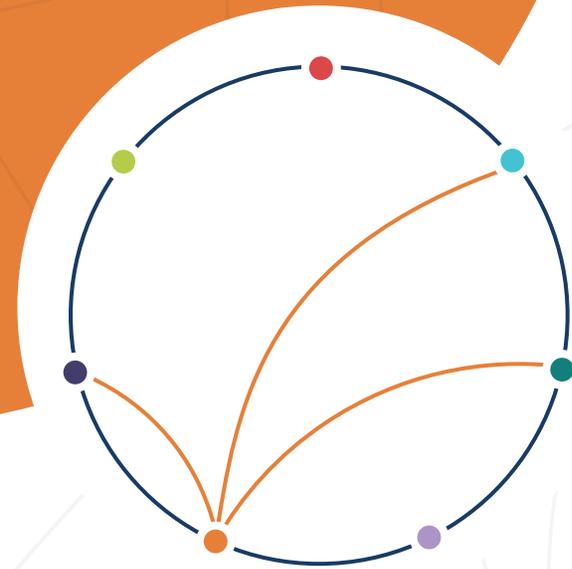
Opportunities to Reinvent Cities

- How can urban planners coordinate human-centered solutions suitable to their local context and share the timely lessons learned that are relevant to other high-growth cities?
- How can multilateral and philanthropic funders help build city leadership and staff capacity while supporting experimentation and implementation, by placing diverse, distributed bets that unlock solution design and scaling?
- What must be true for cities to procure new technologies and services in bulk and in batches, to leverage market competition to bring down cost and scale new and existing solutions while sharing in the benefits of more rapid technology cost reduction?
- How might cities work within their communities and with one another to rapidly test and scale new infrastructure materials and design methods and to implement new codes and standards for construction that are aligned with advanced approaches?
- How can best practices in urban design, public transit, and nonmotorized transportation be applied to rapidly growing cities to dramatically reduce emissions, improve health, provide people-centric mobility options, and increase proximity to vital needs (e.g., food, healthcare, recreation)?
- What are the design criteria by which various cohorts of cities—the “next C40 cities”—can meet both individual and shared needs, constraints, and opportunities?
- How can city and community leaders influence actions by their citizens, businesses, other local governments, and national governments?

5

Boosting Clean Technology

How can we speed the development and rapid adoption of high-impact clean energy technologies?



Boosting Clean Technology

The transition to a low-carbon energy system is now advancing faster than almost anyone thought possible in sectors where globally scaled manufacturing has unleashed steep declines in the cost of clean energy technology. Technologies like wind, solar, and batteries have achieved dramatic cost reductions and crossed critical tipping points for wide adoption.

We can and must add to this list. Transformational advances in cost and performance are needed in other areas ranging from heat pumps and electric vehicles to low-emissions steel and cement to long-duration energy storage. Some of these technologies are near tipping points for rapid scaling, whereas others are less mature, with cost, regulatory, or performance challenges that still need to be overcome.

A range of levers can be used to:

- Stimulate innovation,
- Support commercialization, and
- Drive large-scale manufacturing in the next decade.

These include:

Strengthening innovation ecosystems.

Institutions involved in cleantech innovation can address barriers to technology commercialization by developing well-integrated commercialization ecosystems like those found in the pharmaceutical and biotech industries.

Industrial policy. China has made itself a world leader in manufacturing solar panels, wind turbines, batteries, and electric vehicles through application of focused national policies. Other nations have taken more piecemeal, but nonetheless still effective, approaches in areas such as battery manufacturing (e.g., the European Battery Alliance), solar power (e.g., US Department of Energy SunShot Initiative), and early stage innovation (e.g., US Advanced Research Projects Agency—Energy, ARPA-E).

Demand stimulus and demand aggregation.

Governments and industry have acted, sometimes together and sometimes independently, to boost demand for key technologies and/or to incentivize performance improvements. Notably, India's EESL has created a structure for financing the purchase and deployment at scale of new energy technologies that is being used across a range of key technologies, from LED lightbulbs to electric vehicles.

Industry goal setting and support for innovation.

The exponential improvement in computer chips over the past five decades was supported by a powerful industry consortium called SEMATECH that helped to coordinate industry standards and reduce the cost of research and development. Now, new alliances are beginning to emerge to encourage new technology in areas such as low-emissions shipping and last-mile urban freight delivery. Such efforts may be needed in areas such as green hydrogen and long-term energy storage.

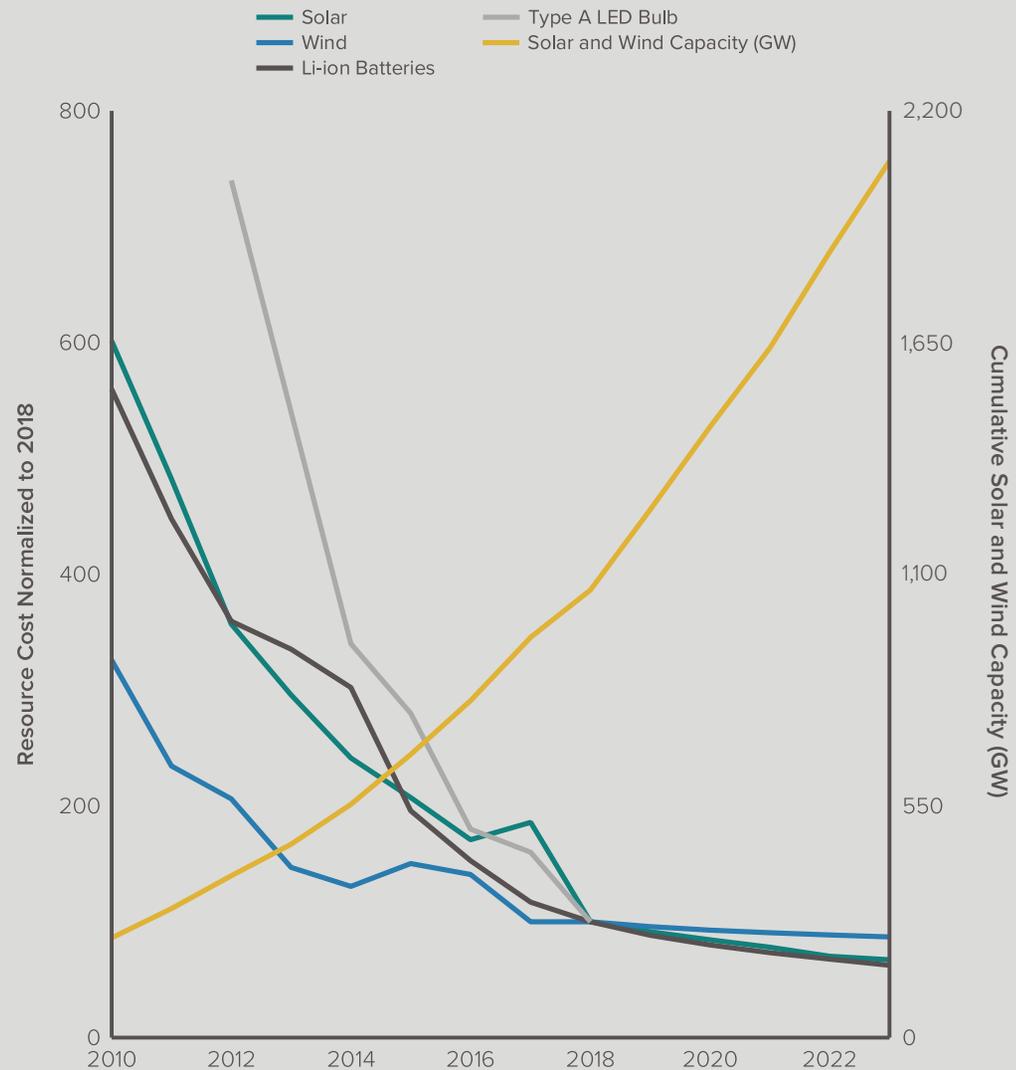
A New Paradigm in Clean Energy Technology

The combined force of technology innovation, learning by doing, and scaling has reduced the costs of solar, wind, batteries, and LED lighting by more than 80% over the past decade (see Exhibit 33). Real solar contract prices have declined 99% since 1980; now solar has over 50 times the capacity the International Energy Agency (IEA) forecast in 2002, is set to reach its first trillion watts of installed capacity by 2023, and by 2028 is projected by BNEF to outproduce global nuclear power—sooner than a reactor ordered now could probably be built. This is the force of global innovation, multiplied across dozens of countries and thousands of companies.

These price declines have changed the conversation about what is possible and how much the energy transition will cost. Across most geographies, the question is no longer if but when renewable generation will outcompete coal, natural gas, and other traditional means of power generation. In most regions, it already does. Cheap batteries are now disrupting previous assumptions about how we manage the electricity grid, the economics of living off-grid, and fossil-free transportation.

EXHIBIT 33

Real Cost Declines for Key Clean Energy Technologies: 2010–2023



Source: RMI, BNEF, Cadmus⁵⁷

Patterns of Technology Change

These price declines are not the result of singular discoveries of breakthrough technologies. Rather, they are the fruit of step-by-step processes that drove down costs by rapidly scaling manufacturing globally while continuously improving design, materials, production processes, quality, performance, logistics, and product integration. Some technologies, like batteries, play roles like those of keystone species in complex ecosystems: they enable a whole system to thrive, and as their costs fall, they successively open new markets to transformation.

The pattern of exponential improvement in technologies is both widespread and, within certain degrees of error, reliably forecastable. Most technologies, going back to Ford's Model T, follow a relationship known as Wright's Law: costs drop exponentially, at different rates depending on the technology, in proportion to the increase in cumulative production volumes. For example, solar costs have fallen 20% for every doubling of manufacturing capacity. Once technologies move onto this learning curve and become attractive to early adopters, they can reach a tipping point where they are cheaper than alternatives. The faster the growth in production volume, the faster the decline in cost. **Thus, the transition to a clean, increasingly electrified energy economy can become a self-reinforcing virtuous cycle.**

Battery Cost Learning Curve and Market Opportunities

Micro-mobility (e-bikes and scooters) business models become competitive.

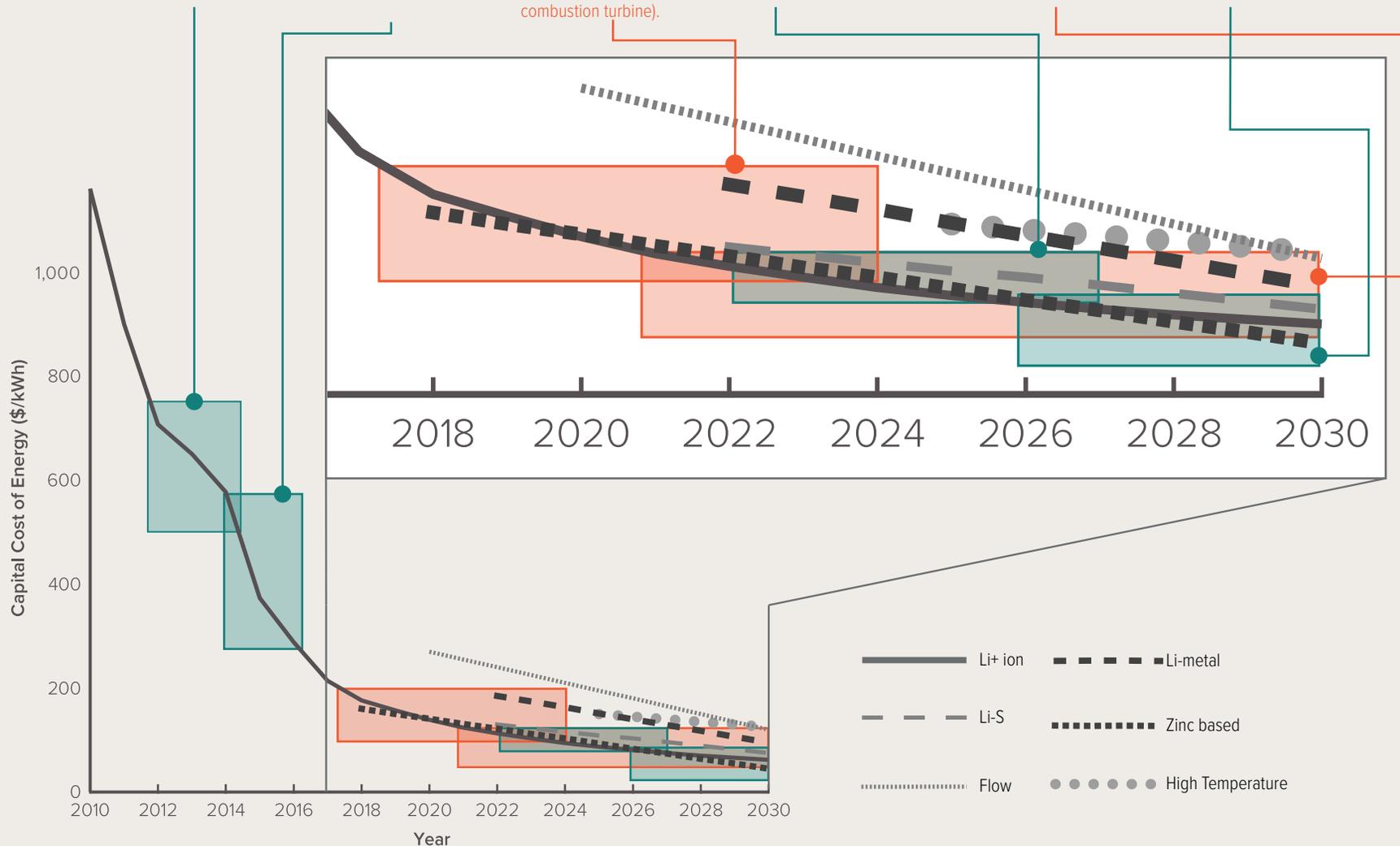
EVs become more cost-effective on a lifetime basis: Total cost per mile of four-wheel electric vehicles becomes less than internal combustion engine vehicles.

New Natural Gas Plants: Clean Energy Portfolios (CEPs) with batteries will become cheaper than new natural gas generation (combined cycle and combustion turbine).

EVs in India: Capital cost of electric two-, three-, and four-wheelers in India is cheaper than internal combustion engines (ICEs).

Existing Natural Gas Plants: CEPs with batteries compete with existing gas turbines in the South, West, and Northeast of the United States.

EVs in US: Larger-bodied electric vehicles, popular in the United States, become competitive with ICE vehicles on a *capital cost* basis.



Source: RMI⁵⁸

Stepping-Stones to Globally Competitive Solar PV

Concerted actions by industry and government have helped to drive sustained improvements in some clean energy technologies. Solar's cost history provides an example that could be replicated with other technology areas to accelerate the energy transition.

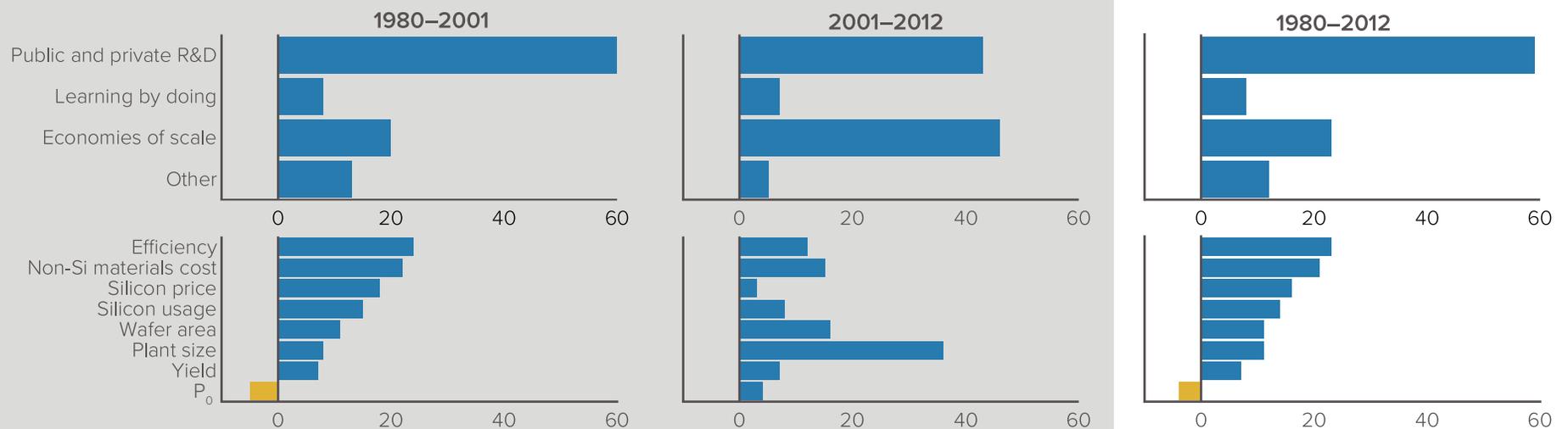
Solar modules' price drops had two main phases. In the early years, most drops were driven by R&D-enabled technical improvements.

Efficiency increases and smarter materials utilization (such as thinner saws to wring more wafers from each silicon boule) contributed to about 65% of solar modules' price drops during 1980–2001.⁵⁹ This R&D occurred in government, academic, and corporate labs around the world, notably in institutions such as the US National Renewable Energy Laboratory and Germany's Fraunhofer Institute.

EXHIBIT 35

Mechanisms Driving Solar PV Cost Declines, 1980–2012

Percent Contribution to Module Cost Reduction



Source: Energy Policy⁶⁰

In later years, price declines were mainly driven by other factors not linked to R&D. Increasing manufacturing plant sizes and their economies of scale contributed approximately 45% of the observed price drops in 2001–2012.⁶¹ The increase in plant size, and the demand required to support them, resulted not just from free markets but also from government policies around the world. The influence of government policy has strengthened in recent years.

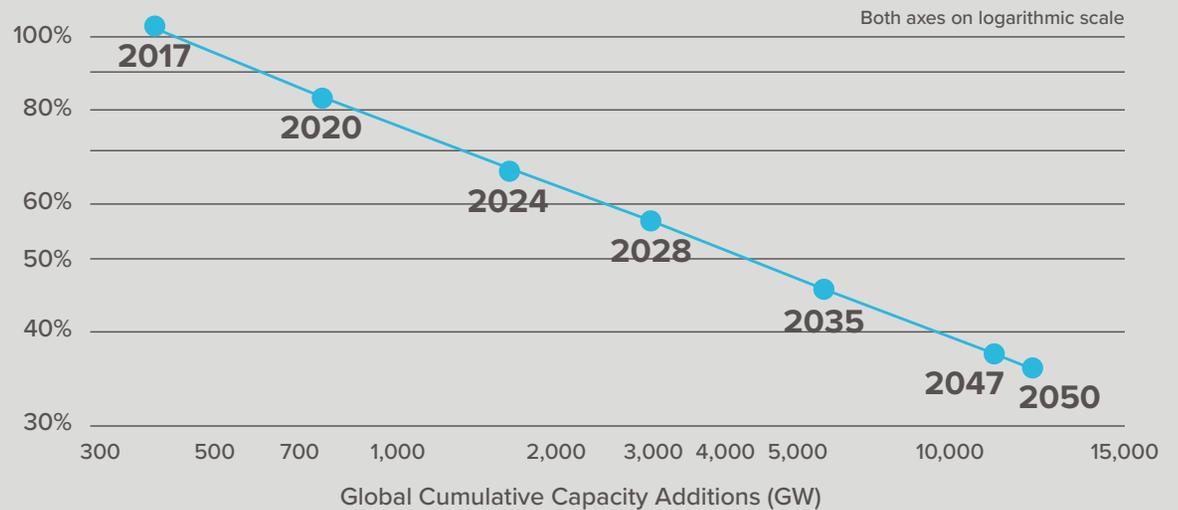
Feed-in tariffs in Germany and China, renewable portfolio standards in US states, and tax incentives in China and the United States lowered the effective cost of solar and spurred demand. Germany's willingness to pay higher early costs strongly influenced China's choice to scale up production, triggering dramatic cost drops worldwide. Private-sector innovations such as 20-plus-year power purchasing agreements and financing to shrink customers' up-front capital needs also significantly boosted demand. On the supply side, China's tax credits for suppliers rewarded capacity expansion. In India, bulk purchasing programs by the government-owned super-ESCO, EESL, cut LED costs by over 80% while distributing nearly 300 million lightbulbs, offsetting 9 gigawatts of electricity demand, and saving more than \$2 billion per year for Indian consumers.

Analysts now project sustained ongoing price declines of solar panels will help drive renewables' share of total electricity generation globally from their 2018 market share of 68% of global net capacity additions without big hydroelectric dams (see Exhibit 36).

EXHIBIT 36

The Solar PV Learning Curve at Gigawatt Scale

Unit cost relative to 2017



Source: DNV GL⁶²

Expanding the Toolkit

But what about technologies that are not yet on such steep cost decline curves? How can we pull more new winning technologies into the market sooner for greater impact in the next 10 years?

New technologies are challenged by a variety of hurdles, commonly known as valleys of death, on their path to widespread adoption. Scientists face technical hurdles. Startups face commercialization hurdles. Products face demonstration and validation hurdles. Currently, a patchwork of organizations and initiatives exists to bridge the individual valleys, such as the US ARPA-E funding basic research and engineering, incubators and accelerators helping startups refine their business models, and private equity firms providing growth capital. These disparate initiatives may help technologies cross specific valleys of death in product development, commercialization, and growth. But each requires tremendous bursts of effort, making overall progress erratic and unduly risky.

As an alternative, the institutions and actors involved in cleantech innovation could develop a better-integrated and systems-level commercialization ecosystem akin to those of the pharmaceutical and biotech industries. The estimated average cost of bringing a new drug from lab to market is \$2.7 billion. Yet academia, venture capital, and pharmaceutical companies together form an integrated value chain to successfully commercialize scores of new drugs annually.

To limit global temperature rise to well below 2°C, we must spur the momentum of cost reduction for a widening portfolio of key technologies in transportation, industry, and buildings. Exhibit 37 summarizes key technology gaps across sectors—and some promising technology solutions.

EXHIBIT 37

Key Technology Gaps and Potential Solutions

	CRITICAL NEED	DESCRIPTION	EXAMPLE TECHNOLOGIES
Electricity	Grid flexibility	High wind and solar fractions make a significant portion of generation vary, requiring balancing resources like demand flexibility, wider integration, or thermal or electrical storage	Demand-side controls and software; lithium, alkaline, and flow batteries; hydrogen electrolyzers; pumped hydro energy storage; advanced data, forecasting, power electronics
Buildings	Cooling	Global space-cooling demand is forecast to triple by 2050, equivalent to the total combined electricity use of the United States, Germany, and Japan	Barocaloric, thermocaloric, radiative surfaces; high-efficiency heat exchangers; cheap insulation and glazing
Transportation	Long-haul transport (trucking, marine shipping, aviation)	Batteries lack the volumetric or gravimetric energy density for long-haul applications	Advanced synfuels or biofuels, hydrogen, higher-energy density batteries, efficient vehicles
Industry	Carbon capture and utilization	Direct air or flue-gas CO ₂ capture may be needed to remove atmospheric CO ₂ and make synfuels or biofuels	Absorbents or CO ₂ mineralization, natural-systems carbon removal
	Steel and cement manufacture/displacement	Steel and cement manufacturing emit ~8% and 6% of global CO ₂ , respectively	H ₂ , CO, or electrolytic iron ore reduction; CO ₂ mineralization, alternative building materials like timber and carbon fiber

As wind and solar become the lowest-cost generators, managing their variability becomes a greater challenge for a largely or perhaps ultimately a wholly renewable grid. Current EV technologies are fit for most urban vehicles, but today's batteries need more energy density (with low weight, cost, and risk) for long-haul trucks, ships, and planes. Very little progress has been made in decarbonizing heavy industry—especially steel and cement, which emit 14% of global CO₂ during periods of rapid urbanization and construction.

We do not have time to wait for new technology to trickle from labs to markets. The US Apollo Program offers inspiration for rapidly developing and deploying new technology. In less than a decade, before computer-aided design, the US National Aeronautics and Space Administration (NASA) pursued nearly simultaneous research, development, and demonstration of almost unimaginable new technologies for a human moon landing and return. At its peak, the Apollo program cost 0.75% of GDP. The private sector will profitably finance most of the energy transition. More recently, the Human Genome Project successfully sequenced human DNA in under 12 years (two years ahead of schedule), through a collaboration of over 20 universities and government agencies around the world. Sequencing a human genome cost \$2.7 billion in 2003; it costs less than \$1,000 dollars now, and costs continue to fall.

Intervening to Speed Technology Adoption

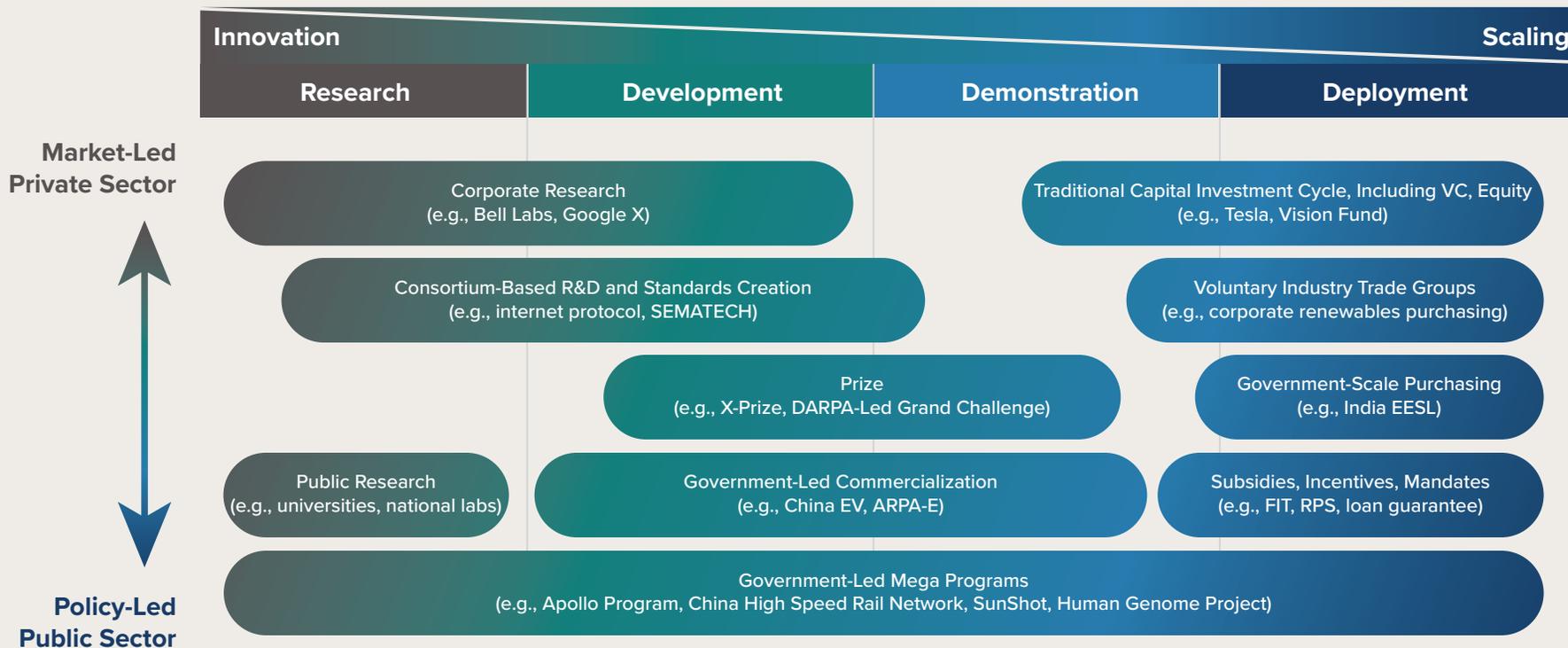
Accelerating new technology development and adoption requires different sets of interventions depending on the type of technology, its maturity, and market conditions (see Exhibit 38). For technologies that have overcome fundamental technical risks but may still be too costly, we can spur demand or supply to steepen learning curves and drive down costs. For less mature technologies, we can create ecosystems where academia, entrepreneurs, venture capital, corporations, and government coordinate seamlessly to shepherd high-impact technologies across multiple valleys of death.

Finally, collaborative actions targeted to emerging, high-leverage opportunities where new technology is being deployed can help to speed integration, learning, and deployment. For example, Deliver Electric Delhi is a pilot hosted by RMI and the Government of Delhi in India on the electrification of final-mile delivery vehicles there. The pilot involves collaboration among 35 leading private-sector organizations, including e-commerce companies, fleet aggregators, vehicle manufacturers, charging and swapping station providers, and distribution companies, with support from local government bodies like the Department of Transport. The goal of the pilot is to design, execute, document, and analyze the

deployment of 1,000 EVs in Delhi to support EV policy rollout and further actions by the private sector and cities and states beyond Delhi.

The multistakeholder collaboration through the pilot has strengthened innovation in the freight ecosystem in Delhi. Through the network of leading companies, vehicle manufacturers are getting an opportunity to work directly with fleet aggregators and e-commerce companies to enhance their product offerings as per their customers' needs. RMI also plans to collect data from the deployed vehicles, routes, and activities to support policymaking on road access for EVs, analysis of charging loads, grid capacity, and site selection for charging infrastructure.

Key Levers for Boosting Technology Development



Source: RMI

Opportunities to Boost Clean Technology

- For commercially ready but high-cost technologies (e.g., flow batteries), how can we boost supply and demand to drive down costs and enable wider adoption?
- How can the private sector, government, and academia build an integrated systems-level solution to more quickly cross multiple valleys of death for commercializing new technology?
- China has led the world in scaling wind, solar, EV, and battery manufacturing with strongly aligned government policies. How can other nations with very different policy and industrial systems learn from or partner with China to strengthen these capabilities?
- How can coordinated action in the private sector accelerate progress and boost demand, particularly where governments have been slow to act?

6

Redesigning Industry

How do we shift the way we produce, transport, and use energy and materials in global products and infrastructure?



Redesigning Industry

Accelerating emissions reductions in heavy industry, long-haul transportation, and aviation is urgently needed to set these sectors on decarbonization pathways comparable to those in electricity supply. This can be achieved through a combination of fast-action, near-term steps to reduce carbon intensity and transformative, long-term solutions—started on immediately—to increase productivity of materials and energy and to scale new supply solutions. The complete decarbonization of global goods and services will require sweeping action across sectors. The co-evolution of new product and service designs, supply chains, and technology research, development, and demonstration will fundamentally reshape commodity, energy, and transport markets. Consumer and financial sector pressures, alongside formative policy, will accelerate these changes on the final frontier of the global energy transition.

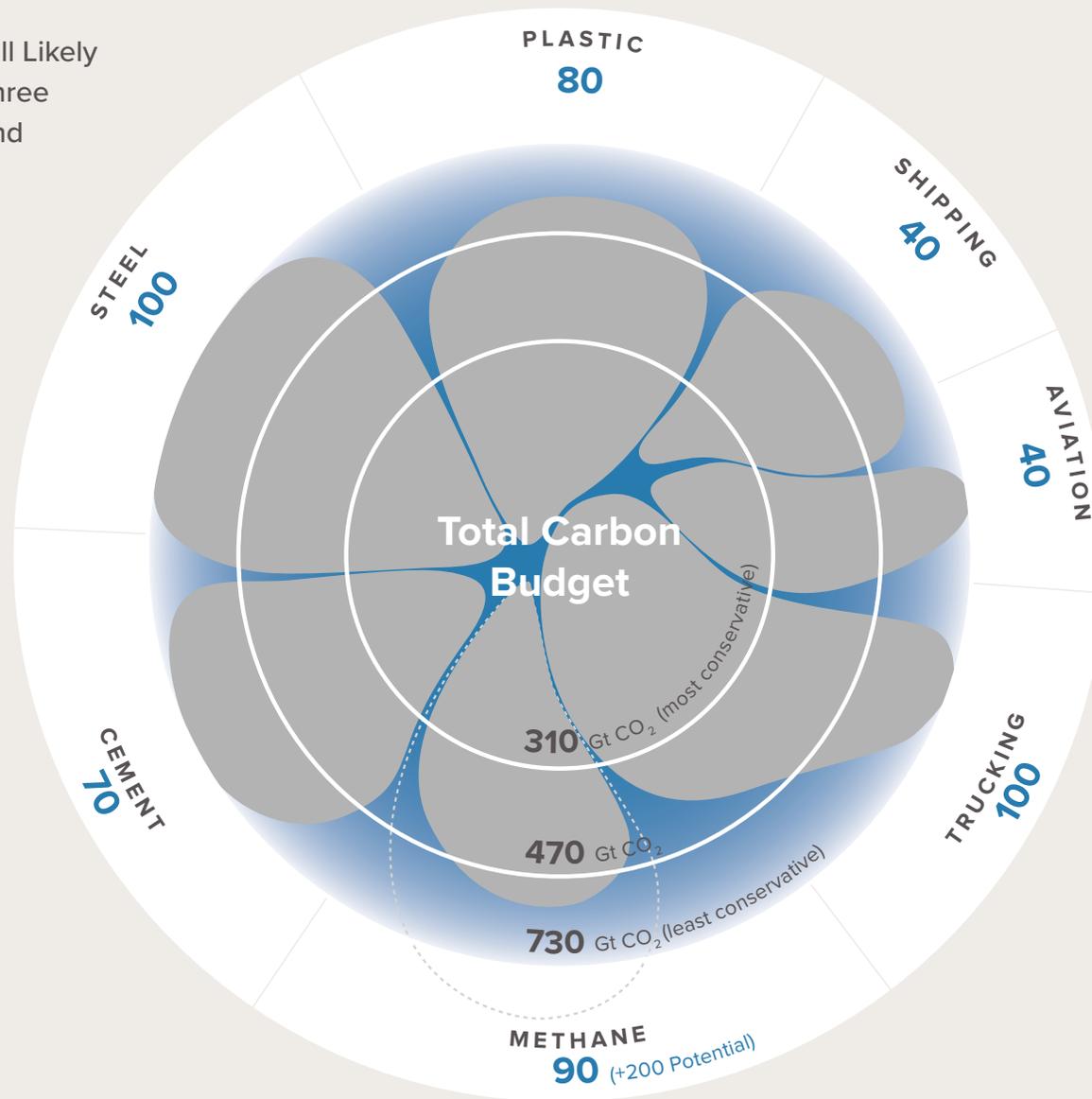
- The next industrial revolution will rely on three pathways—dematerialization, energy productivity, and zero carbon material and energy substitution—to mitigate 42% of global carbon emissions equivalent by 2050.⁶³
- Four cross-cutting and cross-sectoral levers—climate-aligned and venture finance, top-down and bottoms-up policy, competitive market dynamics, and catalytic collaboration—can realign incentives to drive industry decarbonization.
- Transforming the economy to circulate materials and energy can reduce emissions by 40% by 2050, notwithstanding the deeper potential from more frequent “deep redesigns” of products and services to incorporate technology and design improvements.
- Unexpected energy productivity improvements in materials production of 10%–20% and transport logistics and vehicle design of 20%–60% can be achieved with more rapid capital turnover.
- Rapid substitution of new material and energy supplies, like green hydrogen and steel, within two to three decades is not unprecedented and can be achieved with coordinated action on technology and market design.

Reindustrialization Is Inevitable

The industrial revolution forever changed the course of civilization by multiplying the power of human activities with the combustion of fuels. Three centuries on, the consequences of the combined growth of global population and energy intensity gives us cause to reconsider.

Today’s heavy industries produce and process raw materials and fuels, moving them across the globe in long and complex value chains, accounting for 42% of global GHG emissions. A new industrial revolution is needed to reduce the footprint of economic growth to sustainable levels. No decarbonization pathway is feasible without addressing emissions in the largest industrial subsectors: steel, cement, chemicals, long-distance transport, and natural gas. By 2030, according to the Intergovernmental Panel on Climate Change, industry sectors need to reduce emissions by between 40% and 50% to limit the worst effects of climate change.⁶⁴

The 1.5°C Carbon Budget Will Likely Be Consumed in the Next Three Decades by Commodities and Consumer Goods Alone



- 1.5°C Carbon Budget
using IPCC estimates
- Industry Sector
2020–2050 Footprint

Source: RMI, IPCC⁶⁵

Aligning Incentives for Speed

The next industrial revolution will proceed along three major pathways: reducing the amount of materials and products we use (dematerialization); producing the same amount with less energy (energy productivity); and changing production processes to zero out emissions (decarbonization).

Four levers are critical for shifting us onto these pathways within the desired time frame:

1. **Competitive market dynamics** can tap rapidly growing demand for accredited low-carbon commodities to induce new technologies and business models, helping manufacturers adopt climate-aligned pathways.
2. **Climate-aligned and catalytic finance** as investor sensitivity to climate and transition risks prompts a “climate alignment” of assets and liabilities. This reappraisal will be supported by increased physical risk awareness and venture capital risk tolerance to commercialize low-carbon industry technology solutions at a scale and on a time frame required to enable reallocation of capital away from high-carbon assets (see Challenge 7).

3. **Top-down and bottom-up policy** ranging from national industrial policy and market development support to growing public demand for accredited green products.
4. **Cross-sector, multistakeholder collaboration** focused on near-term, practical technical or market solutions to abate emissions. For example, the Global Maritime Forum advances critical thinking and discussion on sustainable global shipping and was integral to the development of the Poseidon Principles, a global framework for assessing and disclosing the climate alignment of ship finance portfolios (see Challenge 7). Systems-level collaboration on difficult challenges can align sectors with global decarbonization trajectories—or build new solutions altogether—on both 2030 and 2050 time frames.

Through these and other leveraged solutions, the ultimate cost of decarbonization as seen by the consumer can actually be quite low—and can likely fall to zero through coordinated action to test and rapidly scale new solutions. Based on the ETC *Mission Possible* analysis, the cost of decarbonizing heavy industry would be as low as 1%–2% of the consumed end products. For example, the final cost to an end consumer to decarbonize a \$60 pair of jeans is approximately \$0.30.⁶⁶

EXHIBIT 40

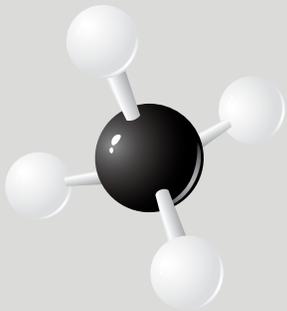
How We Can Shift onto a Zero-Carbon Trajectory for Industry

		LEVERS		
		<i>How do we speed progress down industry decarbonization pathways?</i>		
		Market evolved value chains	Finance lubricant and constraint	Policy top-down and bottom-up
PATHWAYS	Dematerialization	<ul style="list-style-type: none"> Digital disruption: 3D printing, robotics Mobility as a service displaces steel production Topological optimization of building structural forms 	<ul style="list-style-type: none"> Retained value business models are strongly rewarded by investors New business models to manage risks of extensive horizontal integration 	<ul style="list-style-type: none"> Feed-in tariffs for industrial assets in the developing world Border adjustment mechanisms in the absence of comparative advantage
		Institutional learning: systemic solutions (i.e., World Economic Platform for Accelerating the Circular Economy)		
	Energy Efficiency	<ul style="list-style-type: none"> Electrification reduces total final energy intensity Integrative design unlocks more value from less waste 	<ul style="list-style-type: none"> Efficiency-as-a-service models Green bonds for ESCO contract refinancing 	<ul style="list-style-type: none"> Public procurement metrics can include max energy intensities
Trust but verify: sectoral consensus to replace inefficient technologies on a shared schedule				
Supply-Side Substitution	<ul style="list-style-type: none"> Electrification with low-cost renewables Differentiated markets for low-carbon commodities Process innovations 	<ul style="list-style-type: none"> Investor pressure on industrials to decarbonize their footprint Reverse auctions to select new solutions at least cost 	<ul style="list-style-type: none"> Low-carbon industrial policy Electricity market designs (i.e., for seasonal H₂) 	
	Chicken and the egg: fragmented sectors can align metrics, roles for mutual decarbonization (i.e., aviation fuels)			

CASE STUDY

Mission Critical: Staunching Methane Leakage by 2025

Methane is a potent GHG responsible for around 25% of global warming. Eliminating oil and gas-related methane leakages can abate as much as 6 gigatons per year of CO₂e; this is approximately 30% of the emissions reduction needed by 2030 to leave open the possibility for global average temperature rise to remain below 1.5°C. Reliable indicators and transparent data can create a functioning market for green methane, help operators gain a deeper understanding of how best to change business processes and cultures to reduce emissions from their operators, empower investors to make investment decisions based on risks around methane emissions, improve upon existing regulations, and inspire public dialogue to ensure that the carbon footprint from natural gas production is reduced.

**Doing More With Less Materials, Before and After Initial Use**

An estimated 40% of CO₂ emissions from steel, aluminum, plastics, and cement can be eliminated through improved waste elimination, product reuse, and material recycling.⁶⁷ Designing materials to last for repeated usage or extended lifetimes is a major component of the circular economy paradigm.

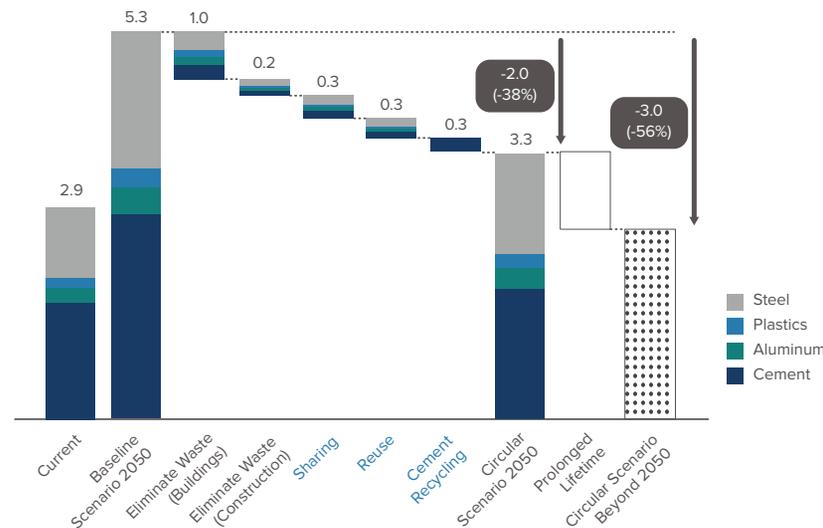
But designing to use less material with radically new techniques, thus reducing waste from each new product line for dramatic performance improvements, has not been considered in detail. From factory to finished product, less than

10% of material is used to its design capacity.⁶⁸ The other 90% is simply structural fill, occupying space between and around required material. Whereas tension structures need 80%–90% less material than compression structures, waste is the norm today because our supply chains start with bulk materials. Nature, which has evolved to avoid toxic by-products and extreme manufacturing conditions, provides many examples of material efficiency and circularity, from honeycombs to diatoms. The tools for industry to mimic nature's material efficiency are available and proven today.

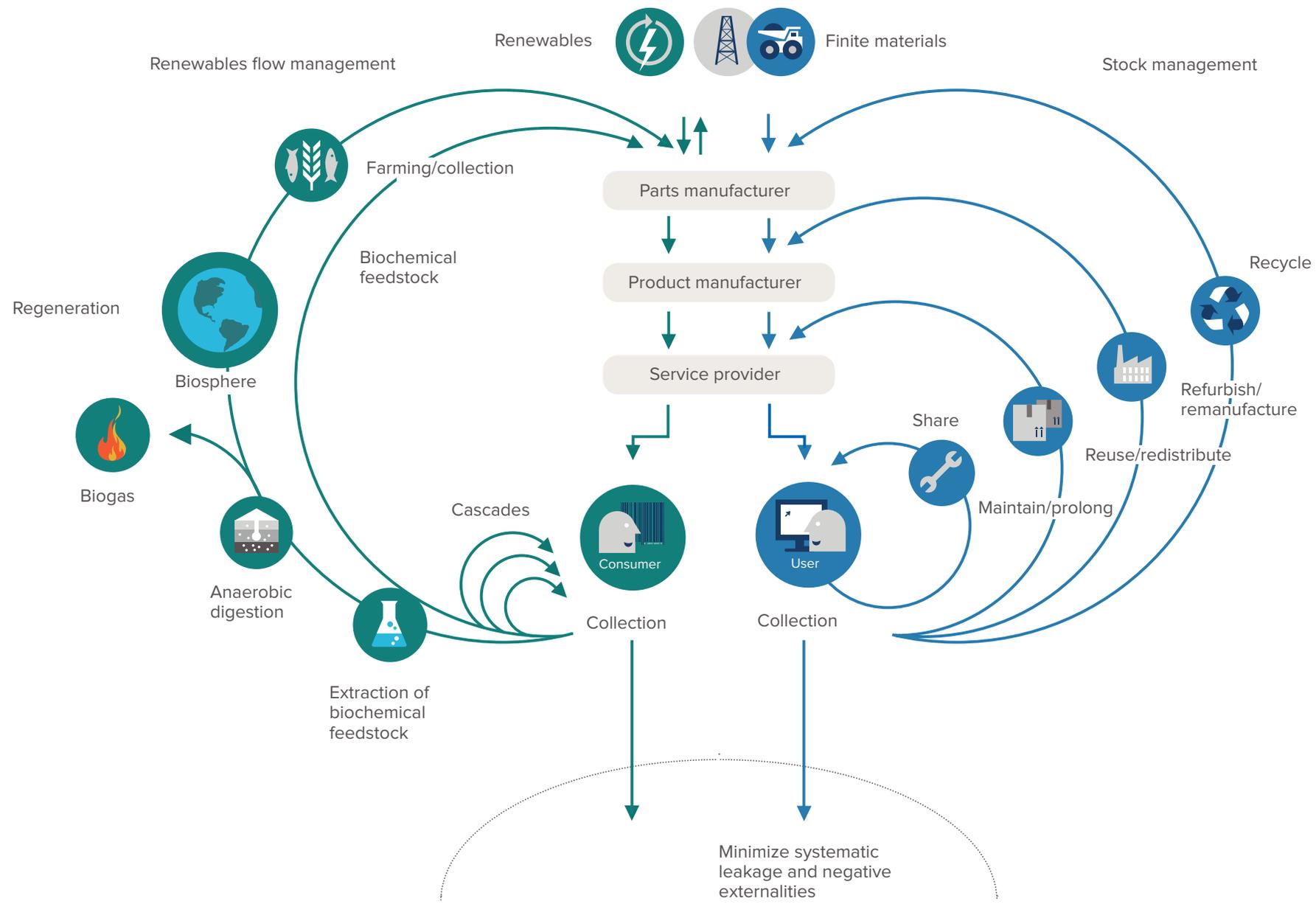
EXHIBIT 41

Circular Economy Could Reduce Annual Global Emissions 40% By 2050

Gigatons of CO₂ emissions, annually

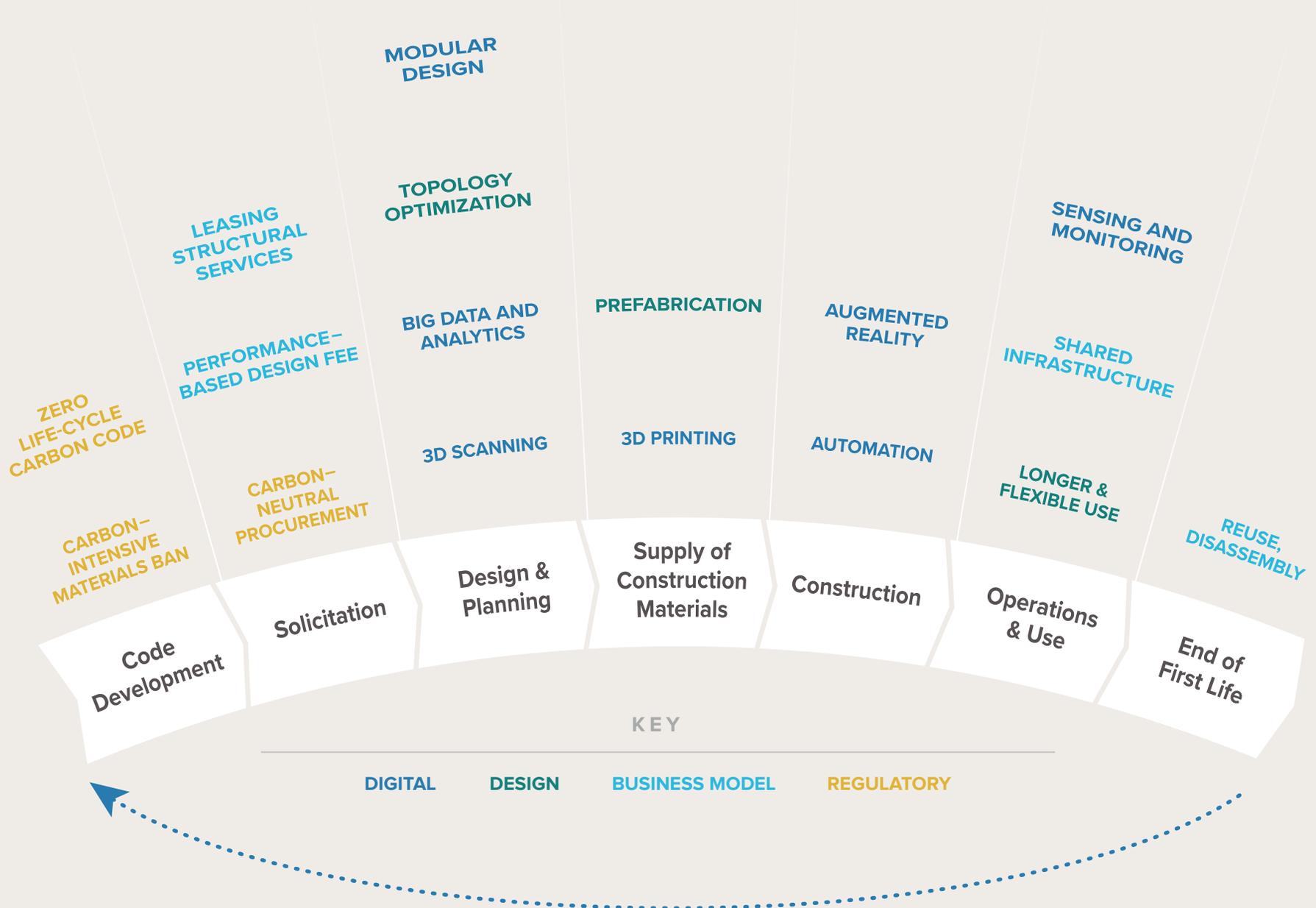


Source: Ellen MacArthur Foundation⁶⁹



Source: Ellen MacArthur Foundation⁷⁰

Harnessing Technology to Reshape the Construction Value Chain



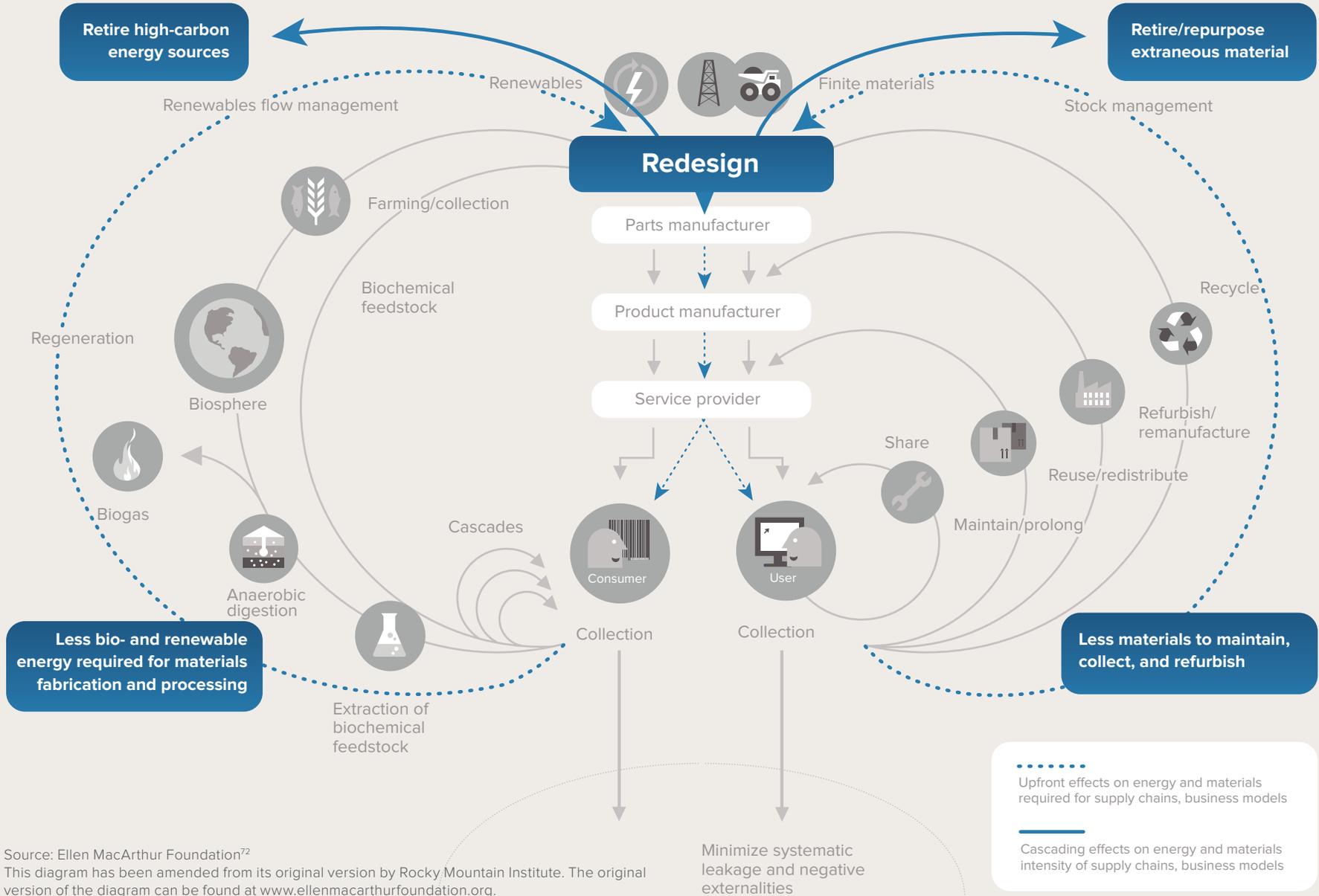
Source: RMI

Instead of evolving over millennia, each cycle of asset investment or turnover is a chance to deploy new tools throughout the value chain. (These cycles can be further accelerated with new financial tools and incentives as described in Challenge 7.) For example, machine learning can optimize designs for 3D printers to deposit form without waste (see Exhibit 43). Thus, a circular economy becomes an increasingly dematerialized one.

With some exceptions for new technologies, this **extension of the circular economy can eliminate new material additions to the system so long as technological improvement to design and delivery outpace end-use growth (see Exhibit 44)**. A new paradigm of business models, financial valuation, and policy focused on materials dynamism can help incentivize and manage the implications of this shift to how products and services materialize in the global economy.

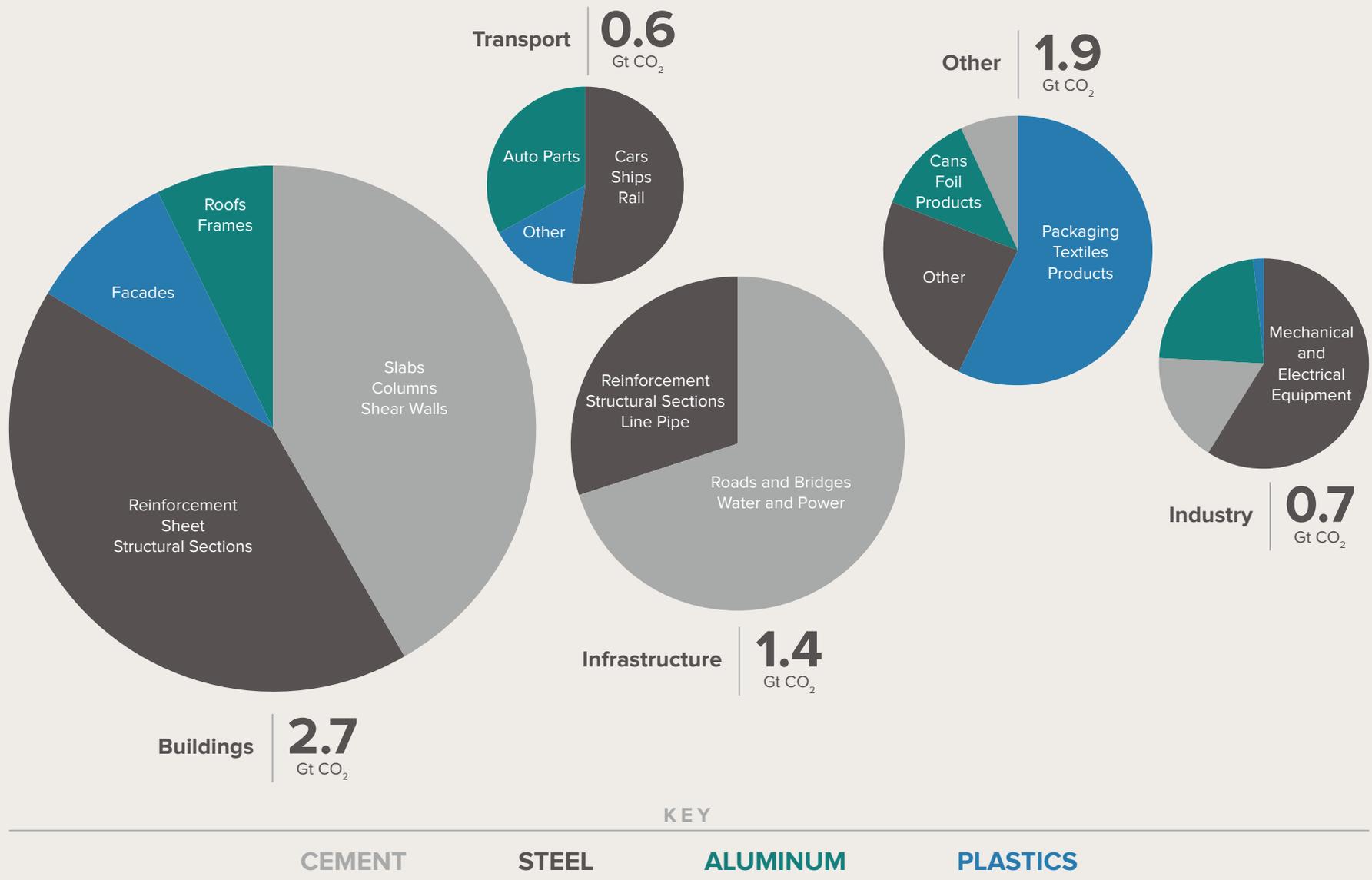
The industrial sector can be readily dematerialized because the top five end-use forms and services supported by industrial materials are agnostic to material selection or quantity (see Exhibit 45). In the buildings sector (the single largest source of demand for materials), Nearly 80% of the concrete goes into slabs which could be one-fifth the thickness by replacing steel rebar with carbon fiber reinforcement.⁷¹ This commercially proven design change can eliminate approximately 1 Gt CO₂e per year worldwide.

EXHIBIT 44
Better Design Can Further Reduce Emissions at Less Cost



Breakdown of Materials End-Use Form and Functions Indicate Extensive Redesign Opportunities

Gt CO₂



Source: RMI, Chatham House⁷³

Doing More With Less Energy

Both redesigning and recirculating materials offer untold energy productivity improvements that will ripple through the economy.

More conventionally, converting energy inputs and 5%–15% in pure process gains underlie the energy intensity improvements of the IEA Efficient World Scenario. For example, electrification can offer two to five times the improvements in energy productivity (e.g., using heat pumps).

Yet in many cases, deep industrial process efficiency opportunities remain untapped. For example, replacing long, thin, crooked pipes and ducts with their fat, short, straight counterparts reduces friction by 80%–90%. As fans and pumps use approximately one-quarter of the world's electricity, design for higher efficiency could save, in this application, one-fifth of the world's electricity—equivalent to about half of all coal-fired electricity. Associated paybacks would be realized in under a year in retrofits and instantly in new builds.⁷⁴

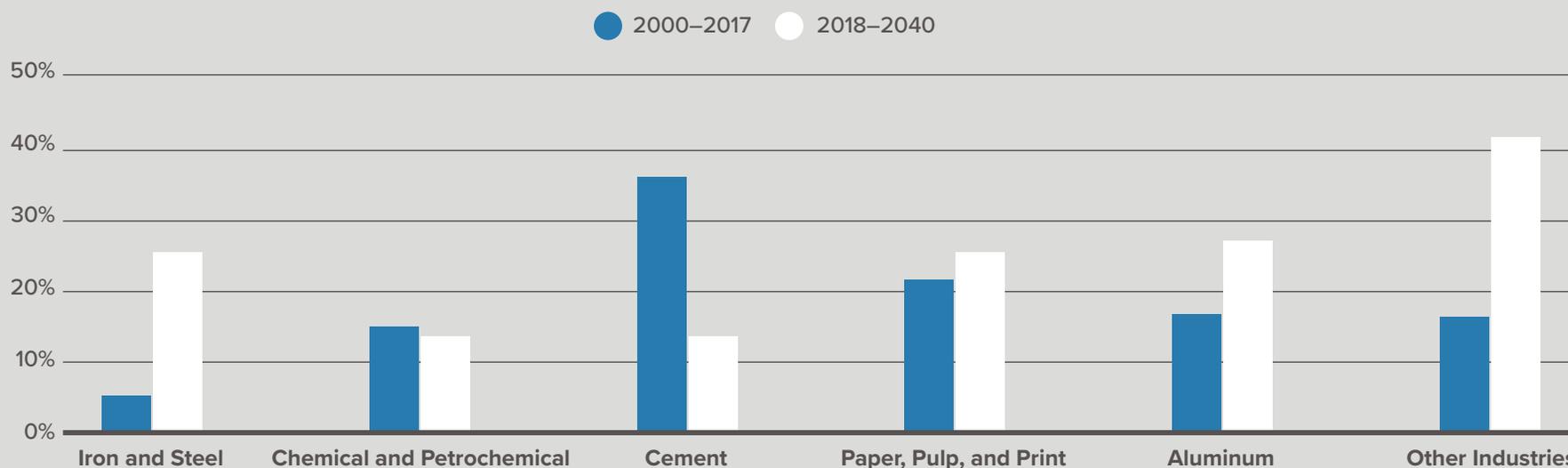
These opportunities are not limited to upstream industry. End-use efficiency in aviation and freight are largely untapped although well known. Doubled truck efficiency has already been demonstrated in existing vehicles with retrofitted streamlining and better driving. Boeing, NASA, Massachusetts

Institute of Technology, and others designed three to five times more efficient, economically promising airplanes over a decade ago. Technologies in both industries keep improving, yet risk-averse makers and buyers can cut gains significantly each generation. Increasing risk tolerance, alongside improved consumer pull where fleet turnover is predictable, can make integration of new components and clean fuels cost-competitive without sacrificing performance.

Looking from one vehicle to entire fleets, the operational savings opportunities are clear. Walmart doubled the efficiency of its fleet by matching load, location, and necessary trips. China, in an effort to reduce nearly half its truck travel, is building software to minimize or eliminate empty haul trips. And now, transparency of data lets marine freight charterers select the most efficient ship to operate, leaving the oil-guzzling ships to be scrapped.

Substantial Energy Intensity Improvements within Reach in Current Heavy Industry

Percentage Improvement in Energy Intensity by Industry Subsector Historically and in the Efficient World Scenario



Source: IEA⁷⁵

Substituting Low-Carbon Inputs

Even as external pressures grow from material improvements, industry sectors today lack the internal incentives to bridge the gap at the pace required. The main inertias preventing change are:

- Bias and gravitation toward status quo cost structures driven by long life cycles of assets.
- The standardization of commodities, implying path dependency on established production processes.
- Siloing of capital in value chains, inhibiting investments in new technology where it is needed.

But proven technology and maturing solutions can make deep decarbonization feasible and cost-effective long before 2050. Historical experience proves that major industrial transitions can happen in the span of just a few decades. Critically, demand for low-carbon value chains is rapidly growing among consumers and investors alike, creating a market opportunity

to escape global commoditization and local cartels to pull green methane and materials through value chains, new and old. Carbon-free materials such as cross-laminated timber beams and sheets and carbon fiber provide structural support with increased fire rating compared to steel while offering long-lasting carbon sequestration. New distributed and modular technologies, from hydrogen to advanced manufacturing, portend disruption of centralized high-carbon processes in the next two decades.

Three Case Studies Demonstrate That Decarbonization Might Be Radically Accelerated:

1. **Cost-competitive green hydrogen could arrive by 2030**

Polymer electrolyte membrane (PEM) electrolyzers are a keystone technology for renewably electrifying industrial sectors. Potential cost reductions are achievable in relatively marginal markets that could speed cost-effectiveness for industrial applications such as green steel (see Exhibit 47). When integrated with low-cost renewable energy generation, modular and highly rampable PEM electrolyzers create a compelling prospect for the delivery of green hydrogen, even in the absence of large-scale distribution infrastructure. Our hydrogen demand scenario indicates that PEM electrolyzers can drop below \$300/kW—**making hydrogen competitive with natural gas far below \$1.5/kg in geographies with strong wind and solar resources**—along a modest learning curve over the next decade as production cumulates to 11–12 GW. Global demand pools identified below could easily generate demand in excess of this total by 2030. Unlocking these initial demand pools is feasible, based on iterative and coordinated efforts among key businesses, policymakers, and consumers, with a particular focus in the United States, China, and Australia.

2. **Green steel: The second rapid steel transition since World War II**

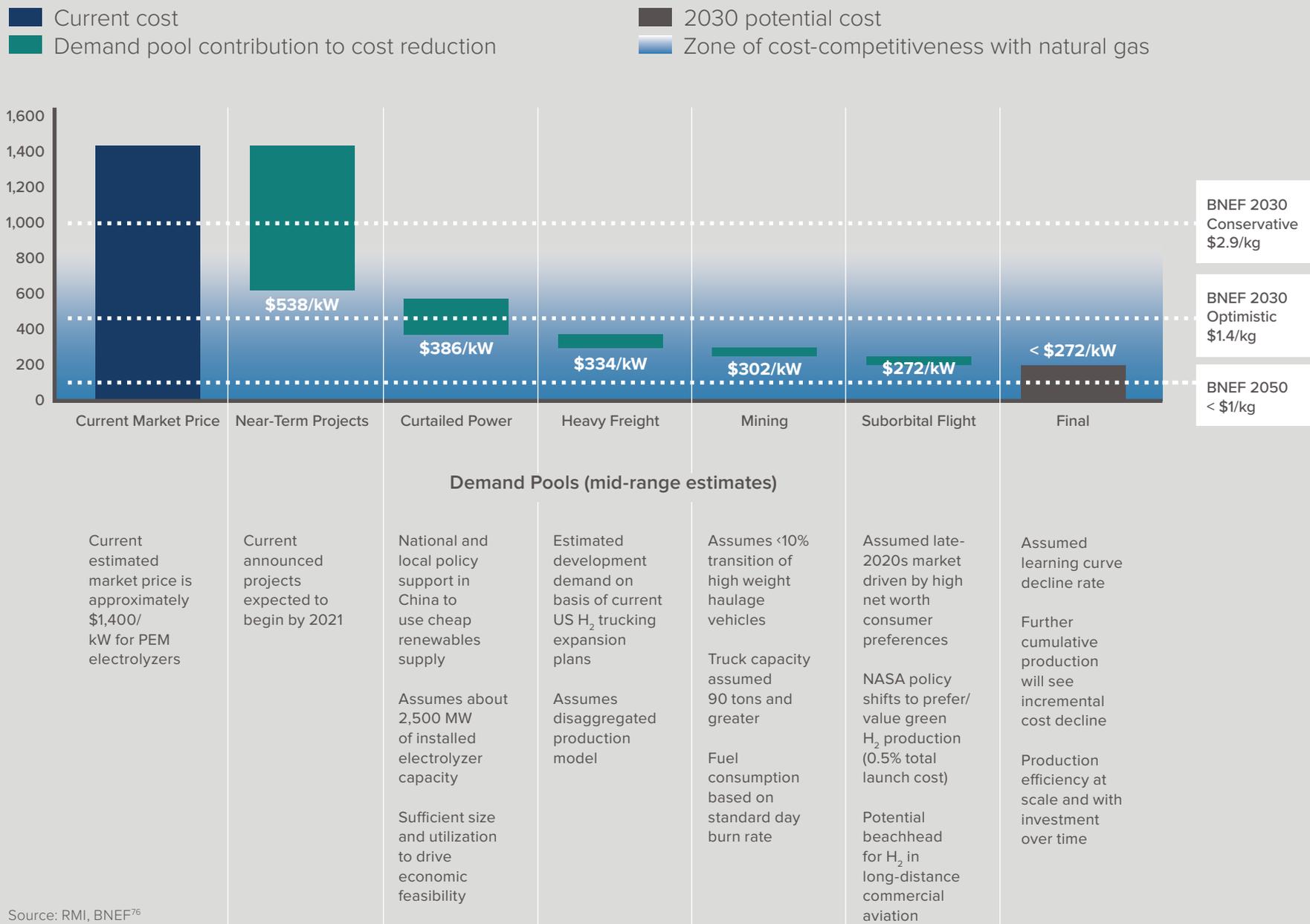
The implications of accelerated renewable energy and hydrogen cost reduction are clear: green steel visionaries like the HYBRIT coalition and Boston Metal will soon be among many producing green steel around the world. That's because the transition can happen quickly: **between 1950 and 1980, open-hearth furnaces declined from 90% of US steel production to a little over 10%**. Due to both economic and technical factors, electric arc furnaces (EAFs) and direct oxygen hearths (DOHs) took their place. Two oil crises and the recessionary fallout spurred the great Steel Crisis, which saw steel production peak in 1974 with 111 million tons and decline by 1984 to 70 million tons. As for technology, EAFs offered a smaller, easily started hearth that allowed smaller mills to compete with large steel production facilities, whereas DOHs offered significant improvements in speed of production and absolute volume. Meanwhile, emerging Chinese competitors drove these new technologies to scale to serve latent demand. The United States, with production stock concentrated around open hearth furnaces, was left to deal with the implications at home.

3. **Carbon transparency for materials and methane pulls new solutions to market**

Carbon transparency refers to the act of embedding a CO₂ footprint into a traded product at any stage in the value chain to create visibility of emissions and standardization of reporting along the entire value chain. **Transparent reporting is foundational to consumers' and investors' ability to exert decarbonization pressures on supply chains** (see Challenge 1). Once emissions are correctly accounted and entirely visible, consumers—both manufacturers and end users—will be able to discriminate between commodities and choose the ones that offer green attributes. Likewise, investors will be able to use carbon reporting to build financial portfolios aligned with their own decarbonization goals, thereby sending signals to investees about the market value of their low-carbon efforts: equity in companies that are climate-aligned will inherently become more valuable to investors, and climate de-risked project finance will be cheaper to access.

Demand Pools for Electrolytic Hydrogen Suggest Faster Cost Reduction than Expected

USD/kW



Source: RMI, BNEF⁷⁶

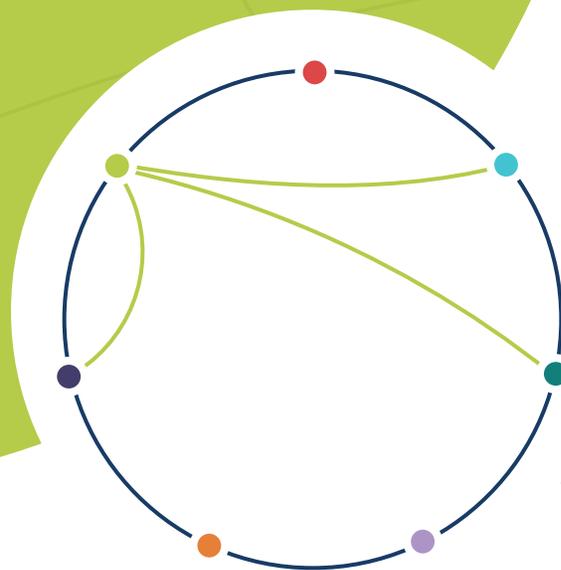
Opportunities to Redesign Industry

- How can we strengthen the network connectivity between infrastructure developers, leading-edge designers, and concessional funders to dramatically scale up next-generation materials in buildings?
- What combination of business models, policies, and consumer demand can trigger step changes in redesign and recirculation rates of current and new building and industrial materials?
- What platforms and standards can we design to unleash consumer pull for low-to no-carbon products and services, and to help the investor community push for greater climate alignment?
- How can different sectors come together to provide stepping-stones to accelerated cost reduction for green hydrogen technologies in the next three to five years?
- What other lessons can we learn from accelerated capital transitions in the past to inform coordinated action on decarbonizing this frontier in the future?

7

Securing a Swift and Fair Transition

How can we manage financial, institutional, and human aspects of the energy transition to transform all economies?



Securing a Swift and Fair Transition

The transition to a clean energy economy can mitigate the worst consequences of climate change while simultaneously delivering large net benefits to our economies and communities. A secure transition is possible only to the extent we supplant all carbon-intensive assets, existing and prospective, with zero-carbon alternatives to minimize undue physical and transition risks. As a consequence, progress at the required pace entails disruption and dislocations that must be predicted and managed. Adopting new tools and methods to **speed investment and capital stock turnover, ensure access to energy, reduce transition costs, and mitigate negative impacts on declining industries and communities** is essential to maximizing net value creation from global clean energy transformation.

Four main financial levers will help transform global energy use:

1. Building new low-carbon assets
2. Halting the build-out of high-carbon assets
3. Accelerating the retirement of existing carbon-intensive assets
4. Improving the productivity of existing and new capital stock

Unprecedented pressure on these levers is building in the financial sector amid the clean energy revolution, shifting norms and awareness of risks and opportunities among regulators and investors.

Private financial institutions, working in partnership with their corporate clients, can play a key role in steering climate-aligned lending and investment consistent with science-based sectoral decarbonization pathways.

New public institutions, such as green banks, are being created to inject capital locally and support local capacity needed to right-size and scale new solutions. In addition to supporting the build-out of new infrastructure that provides clean, cost-effective energy solutions at national and local levels, these institutions can also help orchestrate the orderly retirement of existing fossil power generation.

Anticipating and managing the impacts of energy system changes on workers and communities through better planning, workforce training, and transition support can help ensure broad and uninterrupted access to the benefits of the transition.

Reinventing Climate Finance

The bulk of global GHG emissions are emitted by assets providing essential services in the global economy—power plants generating electricity, vehicles moving people and goods, and factories producing building materials like cement and steel as well as complex manufactured goods. A timely energy transition requires transforming this capital stock and replacing it with new assets that can provide services with minimal climate impact. An integrated approach employs four financial levers:

1. Building new low-carbon assets
2. Halting the build-out of high-carbon assets
3. Accelerating the retirement of existing carbon-intensive assets
4. Improving the productivity of existing and new capital stock (see Challenge 2)

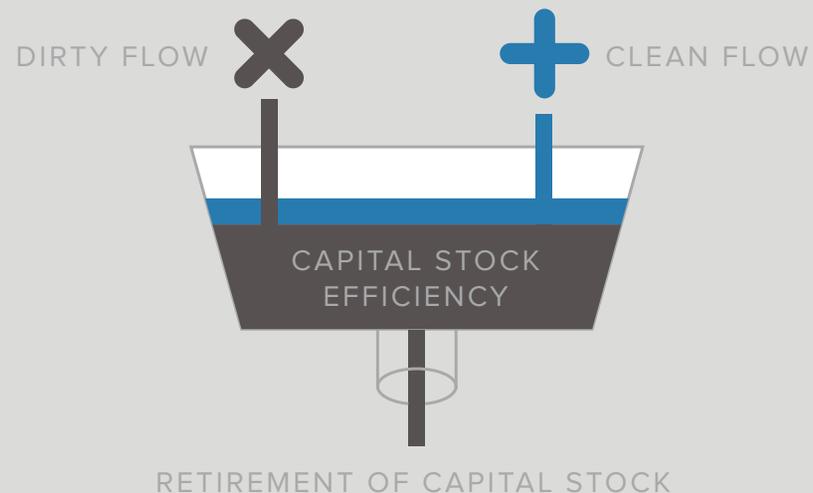
To use the analogy of replacing dirty water with clean water in a bathtub, the four levers consist of opening the clean tap, shutting off the dirty tap, expanding the size of the drain, and adjusting the amount of water needed in the first place.

The transition challenge is sizeable but manageable in the context of overall economic value creation. Globally, the value of carbon-intensive useful assets with potential to generate carbon in excess of the 1.5°C budget is estimated at \$22 trillion.⁷⁷

This is roughly 2% of gross world economic product over a decade. The new investments required to provide clean energy supply to meet world energy demand are projected to be approximately \$3 trillion per year (see Exhibit 49). The total volume required will be substantially reduced with the pace of technology change (see Challenge 5) and improved energy efficiency (see Challenge 2).

EXHIBIT 48

Four Levers to Drive Capital Stock Transformation

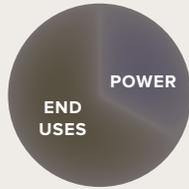


Source: RMI⁷⁸

Global Value of Capital Stocks and Flows in the Energy Transition

Transforming Capital: Stocks and Flows

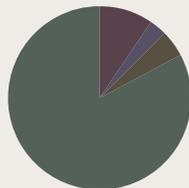
2
Halting New High-Carbon Assets
\$12 Trillion



Total 658 Gt CO₂

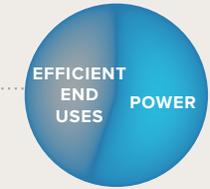
470 Gt CO₂
Carbon Budget for Limiting Warming to 1.5°C

3
Accelerating Retirement of High-Carbon Assets
\$22 Trillion



These estimates are drawn from different sources; they should not be summed. For example, if we turn over inefficient assets faster (3), less energy efficiency is required (4), and efficient end uses and clean supplies can replace them at lower total investment cost (1).

1
Clean Flows to New Low-Carbon Assets
\$40 Trillion



4
Efficiency of Existing Assets
\$30 Trillion



	Percentage of Global Average GDP Per Year	Until
1	0.5%–0.8%	2050
2	0.1%–0.3%	2050
3	2.0%–2.2%	2030
4	0.7%–0.8%	2050

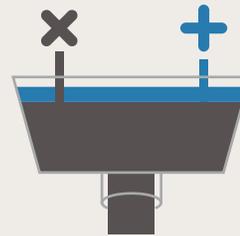
Source: RMI, BNEF, IPCC, IRENA, ETC, Nature, The New Climate Economy⁷⁹

Differentiating the Climate Finance Challenge

Capital stock transformation is key to a timely global energy transition. Transformation may require avoiding or breaking the lock-in effects of long-lived, carbon-intensive energy and industrial assets. The challenges for industrialized and developing countries are somewhat divergent, as illustrated in Exhibit 50.

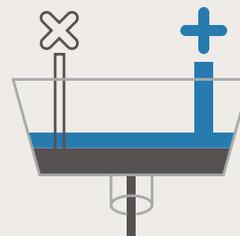
Speeding transformation in both contexts will require coordinated efforts to ameliorate the effects of decarbonization on productive local workforces. It will also require dedicated vehicles for:

1. Decapitalizing high-carbon assets (where market dynamics fail to do so fast enough).
2. De-risking and channeling investment in large volumes to capitalize new clean infrastructure, especially where inadequate access to energy limits economic development.



INDUSTRIALIZED COUNTRIES

Today's industrialized countries are more saturated with existing high-emitting capital stock, requiring a significant shift from high-carbon status quo.



DEVELOPING COUNTRIES

Developing countries, with lower asset lock-in, present an opportunity to leapfrog to a right-sized, low-carbon capital stock.

Source: RMI

Financing Transitions

As a gatekeeper of which assets are built and operated, and as the bearer of economic risk, the financial sector will be a key determinant in the success or failure of the low-carbon transition. Fortunately, investors, banks, and regulatory institutions are **shifting the role of finance from a passive enabler in the economy to an active contributor to societal goals**. Initiatives from all corners are increasing pressure on companies in the real economy to develop and communicate their decarbonization trajectories, get ahead of the transition to low-carbon assets, or face increasingly vocal (and at times painful) regulatory, voluntary, and financial market challenges (see Exhibit 51).

Increasing awareness of the potential **physical risks** of climate change has prompted a sea change among regulators charged with maintaining financial and economic stability, and investors hoping to minimize growing environmental volatility and associated losses. **Estimated at 15%–25% of per capita output by 2100,⁸⁰ these losses represent the cumulative equivalent of the Great Recession of 2008 persisting for decades.**

Alongside increasingly well understood physical risks, the potential scale of losses incurred by sudden swings in the economics of clean energy technologies has brought to attention the potential for outsize energy **market transition risks**. Indeed, if the emerging markets energy leapfrog is successful on even a fraction of the scale required to mitigate carbon emissions (see Challenge 4), already proven clean energy solutions will experience cost reductions that continue to disrupt existing oil and gas, industrial, and utility sectors valued at 27%, 34%, and 13% of global stock market indices, respectively.⁸¹

The Financial Sector Responds to Changing Climate and Energy Markets

Local Investment Policy

Local policymakers mitigate stranded asset risk on the bases of local energy costs, pollutions, and emissions

Example: *The US state of Arizona imposes a moratorium on new natural gas-based electricity due to concerns of climate and cost-competitiveness*



Financial Markets

Disruptive techno-economics impact incumbents' market shares, market growth, and valuations

Example: *GE loses \$193 billion and Siemens exits power generation after demand for natural gas turbines slows*



Decarbonization Pressure Builds in Financial Markets



Financial Regulation

Regulators respond to increasingly apparent physical and economic risks

Example: *The Network of Central Banks for Greening the Financial System shares best practices, begins exploring interactions between climate change and mandates*



Voluntary Approaches

Asset managers and investors mitigate physical and transition risks to portfolios

Example: *Climate Action 100 investors—370 in total, worth \$35 trillion—actively pressure companies to disclose carbon intensity and chart decarbonization trajectories*

CASE STUDY

Poseidon Principles Exemplify Agency in Financial Climate Alignment

The Poseidon Principles are the first global, sector-wide, and self-governing climate alignment agreement among financial institutions. Signatory banks with shipping portfolios worth \$100 billion, and more following on their heels, have agreed to reduce the carbon intensity of their portfolios in line with the International Maritime Organization's climate target of 50% absolute GHG reductions by 2050. The Principles demonstrate that:

Collective agency exists within the financial sector to align portfolios with climate, thus influencing the real economy with climate targets.

Agreement at scale (as a major percentage of a sector's loan book) supports alignment without sacrificing competitive dynamics.

A level playing field, through agreed-upon metrics and measurement protocols, can be designed to support transparency.

Together, these macroeconomic risks are encouraging financial institutions to realize their agency as drivers of the transition. This is most powerfully embodied in the recent deluge of initiatives around **climate alignment**, in which financial institutions aim to align their loan books and investment portfolios with Paris-compliant emissions reduction trajectories. Achieving this end state will require financial institutions—in partnership with the industries they finance—to use their collective leverage to support industry decarbonization pathways, like those that formed the Poseidon Principles (see case study).

Climate alignment is easier when clean technologies cross cost or performance thresholds. With renewables' newfound cost-competitiveness with coal and other carbon-intensive electricity generators, regulators, investors, and owners of coal-fired power plants are also beginning to develop a range of **innovative financial solutions**. One example, known as “steel for fuel,” has been proven to accelerate coal capacity closure, manage potential losses, and transition utility business models toward cleaner, cheaper power production.⁸²



Credit: iStock.com

Clean Capital Flows to Enable Clean Growth

Although developing economies often do not need to wrestle with a large stock of stranded fossil assets, they face the formidable challenge of driving significant new investment in clean energy. Yet over the past decade, only 13% of clean energy investments have flowed to emerging markets, excluding China, with only 0.1% invested in the lowest-income countries.

National energy sector development strategies can be designed to cost-effectively substitute efficiency and right-sized renewables for fossil fuel generation. These holistic strategies can put emerging economies on a fast track to putting energy and industrial investments in service of economic growth without sacrificing environmental and human health. This will also help minimize the risk of underutilized or stranded assets.

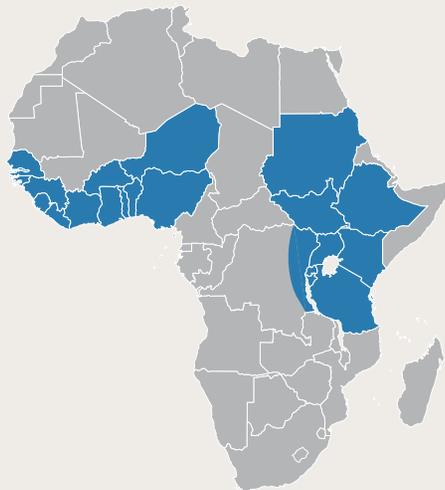
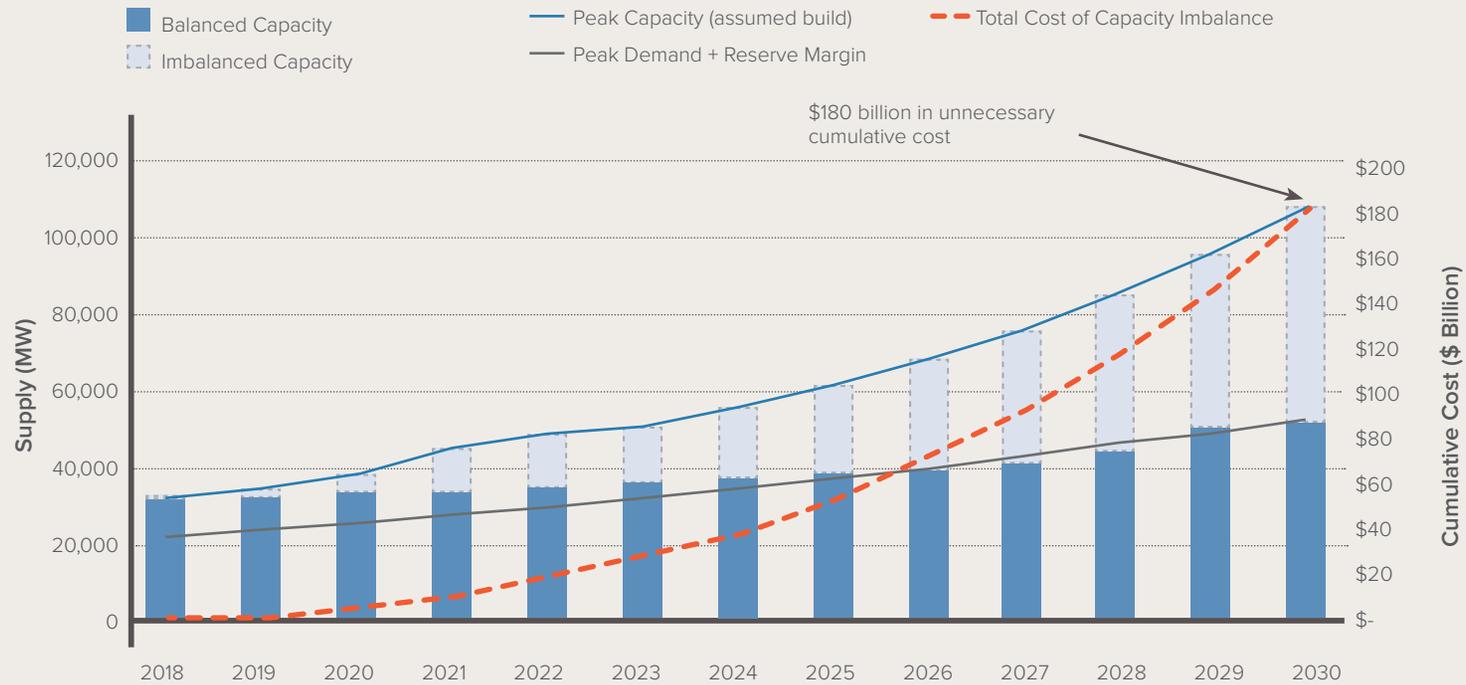
This is especially true in sub-Saharan Africa and South Asia, where 600 million and 300 million people, respectively, still lack access to reliable, affordable, and clean energy. Many of these countries' national grids fail to reach the entire population; where they do, grids may be extremely unreliable. This can severely

hamper economic growth: The Center for Global Development found that power outages cut annual sales by more than 10% for at least 25% of businesses in sub-Saharan Africa's largest economies.⁸³ Against this backdrop, a singular motivation to build electricity sector generation is understandable.

Yet without integrated resource planning with the latest demand- and supply-side technologies and market designs, electricity investments will be neither affordable nor accessible. Across East and West Africa, capacity targets for 2020 were up to eight times the expected demand. On this trendline, the cost of excess capacity through 2030 would exceed \$180 billion—two and a half times Kenya's gross domestic product in 2016 (see Exhibit 52). If planners accounted for transmission and distribution congestion and made more accurate demand forecasts, **these countries could save \$110 billion from 2023 to 2030.**⁸⁴ In Rwanda alone, a mass LED retrofit campaign could save up to \$30 million per year by offsetting diesel generator costs, paying off the investment in one year.

EXHIBIT 52

African Countries Risk \$180 Billion in Oversupply by 2030



This analysis projects planned investment in the following countries: Benin, Burkina Faso, Burundi, Côte d'Ivoire, Democratic Republic of Congo, Ethiopia, The Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Liberia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, South Sudan, Sudan, Tanzania, Togo, and Uganda

* The eastern portion of the Democratic Republic of Congo is represented on the map because it is within the territory of the Eastern Africa Power Pool, which was included in the analysis.

Source: RMI⁸⁵

The extent of these prospective savings could free up private-sector capital to coinvest in more resilient, distributed energy solutions, such as minigrids powered by solar and batteries, that minimize the risk and cost of stranded transmission infrastructure until productivity is high enough to sustain it.

But technologies like minigrids are not yet ready to receive capital in those quantities. This increases the urgency of public–private risk-sharing approaches, bulk equipment procurement strategies, and innovative schemes to improve productive uses—and thus revenues—for energy access investments and to make minigrids cost-competitive with diesel generators *today*. None of these solutions require technological breakthroughs, but rather targeted funding to support commercial viability and effective collaboration between public and private stakeholders.

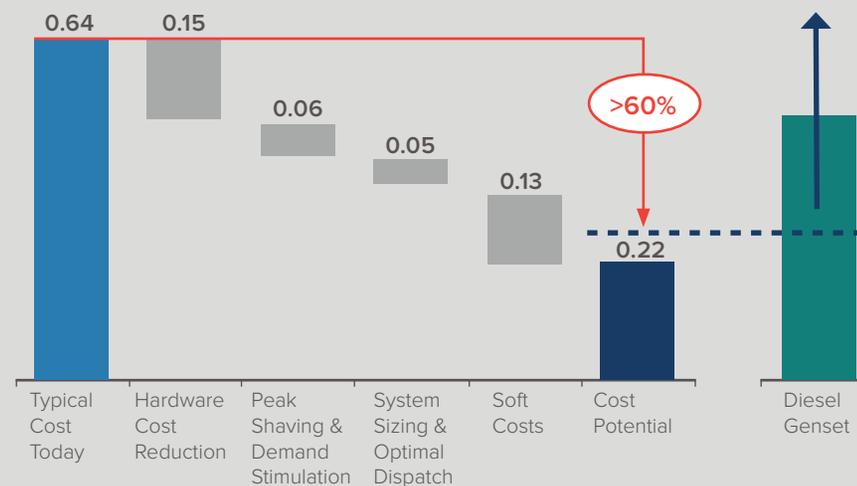
Global networks of green banks and financial advisors can help local institutions structure enabling capital solutions and navigate the web of multilateral finance. By leveraging specific elements in the capital value chain—from concessional and multilateral sources to catalyze technology cost reduction and supply chain development, to equity markets to bring technologies to scale—coordinated efforts can leverage clean energy investments

to bring new energy access solutions to cost-competitiveness and scale. Rapid and intensive coordination across the capital value chain is essential to redirect capital from pipelines of large, carbon-intensive projects to right-sized, clean ones.

EXHIBIT 53

Minigrid Cost Reduction Potentials Require Targeted Capital Support to Outcompete Diesel Generators

USD/kWh



Source: RMI

Laboring for a Speedy Transition

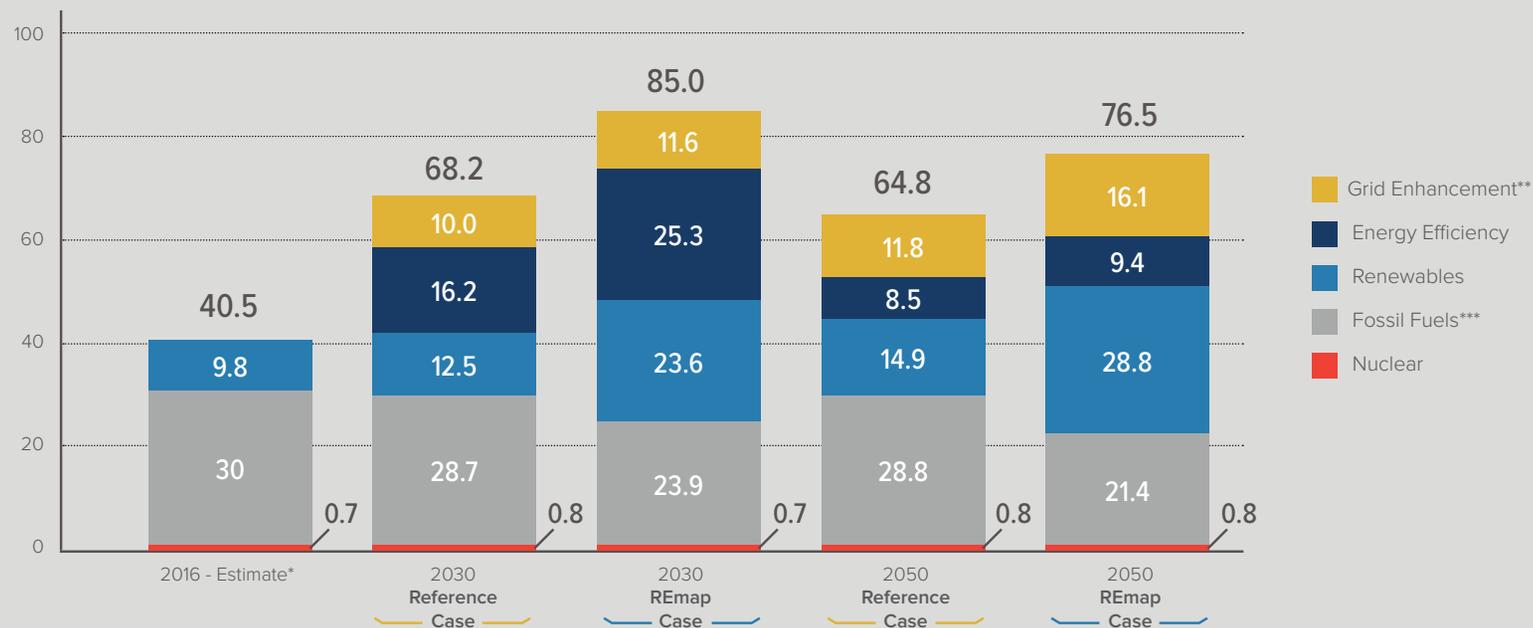
Although the capital transition from high- to low-carbon assets can create long-term net benefits for society, the impacts will be felt unequally across communities. Ensuring a smooth transition will require approaches to

ease the transition of communities that may be negatively affected by the low-carbon transition, such as those that have historically relied on carbon-intensive assets and industries for their livelihoods.

EXHIBIT 54

Net Positive Employment Benefits of the Energy Transition

Million jobs



* Estimates for jobs in energy efficiency and grid enhancement are not available for 2016.

** The jobs in grid enhancement make reference to the jobs for T&D grids and energy flexibility, created in the development, operation, and maintenance of infrastructure to enable the integration of RES into the grid.

*** Includes all jobs in the fossil fuel industry, including in extraction, processing, and consumption

Source: IRENA⁸⁶

The reduction in global fossil fuels industry employment will be outweighed by increases in employment in renewables, energy efficiency, and grid enhancement by 2030. Already, the United States—one of the most advanced energy efficiency markets in the world—employs more than 2 million people. Under an accelerated transition scenario, IRENA estimates that renewables sector employment alone will exceed fossil fuel sector employment in 2030. **In all scenarios, net global employment in fossil fuel sources will fall by between 2 million and 7 million workers, indicating peak employment is independent of the speed of transition.**⁸⁷

To meet the scale of the labor transition required, public and private institutions at all levels share a responsibility and an interest in minimizing disruption to communities. Public-sector investment in communities, social safety nets, and green industrialization strategies will be critically important, as will private-sector commitment to workforce retraining and asset repurposing.

CASE STUDY

Sharing in the Benefits of Change

Diversifying labor to scale new technology: China National Improved Stove Program

In the 1980s, China launched the National Improved Stove Program to extend sustainable fuel access to 150 million households in 16 years while limiting deforestation. To maximize employment benefits and adoption, this program offered information, equipment, and quality-control training through local governments and ESCOs. The main beneficiaries, homeowners, contributed the majority of labor and costs, which local design competitions improved.^{vi}

Social dialogues by Enel: Creating a just transition agreement with employees

Enel is a multinational power company that needs to close at least 13 GW of thermal power to reach its 2050 decarbonization goal. Enel is developing post-plant closure strategy with workers, which includes a commitment to retention, retraining, and redeployment in Enel's new generation portfolio, options for internal mobility training, and early pensions to older employees.

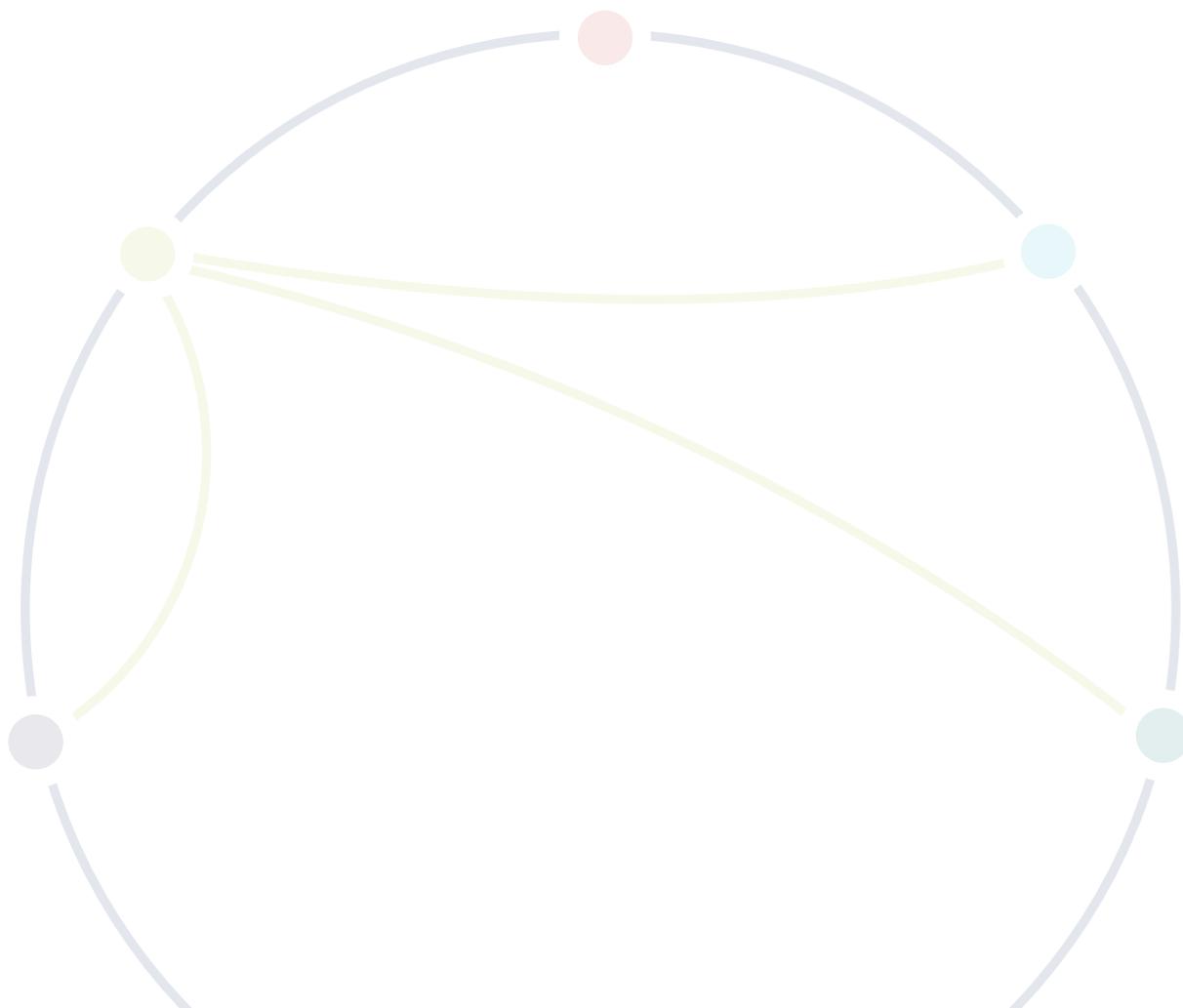
Wage stabilization to aid the labor transition in Colorado

In Colorado, the nation's first *Just Transition Office* will work to provide economic stability for workers and communities by implementing an equitable transition plan for coal-dependent communities in 2020. This plan includes administering wage differential benefits, retraining, economic development planning for affected communities, and requiring advance notice of plant or mine closures.

^{vi} Note: This example demonstrates the scale and scope of employment benefits through innovative programs alongside new investments. Whether these stoves resulted in any public health benefits remains unclear. Improved cookstoves dependent on biomass provide uncertain health benefits.

Opportunities to Secure a Swift and Fair Transition

- Are there lessons to be learned from the 2008 financial crisis about the tools available for managing systemically important financial risks with the help of government intervention (e.g., the US Toxic Asset Relief Program)?
- How can voluntary investor initiatives help to “climate-align” capital allocations, including both new investment and asset retirement?
- How can banks and regulators learn from technology cost-reduction pathways to understand the economics and timing of early asset retirement and minimize stranded assets?
- What types of planning can help ensure developing countries build right-sized, clean energy systems accessible to all?
- What tools do planners need to assess transition risks and solutions?
- Can methods be developed to assist entire nations affected negatively by the energy transition? Can a share of the cost savings created by adding renewables be directed to support a “just transition” in communities affected by the shutdown of legacy energy sources?



Endnotes

1. IRENA, *Global energy transformation: A roadmap to 2050*, International Renewable Energy Agency, 2019, <https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition>.
2. Coalition for Urban Transitions, *Climate Emergency: Urban Opportunity*, Coalition for Urban Transitions, 2019, <https://urbantransitions.global/wp-content/uploads/2019/09/Climate-Emergency-Urban-Opportunity-report.pdf>.
3. W. Brian Arthur, *The Nature of Technology: What It Is and How It Evolves*, Free Press, 2009.
4. Ibid.
5. Kingsmill Bond, Angus McCrone, and Jules Kortenhorst, *The Speed of the Energy Transition*, World Economic Forum, 2019, http://www3.weforum.org/docs/WEF_the_speed_of_the_energy_transition.pdf.
6. Alex Engel et al., *The Growing Market for Clean Energy Portfolios*, Rocky Mountain Institute, 2019, <https://rmi.org/insight/clean-energy-portfolios-pipelines-and-plants>; *New Energy Outlook 2019*, Bloomberg New Energy Finance, 2019, <https://about.bnef.com/new-energy-outlook/>; Chris Russel et al., *LED Incremental cost Study, Overall FINAL Report*, Cadmus, Inc., 2016, http://ma-eeac.org/wordpress/wp-content/uploads/MA-Task-5b-LED-Incremental-Cost-Study_FINAL_01FEB2016.pdf.
7. IPCC, *Second Assessment: Climate Change 1995*, Intergovernmental Panel on Climate Change, 1995, <https://www.ipcc.ch/site/assets/uploads/2018/06/2nd-assessment-en.pdf>.
8. IPCC, *Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2014, https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_full.pdf.
9. International Renewable Energy Agency, “Renewable Capacity Statistics 2019,” 2019, <https://www.irena.org/publications/2019/Mar/Renewable-Capacity-Statistics-2019>.
10. J. Rogelj et al., “Scenarios towards limiting global mean temperature increase below 1.5 °C,” *Nature Climate Change* 8 (2018): 325–332, <http://doi.org/10.1038/s41558-018-0091-3>.
11. J. Rogelj et al., “Scenarios towards limiting global mean temperature increase below 1.5 °C,” *Nature Climate Change* 8 (2018): 325–332, <http://doi.org/10.1038/s41558-018-0091-3>; A. Grubler et al., “A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies,” *Nature Energy* 3 (2018): 515–527 <http://doi.org/10.1038/s41560-018-0172-6>; Sergey Paltsev, *Energy scenarios: The value and limits of scenario analysis*, Working Paper 2016-007, MIT Center for Energy and Environmental Policy Research, 2016, <http://ceep.mit.edu/files/papers/2016-007.pdf>.
12. Emily Chasan, “Global Sustainable Investments Rise 34 Percent to \$30.7 Trillion,” Bloomberg, April 1, 2019, <https://www.bloomberg.com/news/articles/2019-04-01/global-sustainable-investments-rise-34-percent-to-30-7-trillion>; *Principles For Responsible Investment – Annual Report 2018*, UNPRI, 2018, <https://www.unpri.org/about-the-pri-annual-report-2018/3530.article>; Georg Kell, “The Remarkable Rise of ESG,” *Forbes*, July 11, 2018, <https://www.forbes.com/sites/georgkell/2018/07/11/the-remarkable-rise-of-esg/#722964e16951>; Ecolabel Index, accessed September 5, 2019, <http://www>.

- ecolabelindex.com; *The Transparency Imperative: Product Labeling from the Consumer Perspective*, Food Marketing Institute, 2018, <https://www.fmi.org/forms/store/ProductFormPublic/the-transparency-imperative-product-labeling-from-the-consumer-perspective>; Abbie Curtis O'Reilly, "Seafood Consumers Want Less Pollution and More Fish in the Sea," *Globescan*, August 27, 2018, <https://globescan.com/seafood-consumers-less-pollution-more-fish/>; Dave Chaffey, "Global Social Media Research Summary 2019," *Smart Insights*, February 12, 2019, <https://www.smartinsights.com/social-media-marketing/social-media-strategy/new-global-social-media-research/>; *The Latest Social Media Trends to Know*, *Globalwebindex*, 2019, <https://www.globalwebindex.com/reports/social>; *Social Media and the Evolution of Transparency*, *sproutsocial*, 2018, <https://sproutsocial.com/insights/data/social-media-transparency/>.
13. Robin Hicks, "Honest, accurate, transparent? How is China faring at sustainability reporting?," *Eco-Business*, August 27, 2019, <https://www.eco-business.com/news/honest-accurate-transparent-how-is-china-faring-at-sustainability-reporting/>.
14. *The Reporting Exchange: An overview of sustainability and corporate reporting in China*, World Business Council for Sustainable Development, 2018, <https://www.wbcsd.org/391q0>; UNEP, PRI, SynTao Finance, and UK PACT, *ESG Data in China: Recommendations for Primary ESG Indicators*, June 12, 2019, <https://www.unpri.org/download?ac=6500>.
15. World Economic Forum, "How much data is generated each day?" Accessed July 1, 2019, <https://www.weforum.org/agenda/2019/04/how-much-data-is-generated-each-day-cf4bddf29f/>.
16. Conde Nast Traveller, "An App helped Beijing fix its pollution problem," Accessed July 10, 2019, <https://www.cntraveller.in/story/an-app-helped-beijing-fix-its-pollution-problem-delhi-heres-your-cue/>.
17. Institute of Public and Environmental Affairs, Accessed September 5, 2019, <http://wwen.ipe.org.cn/about/about.aspx>.
18. U.S. Environmental Protection Agency, as cited by Rebecca Elliott, "The leaks that threaten the clean image of natural gas," *The Wall Street Journal*, August 8, 2019, <https://www.wsj.com/articles/the-leaks-that-threaten-the-clean-image-of-natural-gas-11565280375>; *Economic Benefits of increasing electric grid resilience to weather outages*, United States Department of Energy and Council of Economic Advisors, 2013, https://www.energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf.
19. US Energy Information Administration, *Monthly Energy Review*, <https://www.eia.gov/totalenergy/data/monthly/>.
20. Valérie Masson-Delmotte et al., *Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, Intergovernmental Panel on Climate Change, 2018, <https://www.ipcc.ch/sr15/>.
21. J. Rogelj et al., "Scenarios towards limiting global mean temperature increase below 1.5 °C," *Nature Climate Change* 8 (2018): 325–332, <http://doi.org/10.1038/s41558-018-0091-3>; A. Grubler et al., "A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies," *Nature Energy* 3, (2018): 515–527, <http://doi.org/10.1038/s41560-018-0172-6>.
22. A. Grubler et al., "A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies," *Nature*

- Energy 3, (2018): 515–527, <http://doi.org/10.1038/s41560-018-0172-6>.
23. Natural Resources Defense Council, *California's Energy Efficiency Success Story*, July 2013, <https://www.nrdc.org/sites/default/files/ca-success-story-FS.pdf>.
 24. United Nations Department of Economic and Social Affairs, Population Division, *World Urbanization Prospects: The 2018 Revision*, 2019, p.9, <https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf>.
 25. K. Blok, “Improving Energy Efficiency by Five Percent and More per Year?” *Journal of Industrial Ecology*, 8 (2004): 87-99, <http://doi.org/10.1162/1088198043630478>.
 26. IRENA, *Global energy transformation: A roadmap to 2050*, International Renewable Energy Agency, 2019, <https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition>.
 27. Amory B. Lovins, *Reinventing Fire: Bold Business Solutions for the New Energy Era*. Rocky Mountain Institute, 2011; and *Reinventing Fire: China: A Roadmap for China's Revolution in Energy Consumption and Production to 2050*, Energy Research Institute, Lawrence Berkeley National Laboratory, and Rocky Mountain Institute, 2016; and Marshall Abramczyk et al., *Positive Disruption: Limiting Global Temperature Rise to Well Below 2°C*, Rocky Mountain Institute, 2017, https://rmi.org/insight/positive_disruption_limiting_global_temperature_rise/.
 28. J. Rogelj et al., “Scenarios towards limiting global mean temperature increase below 1.5 °C,” *Nature Climate Change* 8 (2018): 325–332, <http://doi.org/10.1038/s41558-018-0091-3>; A. Grubler et al., “A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies,” *Nature Energy* 3 (2018): 515–527 <http://doi.org/10.1038/s41560-018-0172-6>; *Energy Transition Outlook 2019*, DNV GL, 2019, <https://eto.dnvgl.com/2019>; *Shell Scenarios: Sky*, Shell, 2019, <https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky.html>; *World Energy Outlook 2018*, International Energy Agency, 2018.
 29. *Lazard's Levelized Cost of Energy Analysis—Version 12.0*, Lazard, 2018 <https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf>; *Lazard's Levelized Cost of Storage Analysis—Version 4.0*, Lazard, 2018, <https://www.lazard.com/media/450774/lazards-levelized-cost-of-storage-version-40-vfinal.pdf>.
 30. Ibid.
 31. Mike O'Boyle et al., *The Coal Cost Crossover: Economic Viability of Existing Coal Compared to New Local Wind and Solar Resources*, Energy Innovation, 2019, https://energyinnovation.org/wp-content/uploads/2019/03/Coal-Cost-Crossover-Energy-Innovation_VCE_FINAL.pdf.
 32. “Annual Technology Baseline: Electricity,” National Renewable Energy Laboratory, 2019, <https://atb.nrel.gov>.
 33. Matt Gray et al., *Powering Down Coal: Navigating the economic and financial risks in the last years of coal power*, Carbon Tracker Initiative, 2018, https://www.carbontracker.org/wp-content/uploads/2018/11/CTI_Powering_Down_Coal_Report_Nov_2018-1.pdf?fbclid=IwAR2j-DnSFBhAlxTCVm_KS9hn16RclR2ZIxj2GgtlQ3M-rS8zLmFuLKc3TPM.
 34. Alex Engel et al., *The Growing Market for Clean Energy Portfolios*, Rocky Mountain Institute, 2019, <https://rmi.org/insight/clean-energy-portfolios-pipelines-and-plants>.
 35. Ibid.
 36. M. Chiang et al., “Storage Requirements and Costs of Shaping Renewable Energy Toward Grid Decarbonization,” *Joule* 3, 9 (2019): 2134–2153.
 37. A. Grubler et al., “A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission

- technologies,” *Nature Energy* 3 (2018): 515–527, <http://doi.org/10.1038/s41560-018-0172-6>;
- IRENA, *Global energy transformation: A roadmap to 2050*, International Renewable Energy Agency, 2019, <https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition>; *Energy Transition Outlook 2019*, DNV GL, 2019, <https://eto.dnvgl.com/2019>;
- Shell Scenarios: Sky*, Shell, 2019, <https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky.html>.
38. United Nations Department of Economic and Social Affairs, Population Division, *World Urbanization Prospects: The 2018 Revision*, 2019, p.9, <https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf>.
 39. Coalition for Urban Transitions, *Climate Emergency: Urban Opportunity*, Coalition for Urban Transitions, 2019, <https://urbantransitions.global/wp-content/uploads/2019/09/Climate-Emergency-Urban-Opportunity-report.pdf>.
 40. United Nations Department of Economic and Social Affairs, Population Division, *World Urbanization Prospects: The 2018 Revision*, 2019, p.9, <https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf>.
 41. “Cities are at the frontline of the energy transition,” International Energy Agency, September 7, 2016, <https://www.iea.org/newsroom/news/2016/september/cities-are-at-the-frontline-of-the-energy-transition.html>.
 42. United Nations Department of Economic and Social Affairs, Population Division, *World Urbanization Prospects: The 2018 Revision*, 2019, p.9, <https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf>.
 43. Jonas Bergmann et al., *Groundswell: Preparing for Internal Climate Migration*, The World Bank, 2018, <http://pubdocs.worldbank.org/en/489521526256472661/051518-Groundswell-seminar.pdf>.
 44. Markus Amann et al., “The 2018 report of the *Lancet* Countdown on health and climate change: shaping the health of nations for centuries to come,” *The Lancet*, 392,10163 (2018): 2479–2514, [https://doi.org/10.1016/S0140-6736\(18\)32594-7](https://doi.org/10.1016/S0140-6736(18)32594-7).
 45. “7 million premature deaths annually linked to air pollution,” World Health Organization, March 25, 2014, <https://www.who.int/mediacentre/news/releases/2014/air-pollution/en/>.
 46. Hilda Gomez and Soames Job, *Why Safety Matters for Sustainable Mobility*, World Bank Group, 2017, <http://pubdocs.worldbank.org/en/535391513887066669/ConNoteSeries-No11-web.pdf>.
 47. Markus Amann et al., “The 2018 report of the *Lancet* Countdown on health and climate change: shaping the health of nations for centuries to come,” *The Lancet*, 392,10163 (2018): 2479–2514, [https://doi.org/10.1016/S0140-6736\(18\)32594-7](https://doi.org/10.1016/S0140-6736(18)32594-7).
 48. *Climate Emergency: Urban Opportunity*, Coalition for Urban Transitions, 2019, <https://urbantransitions.global/wp-content/uploads/2019/09/Climate-Emergency-Urban-Opportunity-report.pdf>.
 49. Ibid.
 50. A. Grubler et al., “A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies,” *Nature Energy* 3 (2018): 515–527, <http://doi.org/10.1038/s41560-018-0172-6>.
 51. Eric Hannon et al., *An Integrated Perspective on the Future of Mobility Part 3: Setting the Direction toward Seamless Mobility*, McKinsey & Company, 2019, <https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/the%20road%20to%20seamless%20urban%20mobility/an-integrated-perspective-on-the-future-of-mobility-part-3-vf.ashx>.
 52. M.P. Bendsøe and O. Sigmund, “Material interpolation schemes in topology

- optimization,” *Archive of Applied Mechanics* 69 (1999): 635-534, https://giref.ulaval.ca/~deteix/bois/documents_references/bendsoe1999.pdf.
53. Iain Campbell and Victor Olgyay, *An Integrative Business Model for Net Zero Energy Districts*, Rocky Mountain Institute, 2016, <https://rmi.org/report-release-integrative-business-model-net-zero-energy-districts/>.
54. Luis M. A. Bettencourt et al., “Growth, innovation, scaling, and the pace of life in cities,” *Proceedings of the National Academy of Sciences of the United States of America*, 104, 17 (2007): 7301-7306, <https://doi.org/10.1073/pnas.0610172104>.
55. Martin Weiss, Martin Junginger, and Martin K. Patel, *Learning energy efficiency: Experience curves for household appliances and space heating, cooling, and lighting technologies*, Utrecht University Copernicus Institute, 2018, <https://dspace.library.uu.nl/handle/1874/32937>.
56. Ibid.
57. Alex Engel et al., *The Growing Market for Clean Energy Portfolios*, Rocky Mountain Institute, 2019, <https://rmi.org/insight/clean-energy-portfolios-pipelines-and-plants>; *New Energy Outlook 2019*, Bloomberg New Energy Finance, 2019, <https://about.bnef.com/new-energy-outlook/>; Chris Russel et al., *LED Incremental Cost Study, Overall FINAL Report*, Cadmus, Inc., 2016, http://ma-eeac.org/wordpress/wp-content/uploads/MA-Task-5b-LED-Incremental-Cost-Study_FINAL_01FEB2016.pdf.
58. Charlie Bloch et al., *Breakthrough Batteries: Powering the Era of Clean Electrification*, Rocky Mountain Institute, 2019, <https://rmi.org/insight/breakthrough-batteries/>.
59. Goskin Kavlak, James McNerney, and Jessika E. Trancik, “Evaluating the causes of cost reduction in photovoltaic modules,” *Energy Policy*, 123 (2018): 700-710, <https://www.sciencedirect.com/science/article/pii/S0301421518305196?via%3Dihub>.
60. Ibid.
61. Ibid.
62. *Energy Transition Outlook 2019*, DNV GL, 2019, <https://eto.dnvgl.com/2019>.
63. Thomas Koch Blank, Ned Harvey, and Leann Baronett, *The Next Industrial Revolution*, Rocky Mountain Institute, 2019, <https://rmi.org/insight/the-next-industrial-revolution/>.
64. Valérie Masson-Delmotte et al., *Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, Intergovernmental Panel on Climate Change, 2018, <https://www.ipcc.ch/sr15/>.
65. Charlie Bloch et al., *Breakthrough Batteries: Powering the Era of Clean Electrification*, Rocky Mountain Institute, 2019, <https://rmi.org/insight/breakthrough-batteries/>; Valérie Masson-Delmotte et al., *Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, Intergovernmental Panel on Climate Change, 2018, <https://www.ipcc.ch/sr15/>.
66. Energy Transitions Commission, *Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century*, 2018.
67. Material Economics, *Completing the Picture*, Ellen MacArthur Foundation, 2019, <https://materialeconomics.com/latest-updates/completing-the-picture>.

68. M.P. Bendsøe and O. Sigmund, “Material interpolation schemes in topology optimization,” *Archive of Applied Mechanics* 69 (1999): 635-534, https://giref.ulaval.ca/~deteix/bois/documents_references/bendsoe1999.pdf.
69. Material Economics, *Completing the Picture*, Ellen MacArthur Foundation, 2019, <https://materialeconomics.com/latest-updates/completing-the-picture>.
70. Ibid.
71. Chris Gärtner, “Climate protection and resource efficiency thanks to innovative building materials,” *Carbon, Concrete, Composite*, April 12, 2019, <https://www.bauen-neu-denken.de/klimaschutz-und-ressourceneffizienz-dank-innovativer-baustoffe/>.
72. Material Economics, *Completing the Picture*, Ellen MacArthur Foundation, 2019, <https://materialeconomics.com/latest-updates/completing-the-picture>.
73. Chatham House, *Making Concrete Change: Innovation in Low-Carbon Cement and Concrete*, 2018, <https://www.chathamhouse.org/publication/making-concrete-change-innovation-low-carbon-cement-and-concrete>.
74. Amory B Lovins et al., 2019 *Environ. Res. Lett.* 14 120201.
75. International Energy Agency, *Energy Efficiency 2018*, <https://www.iea.org/reports/energy-efficiency-2018>.
76. Bloomberg New Energy Finance, *Hydrogen: The economics of transport & delivery*, 2019.
77. Daniel Tong et al., “Committed emissions from existing energy infrastructure jeopardize 1.5°C climate target,” *Nature*, 572 (2019): 373-377, <https://www.nature.com/articles/s41586-019-1364-3>.
78. Lucy Kessler, Tyeler Matsuo, Darius Nassiry, and Paul Bodnar, *Reinventing Climate Finance: Four Levers to Drive Capital Stock Transformation*, Rocky Mountain Institute, 2019, <https://rmi.org/insight/climate-finance-levers-drive-capital-stock-transformation/>.
79. New Energy Outlook 2019, Bloomberg New Energy Finance, 2019, <https://about.bnef.com/new-energy-outlook/>; Valérie Masson-Delmotte et al., *Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, Intergovernmental Panel on Climate Change, 2018, <https://www.ipcc.ch/sr15/>; IRENA, *Global energy transformation: A roadmap to 2050*, International Renewable Energy Agency, 2019, <https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition>; Energy Transitions Commission, *Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century*. 2018; International Energy Agency, *Energy Efficiency 2018*, <https://www.iea.org/reports/energy-efficiency-2018>; Daniel Tong et al., “Committed emissions from existing energy infrastructure jeopardize 1.5°C climate target,” *Nature*, 572 (2019): 373-377, <https://www.nature.com/articles/s41586-019-1364-3>; *Better Growth Better Climate: The Global Report*, The New Climate Economy, 2014, https://newclimateeconomy.report/2018/wp-content/uploads/sites/2/2014/08/NCE-Global-Report_web.pdf.
80. Marshall Burke, W. Matthew Davis, and Noah S. Diffenbaugh, “Large potential reduction in economic damages under UN mitigation targets” *Nature* 557 (2018): 549-553, <https://www.nature.com/articles/s41586-018-0071-9#citeas>.
81. Carbon Tracker Initiative, *2020 Vision: Why you should see the fossil fuel peak coming*, 2018, <https://www.carbontracker.org/reports/2020-vision-why-you-should-see->

[the-fossil-fuel-peak-coming/](#).

82. Annie Benn, Paul Bodnar, James Mitchell, and Jeff Waller, *Managing the Coal Capital Transition*, Rocky Mountain Institute, 2018, <https://rmi.org/insight/managing-coal-capital-transition/>.
83. Vijaya Ramachandran, Manju Kedia Shah, and Todd Moss, “How Do African Firms Respond to Unreliable Power? Exploring Firm Heterogeneity Using K-Means Clustering.” CGD Working Paper 493, 2018, Washington, DC: Center for Global Development. <https://www.cgdev.org/sites/default/files/how-do-african-firms-respond-unreliable-power-exploring-firm-heterogeneity-using-k-means.pdf>.
84. Eric Wanless et al., *Creating a Profitable Balance: Capturing the \$110 billion Africa power-sector opportunity with planning*, Rocky Mountain Institute, 2019, https://rmi.org/wp-content/uploads/2018/05/seed_supply_imbalance.pdf.
85. Ibid.
86. IRENA, *Global energy transformation: A roadmap to 2050*, International Renewable Energy Agency, 2019, <https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition>.

87. Ibid.



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