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BEYOND THE SUPERCYCLE: HOW TECHNOLOGY IS RESHAPING RESOURCES

FEBRUARY 2017

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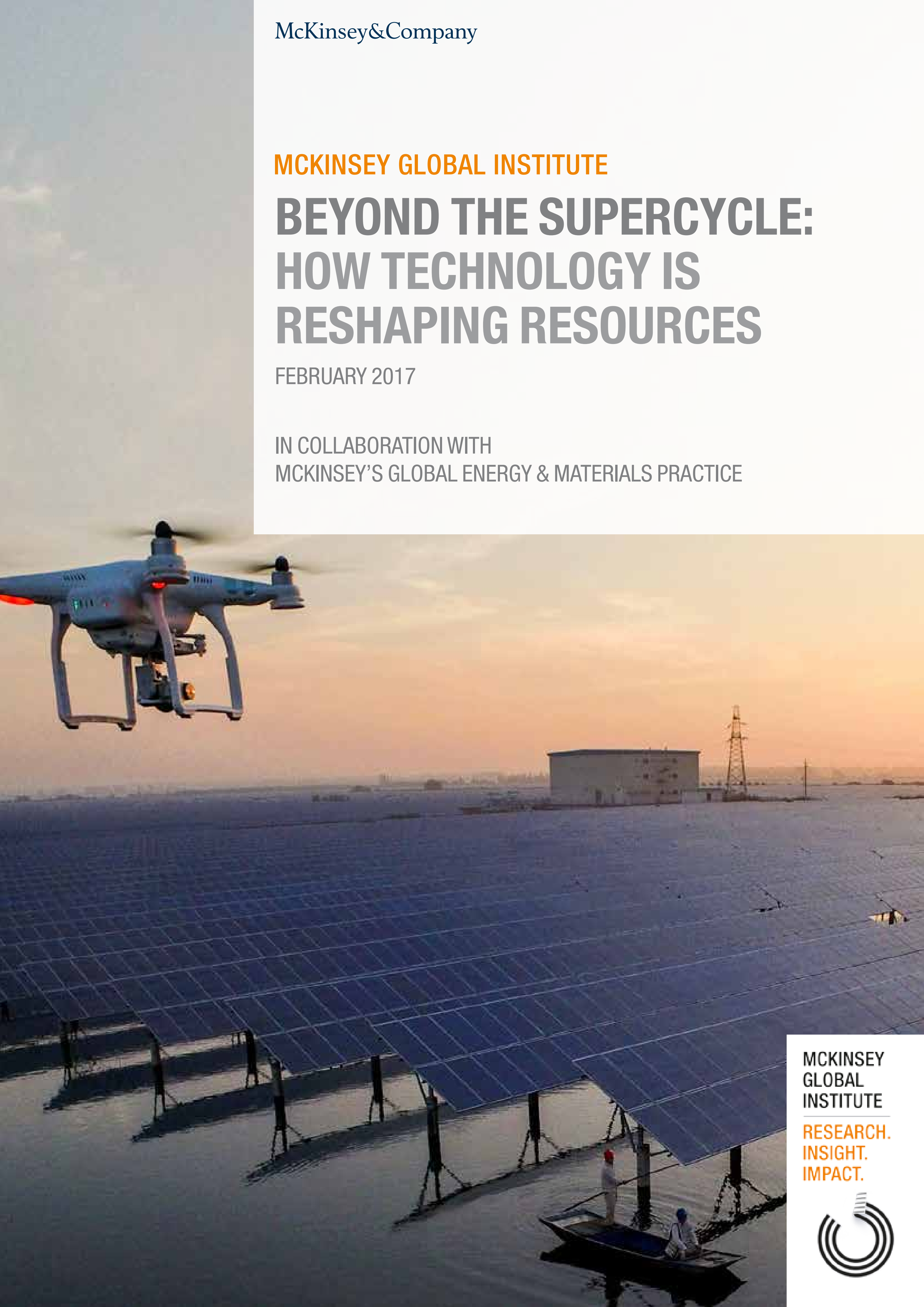

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BEYOND THE SUPERCYCLE: HOW TECHNOLOGY IS RESHAPING RESOURCES

FEBRUARY 2017

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PREFACE

What a difference five years makes. Back in November 2011, we published a report on the outlook for resources at a time when demand for resources of all types was rising sharply and commodity prices were surging toward what would become historic highs.* As we noted at the time, this upswing in demand marked a historic change from the long-term declining trend in resources, and it was driven in large part by a seemingly insatiable appetite for resources in emerging economies, in particular China. Today, the world looks very different. Global growth has slowed, China is shifting to a consumption-driven economic model, and commodity prices have dropped back. One-hundred-dollar-a-barrel oil is now a distant memory.

What has not changed, however, is a significant trend that was overshadowed by the histrionics of the commodity supercycle: a technology-driven shift that is fundamentally reshaping both the consumption and the production of resources. Technological advances from data analytics to artificial intelligence and robotics are enabling substantial efficiencies in energy use, even as they improve the productivity of resource producers and speed the emergence of renewable energies. While our previous report looked at resources and issues of sustainability, this research focuses on technological advances and their potential impact on resource industries and on the global economy over the next two decades.

This report is a collaboration between the McKinsey Global Institute and McKinsey & Company's Global Energy & Materials Practice. The research was led by Jonathan Woetzel, an MGI director and McKinsey senior partner based in Shanghai; Richard Sellschop, a McKinsey partner in Stamford; Michael Chui, an MGI partner in San Francisco; and Sree Ramaswamy, an MGI partner in Washington, DC. McKinsey senior partners Sigurd Mareels, Scott Nyquist, Harry Robinson, Occo Roelofsen, Matt Rogers, Thomas Seitz, Paul Sheng, and Thomas Vahlenkamp guided and helped shape the research. Jared Silvia and Rebecca Ross headed the research team at different times over the course of the project. The team comprised Dan Ashton, Steve Grossman, Ketav Mehta, Andrey Mironenko, Richard Mitchell, Cynthia Shih, Vaibhav Talwar, and Robin Tang.

We are grateful to current and former colleagues within McKinsey who provided valuable advice and analytical support: Jonathan Ablett, Konrad Bauer, Garrett Bray, Oxana Belik, Malte Bornemann, Shannon Bouton, Alex Brotschi, Greg Callaway, Daniel Clifton, Jeffrey Condon, Nicolas Denis, Sulabh Dhanuka, Luciano Di Fiori, Tim Ellringmann, Philip Engels, Alan FitzGerald, Christopher Forr-Rydgren, Matt Frank, David Frankel, Ryan Geraghty, Gerke Gersema, Stephan Goerner, Badri Gopalakrishnan, Liesbet Gregoir, Ines Grund, Christian Gschwandtner, Patrick Hertzke, Clive Hilton, Lars de Jonge, Natalya Katsap, Agnieszka Kloskowska, Stefan Knupfer, Florian Kuhn, Elif Kutsal, Krzysztof Kwiatkowski, Bill Lacivita, Ajay Lala, Jochen Latz, Sebastian Leger, Michael Linders, Charl Lombard, John Lydon, Mukani Mayo, Marcos Meloni, Eduardo Mencarini, Eben van Niekirk, Jeremy Oppenheim, Matthew Parsons, Arnout de Pee, Aaron Perrine, Michael Peters, Dickon Pinner, Angelos Platanias, Ignace Proot, Joe Quoyeser, Agesan Rajagopaul, Oliver Ramsbottom, Sam Samdani, Bram Smeets, Yermolai Solzhentisyn, Rembrandt Sutorius, Humayun Tai, Fraser Thompson, Pawel Torbus, Anna Trendewicz, Christer Tryggestad, Matthew Veves, Steven Vercammen, Amy Wagner, Richard Ward, Katherine Wolosz, and Kassia Yanosek.

* *Resource Revolution: Meeting the world's energy, materials, food, and water needs*, McKinsey Global Institute, November 2011.

This report was edited and produced by MGI senior editors Anna Bernasek and Peter Gumbel, editorial production manager Julie Philpot, senior graphics designers Marisa Carder, Margo Shimasaki, and Patrick White, and data visualization editor Richard Johnson. Matt Cooke, MGI director of external communications, managed communications, in conjunction with Georgia Dempsey and Justin Bambridge.

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This report contributes to MGI's mission to help business and policy leaders understand the forces transforming the global economy, identify strategic locations, and prepare for the next wave of growth. As with all MGI research, this work is independent and has not been commissioned or sponsored in any way by any business, government, or other institution. While we are grateful for all the input we have received, the report is ours, including any errors. We welcome your comments on this research at MGI@mckinsey.com.

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February 2017


Aerial view of fracking wells in Colorado.

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IN BRIEF

BEYOND THE SUPERCYCLE: HOW TECHNOLOGY IS RESHAPING RESOURCES

During the 2003–15 commodity supercycle, spending on resources including oil, natural gas, thermal coal, iron ore, and copper rose above 6 percent of global GDP for only the second time in a century before abruptly reversing course. Less noticed than these price gyrations have been fundamental changes in supply and demand for resources brought about by expected macroeconomic trends and less predictable technological innovation. Our analysis shows that these developments will have major effects on resource production and consumption over the next two decades, potentially delivering significant benefits to the global economy and bringing change to the resource sector.

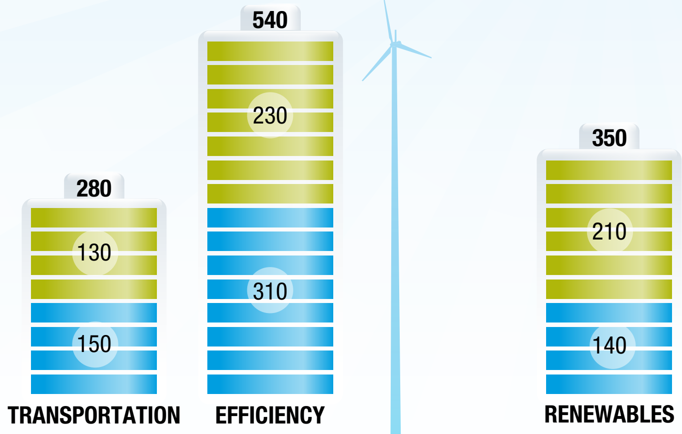
- Rapid advances in automation technologies such as artificial intelligence, robotics, analytics, and the Internet of Things are beginning to transform the way resources are produced and consumed. The advent of electric and self-driving vehicles and ride sharing, greater use of energy-efficient technologies in factories, businesses, and homes, and the growth of renewable energy sources are changing demand for resources. For producers, technology-driven transformations including underwater robots that repair pipelines, drones that conduct preventive maintenance on utility lines, and the use of data analytics to identify new fields could raise productivity.
- Scenarios we modeled show that adoption of these technologies could unlock cost savings of between $900 billion and $1.6 trillion in 2035, equivalent to the GDP of Indonesia or, at the upper end, Canada. Total primary energy demand growth will slow or peak by 2035, despite growing GDP, according to our analysis. Reduced energy demand from transportation, the proliferation of energy efficiency measures, and increased substitution of fossil fuels enabled by cost reductions in renewables could account for as much as $1.2 trillion of the total savings in an accelerated technology adoption scenario. The potential supply-side savings for producers of the five commodities we focus on—oil, natural gas, thermal coal, iron ore, and copper—could amount to $300 billion to $400 billion annually in 2035.
- The price correlation that was evident during the supercycle is unraveling, and a divergence in prospects between growth commodities and declining ones may become more significant. Demand for oil, thermal coal, and iron ore could peak and potentially decline in the next two decades while copper's prospects remain buoyant, according to our analysis, although there may be regional differences. Advanced economies could experience a faster decline in demand for oil with rapid technological adoption, for example, while emerging economies may experience demand growth, regardless of the rate of technological change. However, the resource intensity of GDP growth is continuing to decline globally.
- Policy makers could capture the productivity benefits of this resource revolution by embracing technological change and allowing a nation's energy mix to shift freely, even as they address the disruptive effects of the transition on employment and demand. Resource exporting regions whose public finances rely on resource endowments will need to find alternative sources of revenue. Importers could stock up strategic reserves of commodities while prices are low, to safeguard against supply or price disruptions, and use the savings from avoided resource spending to invest in other areas.
- For resource companies, particularly incumbents, navigating a future with more uncertainty and fewer sources of growth will require a focus on agility. Harnessing digital and other technologies will be essential for unlocking productivity gains, but not sufficient. Companies that focus on the fundamentals—driving up throughput, driving down capital costs, spending, and labor costs—and look for opportunities in technology-driven areas may have an advantage. In the new commodity landscape, incumbents and attackers, including digitally enabled outsiders, will race to develop viable business models.

THE TECHNOLOGY REVOLUTION IN RESOURCES

Technological advances will change supply and demand dynamics in the resource sector, raising productivity, increasing energy efficiency,
and unlocking value to the global economy in 2035

$900 billion to $1.6 trillion

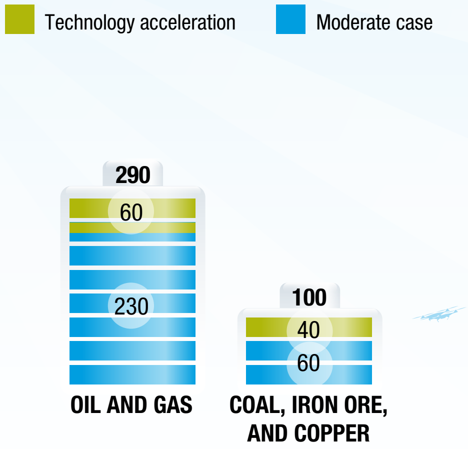
2035 run rate savings opportunity
$ billion 2015



Consumption of energy will become less intense as people use energy more efficiently in homes, businesses, and transportation.

Technological advances will help bring down the cost of renewable energies, such as solar and wind energy, partially displacing fossil fuels.

2035 increased productivity
$ billion 2015



Resource producers will be able to deploy a range of technologies including robotics, Internet of Things, and data analytics in their operations to raise productivity.

The impact of technology on 5 major commodities

OIL
Peak demand for oil could be in sight, as changes in transportation including electric and autonomous cars cut the energy intensity of transport fuel consumption.

NATURAL GAS
Demand could grow in the near term as economies decarbonize, but in the longer term, gas could face competition from renewables.

THERMAL COAL
Peak demand for coal is possible by 2020 as China pushes renewables to displace it in the power sector and natural gas advances with cost reduction and supply increases.

IRON ORE
Growth in demand for iron ore will decline as steel demand growth weakens and recycling gains ground.

COPPER
Copper's future looks buoyant, with a strong demand outlook including from the electronics industry, despite progress in efficiency in demand and supply.

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Autonomous haulage trucks at Rio Tinto's Pilbara mines in Australia.

EXECUTIVE SUMMARY

First came the "fly-up," the price spike on world markets for oil, gas, and a broad range of natural resources that began in 2003. Then came the abrupt bust, as prices tumbled and global spending on natural resources dropped by half in the course of 2015 alone. Now, even as resource companies and exporting countries pick up the pieces after this commodity "supercycle," the sector is facing a new wave of disruption.[1] Shifts taking place in the way resources are consumed as well as produced—less noticed than the roller-coaster commodity price ride but no less significant—will have major first- and second-order effects on both the sector and the global economy. These shifts are the result of technological innovation, including the adoption of robotics, Internet of Things technology, and data analytics, along with macroeconomic trends and changing consumer behavior. We see three principal effects of this technological revolution:

- Consumption of energy will become less intense as people use energy more efficiently thanks to smart thermostats and other energy-saving devices in homes and offices, and the use of analytics and automation to optimize factory usage. Transportation, the largest user of oil, will be especially affected, by more fuel-efficient engines and by the burgeoning use of autonomous and electric vehicles and ride sharing.

- Technological advances will continue to bring down the cost of renewable energies such as solar and wind energy, as well as the cost of storing them. This will hand renewables a greater role in the global economy's energy mix, with significant first- and second-order effects on producers and consumers of fossil fuels.

- Resource producers will be able to deploy a range of technologies in their operations, putting mines and wells that were once inaccessible within reach, raising the efficiency of extraction techniques, shifting to predictive maintenance, and using sophisticated data analysis to identify, extract, and manage resources.

Scenarios we have modeled suggest that these developments have the potential to unlock $900 billion to $1.6 trillion in incremental cost savings throughout the global economy in 2035, an amount equivalent to the current GDP of Indonesia or, at the top end, Canada.[2] As a result of lower energy intensity and technological advances that improve efficiency, energy productivity in the global economy could increase by 40 to 70 percent in 2035. We believe these changes will have profound implications not just for companies in the resource sector and for countries that export resources, but also for businesses and consumers everywhere.

RESOURCE PRODUCERS EMERGED WEAKENED FROM THE SUPERCYCLE, AND LONGER-TERM RESOURCE CONSUMPTION TRENDS ARE SHIFTING

Resource spending during the supercyle exceeded **6%** of global GDP

Driven by seemingly insatiable demand from China, the commodities boom between 2003 and 2015 both galvanized and jolted the global economy. For only the second time in a century, spending on the five commodities that are the focus of this report—oil, natural gas, thermal coal, iron ore, and copper—rose above 6 percent of global GDP, more than triple the long-run average, and unlike the previous fly-up in the 1970s, some of the biggest demand

---

1 A supercycle is a lengthy, above-trend movement in a wide range of commodity prices, although precise definitions differ. See Bilge Erten and José Antonio Ocampo, "Super cycles of commodity prices since the mid-nineteenth century," *World Development*, volume 44, April 2013.

2 This report is an update of our research published during the price upswing. See *Resource Revolution: Meeting the world's energy, materials, food, and water needs*, McKinsey Global Institute, November 2011.

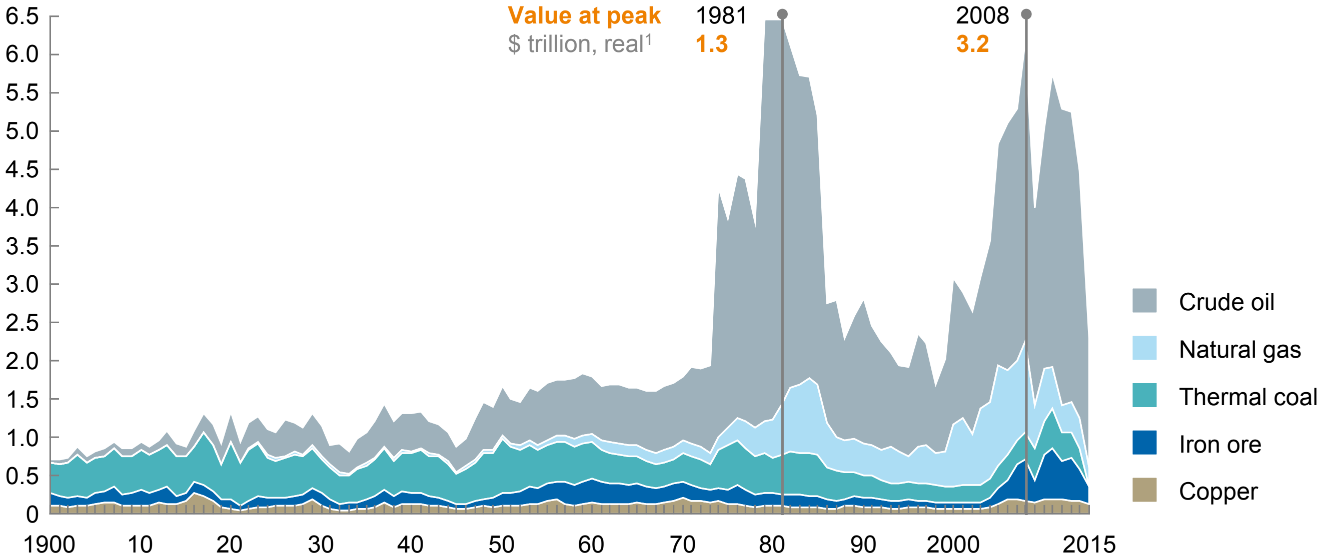
growth was in metals, not only in fossil fuels (Exhibit E1). Then came the wrenching decline in prices, which began in 2008, reversed briefly, and resumed in 2014–15, propelled by the twin forces of slowing demand and increased supply. The resource sector lost $2 trillion in cumulative shareholder value as global spending on commodities fell by 50 percent in 2015 alone.[3] Many producers—both companies and countries—are struggling to deal with the aftermath. At the same time, the outlook for the global economy has changed, and its resource intensity is waning. This will likely have a major impact on resource consumption in the years ahead.

Exhibit E1

Spending on resources during the 2003–15 supercycle exceeded 6 percent of global GDP for only the second time in a century

Resource expenditures as share of global GDP

%



1 Indexed to 1990 dollar values.

SOURCE: Rystad Energy; *BP statistical review of world energy*, 2015; World Bank; The Madison Project; USGS; McKinsey Global Institute analysis

The upswing masked declining productivity and rising costs among producers

The downturn in financial performance for producers began while prices were still rising. Their gains from the up cycle masked declining productivity and rising costs, which continue to take a heavy toll. The resource industry emerged from the supercycle severely weakened and facing significant productivity and investment challenges.

This declining performance came about as a result of growing difficulty in accessing resources, rising costs, a willingness to sacrifice productivity in return for growth, and increasing competition among producers for both assets and services. The return on invested capital for oil companies fell by about 50 percent between 2005 and 2011 (during the up cycle) and further deteriorated to the end of 2015. For the oil majors, the lifting cost per barrel increased from about $8 per barrel of oil equivalent in 2004 to more than $28 in 2014, which amounts to a 12 percent annual decline in lifting productivity.[4] Mining

3 Analysis based on data from Rystad Energy; United States Geological Survey data, January 2015; *World energy outlook 2016*, International Energy Agency; World Bank; and *BP statistical review of world energy*, BP, June 2015.

4 Data on lifting cost is the production-weighted average of costs per barrel of oil equivalent from five companies (BP, Chevron, ExxonMobil, Royal Dutch Shell, and Total) as specified in their annual reports.

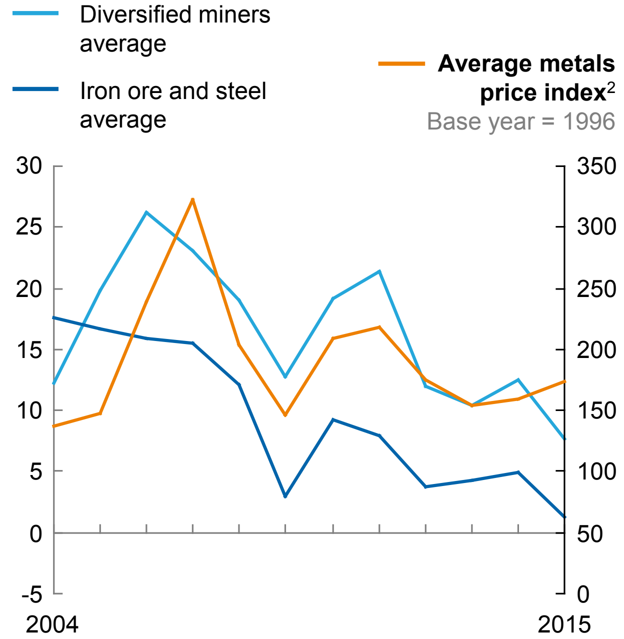
productivity has likewise been declining, by about 4 percent annually, and is at a 30-year low (Exhibit E2).[5]

Exhibit E2

Return on invested capital in the resource sector has declined along with productivity[1]

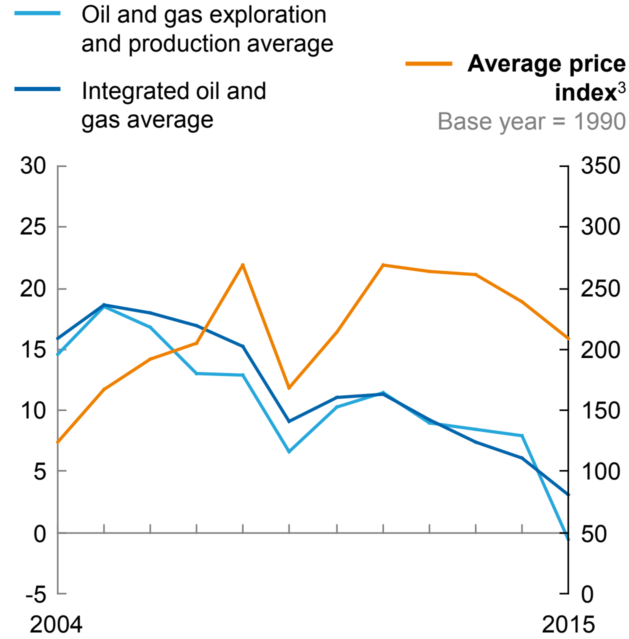
Mining

Mining companies ROIC
%

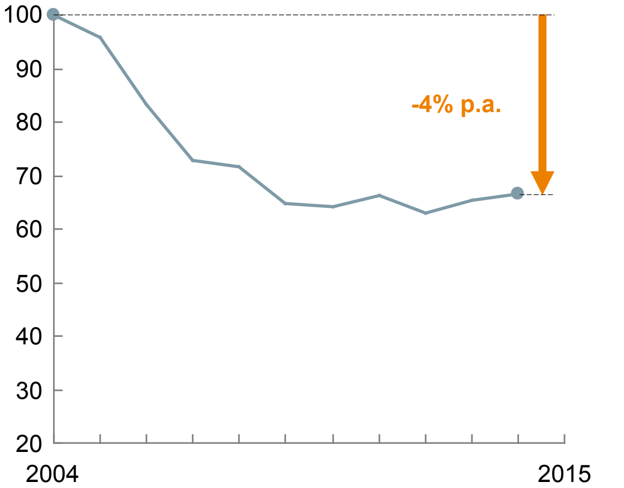


Oil and gas

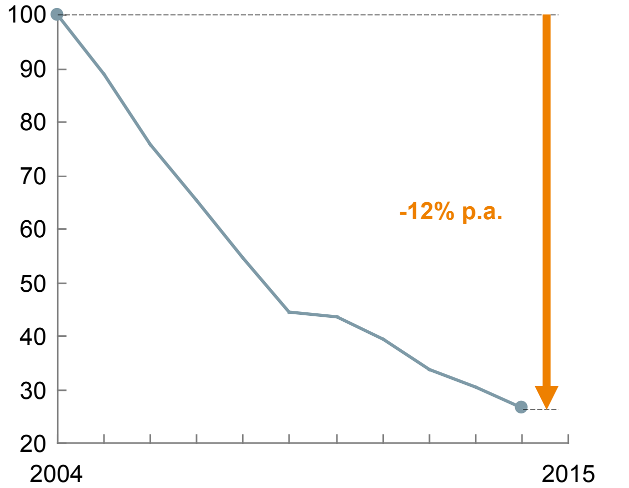
Oil and gas companies ROIC
%



McKinsey MineLens productivity index
100 = 2004



Oil lifting productivity index
Barrel of oil equivalent per $, 100 = 2004



1 Based on companies with >$5 billion market cap and >$1 billion revenue for oil and gas; >$1 billion market cap and >$0.5 billion revenue for metals.
2 Average of aluminum, thermal coal, copper, iron ore, lead, nickel, and zinc.
3 Average of WTI and Brent.

SOURCE: McGraw-Hill Companies' S&P Capital IQ; MGI Commodity Price Index; McKinsey Global Institute analysis

5 McKinsey & Company MineLens Productivity Index.

At the same time, new energy supplies became available through technological advances such as hydraulic fracturing and through a surge of new investment, both in conventional sources, including megamines, and in alternatives such as wind and solar power, which continue to make inroads in the global energy mix. This new investment reached $1 trillion per year at its height, in 2014.[6]

China's changing growth model and global demographic and energy consumption trends will affect future resource demand

China's rapid industrialization, its urbanization on a massive scale, and its surging economic growth were the primary factors that drove up prices of metals during the supercycle; by 2015, China was consuming more than half of the global supply of iron ore and thermal coal and about 40 percent of the world's copper. However, the end of the supercycle coincided with a shift within China, as it began transitioning from an investment-driven economic model to a services- and consumption-led one, and reduced its appetite for additional resources. This will affect resource demand going forward.

The abrupt fall of commodity prices has not been the boon to the global economy that many economists had expected. Lower commodity prices could in theory act as a stimulus to consumption and growth, but the shock of the downturn exacerbated prevailing trends of weak investment and job creation, slowing trade and economic growth, and increasing deflationary risks.[7]

The outlook for projected global GDP growth over the next two decades is more subdued than it was in the years before and during the supercycle.[8] This is due in part to global demographic trends, including the declining share of working-age population in countries from Japan to Germany. China's working-age population has been in decline since 2012 and could fall by more than 20 percent by 2050.[9] Productivity will need to compensate for employment declines in order for GDP growth to accelerate—but measured productivity growth has been weakening in the past decade.[10]

70%
decline in China's resource intensity per unit of GDP in 1980-2010

Could there be another China, one or several large emerging economies with voracious appetites for resources which unleash another supercycle? Several factors suggest that could be unlikely. In addition to a slower pace of GDP growth than we have seen historically, the resource intensity of this growth will be lower, continuing a declining trend that dates to the 1970s. Emerging economies will continue to drive demand for resources as infrastructure is built out and citizens consume more goods. However, no other emerging economy, including India, is likely to replicate the scale or the investment intensity and resource intensity of China's industrialization. That is because much of this economic growth will benefit from technology-enabled improvements in resource productivity that are the focus of this report. China itself is illustrative of this trend: while its economy increased 18-fold from 1980 to 2010, energy consumption increased only fivefold. Energy intensity per unit of Chinese GDP declined by about 70 percent during the same period.[11] In advanced

6 Rystad Energy; World Bank; *BP statistical review of world energy*, BP, June 2015.

7 Maurice Obstfeld, Gian Maria Milesi-Ferretti, and Rabah Arezki, *Oil prices and the global economy: It's complicated*, IMFdirect, March 24, 2016; John Baffes et al., *The great plunge in oil prices: Causes, consequences, and policy responses*, World Bank Group Policy Research note number 15/01, June 2015; Rabah Arezki and Olivier Blanchard, *Seven questions about the recent oil price slump*, IMFdirect, December 22, 2014; Aasim M. Husain et al., *Global implications of lower oil prices*, IMF staff discussion note number 15/15, July 2015.

8 In this report we assume an average annual global GDP growth rate of 2.7 percent to 2035. This is a projection from McKinsey & Company's proprietary Global Growth Model, which provides complete time-series data for more than 150 concepts and 110 countries over 30 years. See the technical appendix for details.

9 Joe Myers, *China's working-age population will fall 23% by 2050*, World Economic Forum, July 25, 2016.

10 For a detailed discussion of the global economy's slowing growth and productivity challenge, see *Global growth: Can productivity save the day in an aging world?* McKinsey Global Institute, January 2015.

11 *Bringing China's energy efficiency experience to the world: Knowledge exchange with Asian countries*, World Bank, June 27, 2014.

economies, meanwhile, peak consumption of many mineral resources could become a reality as technology makes economic activity more productive and as these economies continue their shift to more consumer-driven, service-centric growth.

THE $1 TRILLION TECHNOLOGY OPPORTUNITY FROM RESOURCES

In the past, changes in the resource sector have often come about as a result of regulation. Over the next two decades, however, we expect technology and its effect on costs will be the main drivers of change and bring significant disruption to the sector, although policies and regulations could still have a substantial impact. We model two scenarios for resource supply and resource demand. The first is a "moderate" technology adoption case, which assumes improved energy productivity from the greater deployment of technology to support energy efficiency and reduce the cost of renewables, as well as increased productivity for resource producers. The second scenario, which we call a "tech acceleration" case, assumes a faster rate of adoption of technologies and therefore greater energy and resource productivity.[12] For both of these scenarios, we assume that the productivity of resource extraction for our five focus commodities will improve as oil and gas and mining companies deploy robotics, data analytics, Internet of Things, and other technologies.[13] The main difference between the two scenarios is the pace and extent of technological adoption by both producers and consumers.

We find that the incremental savings to the economy from technology-driven changes in 2035 could amount to between $900 billion and $1.6 trillion, depending on the scenario, from a combination of demand reduction, substitution, and increased productivity by resource producers. These figures reflect the opportunity to reduce spending on resources and redeploy the savings to other, more productive parts of the economy.

At least two-thirds of this saving is derived from reduced demand for energy as a result of greater energy productivity and from growing use of renewables (Exhibit E3).[14] The technology payoff from resources will have far-reaching benefits for the global economy. In the United States, for example, while resources make up only 5 percent of GDP and 8 percent of employment, the sector accounts for one-third of total capital expenditure and 40 percent of input costs in housing, transportation, and food—the three largest items in the median household budget.[15]

By 2035, annual fossil fuel consumption could drop by at least

140M

terajoules

The combination of increased efficiency in energy use and a shift to renewable energies could mean that primary energy demand peaks in 2025 in a tech acceleration scenario. Even in a moderate case scenario, without accelerated deployment of technology, total primary energy demand growth would slow by 2035, despite growing GDP. Moderate technology adoption could reduce fossil fuel consumption annually by more than 140 million terajoules in 2035 compared with a scenario in which there is no improvement in energy productivity. The tech acceleration scenario would cut annual consumption of fossil fuels by a further 100 million terajoules. At today's prices, this represents a reduction of 13 percent in resource expenditure by 2035 in the moderate case and of 26 percent in the tech acceleration scenario.

The projected reduction in fossil fuel consumption will have an impact on greenhouse gas emissions; in our moderate technology adoption case, emissions will continue to increase through 2035 but at a slower pace of growth, while in the tech acceleration scenario,

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12 We developed our models with help from our colleagues at McKinsey & Company Energy Insights and the McKinsey Basic Materials Institute. See the technical appendix for details of our methodology.

13 We calculated the increased productivity as compared to a reference case that used the same macroeconomic assumptions but assumed no further technology adoption beyond today's levels. See technical appendix.

14 Energy productivity is defined as the terajoules of energy required to generate a unit of GDP.

15 *The US economy: An agenda for inclusive growth*, McKinsey Global Institute, November 2016.

emissions will peak in 2025 and then start to decline. However, even under this latter scenario, the decline in CO2 emissions will not on its own be sufficient to meet international targets agreed at the Paris climate change conference in December 2015.

Exhibit E3

Technology will create opportunities for increased productivity

Moderate case | Technology acceleration

		Run rate savings opportunity, 2035 ($ billion, 2015): Moderate case	Technology acceleration	Total	Cost reduction vs. reference case[1] (%): Moderate case	Technology acceleration	Description of opportunity
Reduced energy demand	Transportation	150	130	280	13	24	Disruption in the transportation sector from electric and autonomous vehicles and ride sharing reduce energy demand, particularly fossil fuels
	Efficiency	310	230	540	12	21	Increased energy productivity of the economy due to shifts away from manufacturing, smart thermostats and other devices in homes and offices, and technology-optimized energy in factories
Substitution	Renewables	140	210	350	16	40	Substitution of fossil fuels for power by renewables as costs decline, resulting in increased energy conversion efficiency
Increased productivity of resource producers	Oil and gas	230	60	290	19	25	Adoption of automation, Internet of Things, data analytics, and other sector-specific innovations enable improvements in productivity for resource producers
	Coal, iron ore, and copper	60	40	100	14	22	
Total		**890**	**1,570**				

1 The reference case used the same macroeconomic assumptions but assumed no further technology adoption beyond current levels

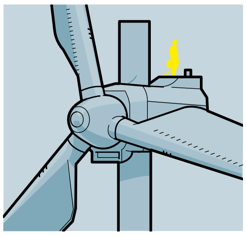
NOTE: Numbers may not sum due to rounding

SOURCE: Energy demand based on demand scenarios from *Global energy perspective*, McKinsey Energy Insights; resource productivity based on McKinsey Basic Materials Institute; additional analysis by McKinsey Global Institute.

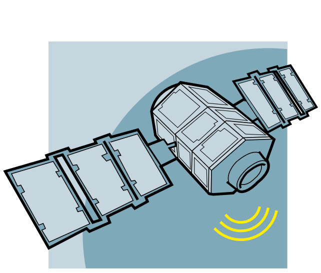
Technology can improve the efficiency of resource use and reduce consumption

A significant increase in the energy productivity of the global economy will come from changes in the transportation sector, increased energy efficiency in industrial, residential, and power usage, and greater substitution by renewables (see illustration, "Technology will change the ways consumers live and reduce resource consumption"). We estimate that this combination of reduced demand and substitution could amount to a total annual savings opportunity in 2035 of between $600 billion in a moderate case and almost $1.2 trillion in a tech acceleration case.

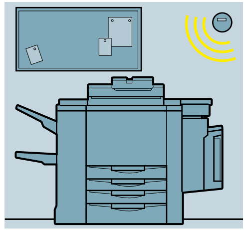
Technology will change the ways consumers live and reduce resource consumption



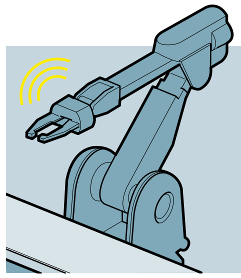
1. Renewable energy may become the cheapest form of power, used in a combination of decentralized and centralized sources.



2. Long-haul transportation adopts greater levels of autonomy as **telematics of travel patterns**, platooning, and analytics enable greater fuel economy.

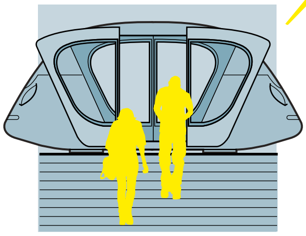


3. Electrical sensors in the office and home enable optimization of heat and light based on usage, weather, and occupancy data.

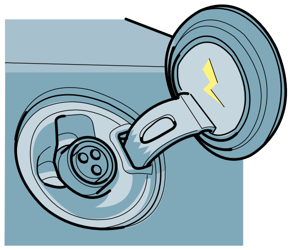


4. Industrial sites capture efficiency improvements with sensors, analytics, and automation, improving overall productivity and safety.

5. Utilities communicate with users and devices to identify optimization opportunities like retrofits or upgrades to new appliances.



6. Autonomous ride sharing services collect passengers at their homes, optimizing route and picking up other commuters to carpool, reducing number of vehicles on the roads.



7. Electric vehicles may account for the majority of new car sales, taking advantage of their lower total cost of ownership.

McKinsey&Company | Source: McKinsey Global Institute analysis

15%
of new cars sold in 2030 could be fully autonomous

Transportation, which accounts for more than half of total primary oil demand, may experience significant shifts in the future as improved engine performance and fuel efficiency, and innovation in technology-enabled mobility such as self-driving and electric vehicles, come to the fore. McKinsey has estimated that 15 percent of new cars sold in 2030 could be fully autonomous.[16] Autonomous vehicles will be more fuel efficient. Electric vehicles will replace oil with electricity, and ride sharing will reduce the number of cars on the road. Together they will end up reducing oil demand. Such trends will affect global consumption of oil. The net effect is that in our moderate scenario, oil demand in the light vehicle segment peaks and starts to decline slightly between 2015 and 2035.[17] In the tech acceleration case, we forecast demand for new vehicles could be roughly 13 percent lower than the moderate case, resulting in lower oil demand for light vehicles of about 4.5 million barrels per day by 2035.[18]

Changing demand for vehicles and shifting usage of them will have second-order effects on resource demand, including for metals. Reduced sales of cars and use of more lightweight materials could lower demand for steel and therefore for iron ore. Car sharing, which would lower the volume of vehicles on the roads, could reduce the need for construction of new roads, potentially reducing demand for steel, cement, and other infrastructure materials. At the same time, a trend toward lighter vehicles could enhance the role of plastics as a structural material.

Beyond transportation, technology will improve energy efficiency for consumers and industry. In residential and commercial buildings and in factories, the combination of advanced sensors, control systems, and analytics could substantially reduce energy demand. Already, many manufacturing plants have significantly reduced energy demand through retrofit efforts. In the moderate case scenario, we see potential for a 12 percent reduction in fossil fuel costs due to greater energy efficiency. In the technology acceleration scenario, increased efficiency could generate a further 9 percent, or $240 billion, opportunity.

In assessing the potential benefit from further deployment of technology, we consider that adoption rates for these technologies are likely to vary from region to region and country to country, depending on factors including government policy, the cost of deployment including hardware and software costs, and the level and rate of economic development.

Technology advances in renewables will displace fossil fuels

36%
Potential share of power generation by renewables in 2035, up from 4% today

Renewable energy usage has been rising rapidly as costs have fallen. Since 2001, total solar generation worldwide has grown by 50 percent annually, while wind power generation has been growing at an annual rate of 24 percent.[19] Costs have been falling sharply with widespread deployment of the technology; new solar power plants being contracted today are being bid at below $0.03 per kilowatt hour (kWh)—about one-tenth of the cost of solar plants just six years ago.[20] If that trend continues at the current pace, solar and wind energy could be competitive by 2025, without subsidies, with the marginal cost of thermal coal or natural gas generation in most regions globally. Renewables could grow from 4 percent of power generation today to as much as 36 percent of global electricity supply

16 Paul Gao, Hans-Werner Kaas, Detlev Mohr, and Dominik Wee, "Disruptive trends that will transform the auto industry," *McKinsey Quarterly*, January 2016.

17 *Global energy perspective 2016*, McKinsey & Company Energy Insights.

18 These projections are constructed on modeling of aggressive assumptions about the total cost of ownership and its impact on adoption rates of technology, estimates of impact from proven deployments or pilots of technology, and current policy initiatives. See technical appendix for details.

19 Electricity power and generation data from GlobalData, 2016.

20 Anna Hirtenstein, *New record set for world's cheapest solar, now undercutting coal*, Bloomberg, May 2016; Stephen Lacey, "Jinko and Marubeni bid 2.4 cents to supply solar in Abu Dhabi. How low can solar prices go?" *Greentech Media*, September 20, 2016; *Renewable energy technologies: cost analysis series,* International Renewable Energy Agency, 2012.

by 2035 in a tech acceleration scenario. This would represent avoiding up to $350 billion in resource expenditure.

85
planned coal-fired power plants scrapped by Chinese authorities

Renewable energies already today are competitive without subsidies in some locations. The speed with which they substitute for some fossil fuels will depend on their ability to overcome obstacles including integration, scaling, and storage issues. Continued investment in technological innovation will help solve many of these challenges, and in the right policy environment, it is possible that even greater adoption will occur in the next 20 years. China's National Energy Administration, for example, in January 2017 announced it is scrapping construction of 85 planned coal plants and will invest $350 billion in renewable energy sources.[21] In India, as much as 40 percent of power could come from non-fossil fuel sources by 2030.[22]

A significant shift to renewables would help meet rapidly growing demand for electricity, which is set to outpace overall energy demand in the coming 20 years. Renewables are not only substitutes for fossil fuels, but also reduce overall demand for energy, as they do not incur the heat losses associated with fossil fuel power generation. Even as primary energy demand slows, electricity demand will grow as the developing world seeks access to energy and can leverage renewables as opposed to fossil fuels. Increased electrification in the developed world, including higher needs for electric vehicles, data centers, and cloud computing, and greater access to electricity in the developing world are major drivers of growing electricity demand. Renewable energies could also enable accelerated "sector coupling," the combination of power, heat, and mobility, as the energy used to supply homes and offices is also used to power cars and other transportation.[23]

Technology will enable resource producers to raise productivity and unlock substantial value

The resource sector as a whole, and mining companies in particular, have tended to be relatively slow to adopt new technology.[24] This is partly due to risk asymmetry: the downside for technological failure is very large in such a capital-intensive industry. However, productivity-enhancing technology is increasingly being deployed. Automated haul trucks and drilling machines are being tested in numerous mines across the world. Rio Tinto's mines using automation technology in Australia's Pilbara are seeing 40 percent increases in utilization of haul trucks, and automated drills are seeing 10 to 15 percent improvements in utilization—alongside improved safety, better maintenance, lower energy use, and greater operational precision.[25] For energy producers, horizontal drilling and hydraulic fracturing have become an economically viable extraction technique for hydrocarbons trapped in shale deposits.

Technologies including automation, data collection, mobile computing, and analytics can transform resource exploration and extraction and improve yields across different commodities. Innovations include sensors at the tips of drill bits that are able to measure ore grade in real time and crawling drill rigs that move between drill pads autonomously. Technology can also improve operational efficiency, by enabling predictive maintenance and yield and energy efficiency optimization—areas where resource companies have been

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[21] Lucy Pasha-Robinson, "China scraps construction of 85 planned coal power plants," *Independent*, January 17, 2017.

[22] *Transforming energy to transform India*, McKinsey & Company, December 2016.

[23] Kurt Rohrig and Dietrich Schmidt, *Coupling the electricity and heat sectors: The key to transformation of the energy system*, Presentation to workshop on renewables and energy systems integration, Golden, Colorado, September 2014.

[24] For example, the mining sector ranks near the bottom of the MGI Industry Digitization Index, which measures the state of digitization in sectors of the US economy. Oil and gas companies and utilities rank higher but still below digital leaders including banking, media, tech, and business services. See *Digital America: A tale of the haves and have-mores*, McKinsey Global Institute, December 2015.

[25] Michael Gollschewski, *Productivity improvements in a changing world,* presented at Australasian Institute of Mining and Metallurgy iron ore conference in Perth, July 13, 2015.

slower to move. Data analytics is a potentially key competency, which can prove highly effective in finding new deposits. One example is a gold mine in Red Lake, Ontario, operated by Goldcorp. Goldcorp's CEO sought to find new deposits of gold in the mine through an unusual crowdsourcing exercise, by publishing megabytes of geological data about the 55,000-acre site on the company's website with a cash reward for the best answers. The exercise helped the company identify 110 deposits, half of which its own geologists had not known.[26] Overall, we estimate that the deployment of data analytics, robotics, and other technologies can boost productivity across resource-producing sectors, with the gains in terms of cost reduction in our accelerated technology adoption scenario reaching close to 30 percent for oil and 40 percent for iron ore. Overall, the productivity increases could potentially unlock between $290 billion and $390 billion in annual savings for producers of our five focus commodities in 2035.

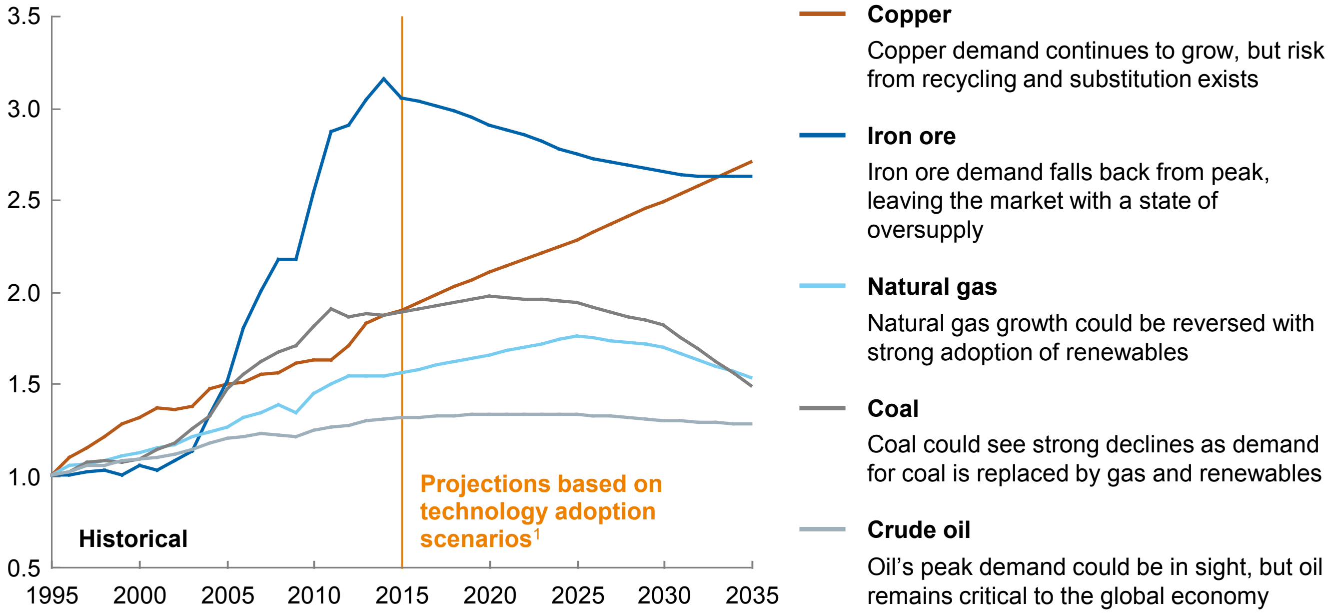
THE CORRELATION BETWEEN MARKETS FOR KEY COMMODITIES IS UNRAVELING

One of the striking characteristics of the down phase of the supercycle was the unraveling of what had been a close correlation between the markets for coal, copper, iron ore, and other commodities and those for oil and gas. While these markets rose in unison, seemingly as a monolithic group, during the upswing, divergences in supply and demand fundamentals for each commodity have meant that the correlation no longer holds. We expect this divergence to continue over the next 20 years, with ongoing shifts in demand and supply for oil, natural gas, thermal coal, iron ore, and copper, as well as for niche resources such as lithium and rare earth metals (Exhibit E4). Regional demand for commodities will also change. By 2035, according to our moderate case, China could account for 28 percent of the world's primary energy demand, up from 23 percent today, and India for 10 percent, up from 6 percent today, while the figure for the United States falls to 12 percent from 16 percent.

Exhibit E4

Demand growth for resources could be muted, with declines a possibility for some commodities

Commodity demand indexes
1 = 1995 demand level



1 Accelerated technology scenario for oil, gas, and thermal coal. Moderate adoption scenario for iron ore and copper. See technical appendix for details.

SOURCE: McKinsey Global Institute analysis

[26] *Open innovation: Goldcorp challenge*, Ideaconnection, October 22, 2009.

Investors, producers, and buyers will need to understand the unique characteristics of each commodity type, including these regional demand patterns, to anticipate the potential trajectory of demand and supply.

2%
decline in oil demand in 2035 vs 2013, in our tech acceleration scenario

- **Demand for oil will peak under our tech acceleration scenario, although the global economy will remain dependent on oil.** By far the biggest consumer of oil is the transportation industry, accounting for about 56 percent of total primary oil demand. From a regional perspective, the United States, China, Japan, India, and Russia are the major consumers, but trends in demand differ among them. For example, in China and India, demand is growing strongly due to a rapidly emerging middle class that is increasing its demand for mobility as well as for plastics and other chemical-derived goods. Our two scenarios for technology adoption have divergent outcomes. In the moderate adoption scenario, demand for oil increases by about 11 percent between 2013 and 2035. In our tech acceleration scenario, however, demand for oil peaks around 2025 and then drops back. By 2035, under this scenario, oil demand would be 2 percent below its 2013 levels. Declining demand for oil in the transportation sector accounts for most of this decline. Oil supply could become more elastic, as technological innovation gives producers the ability to meet changing demand more rapidly; this is especially the case in North America, where hydraulic fracturing and horizontal drilling techniques have given producers the ability to add incremental capacity in a relatively short development cycle. Despite the longer-term outlook, the industry will need to continue investing in development of new fields to replace mature fields as they decline.

- **Growth of natural gas will ultimately be limited by renewables.** The biggest user of natural gas is the power sector, accounting for about 40 percent of total primary natural gas demand. In the United States, natural gas has already replaced coal as the largest source of electric power generation due to low gas prices and more stringent environmental policies that have reduced generation from coal. Some countries are looking to increase natural gas to help decarbonize their economies by promoting domestic upstream development or importing it via pipeline or in the form of liquefied natural gas (LNG) from neighboring regions. For example, China wants to increase natural gas to 10 percent of its energy mix by 2020 from 6 percent today.[27] In other countries, including India, investment is limited because of the high cost of imported natural gas compared with local fuel options such as coal. In Europe, meanwhile, efficiency efforts, the expansion of renewables in electric power generation, and sluggish economic growth are limiting the demand for natural gas. In the near term, we expect natural gas demand to grow, but in the longer term, it could face increasingly competitive challenges from renewable energies, and possibly also cheaper coal. In our moderate case scenario, demand for gas continues to grow rapidly until 2035. In our tech acceleration scenario, which includes greater growth of renewable power generation and improved end-use efficiency, natural gas demand is likely to grow through to 2025 but then decline. Under this scenario, demand in 2035 will be just 1 percent above 2013 levels.

Coal demand could peak by
2020

- **Thermal coal may be headed for long-term decline as cleaner and cheaper substitutes penetrate the market.** Although coal has been the dominant fuel for generating electricity in the global economy, its role is under attack, and peak demand for thermal coal is a possibility in the next five years. In our moderate technology adoption scenario, thermal coal demand globally would peak in 2020 and by 2035 it would fall back to 2013 levels. In a scenario based on aggressive technology adoption, thermal coal demand would similarly peak in 2020, but then decline by 24 percent by 2035 compared with its 2013 level. Not all regions will be affected equally. While thermal

[27] Gabriel Nelson, Michael Ratner, and Susan Lawrence, *China's natural gas: Uncertainty for markets*, Congressional Research Service, May 2016.

coal demand will fall substantially in Organisation for Economic Co-operation and Development (OECD) countries, dropping to around 3 percent of total primary energy demand in 2035 compared with 14 percent today, demand will likely remain robust in some non-OECD countries. In India, for example, thermal coal demand could expand further as the economy continues its rapid expansion. Coal prices spiked unexpectedly in late 2016. However, even these forces are unlikely to fix the medium-term challenges the industry faces.

- **Iron ore producers must contend with oversupply for the foreseeable future.** By far the biggest demand for iron ore comes from the construction industry, accounting for almost half of the total, followed by machinery and equipment (17 percent). Supply expanded rapidly during the supercycle as investment poured in on the expectation of continued strong price growth. However, with the outlook for steel demand growth weakening, and recycling and scrap rates potentially increasing, especially in China, iron ore demand could fall. Under our moderate technology adoption scenario, demand would decline by 14 percent in 2035 compared with its 2015 level. Absent a repeat of China's massive industrialization, even strong economic growth in India and other emerging markets will be unlikely to focus on infrastructure investment in the same way. Current supply could be sufficient to meet global needs over the next 20 years, and major investment may not be needed to meet declining demand.

43%
potential increase in copper demand by 2035 vs today

- **Copper could see sustained growth as demand for consumer products accelerates, but recycling and substitution pose risks.** Copper has a wide range of uses in the modern economy, with far more consumer applications than iron ore. Just under half of copper demand today is from the electronics industry, with about one-quarter going to building and construction. The remainder feeds a range of industrial machinery, vehicles, and consumer products. Barring large-scale substitution by aluminum and other materials or a significant increase in recycling, primary copper demand could potentially grow to 31 million tonnes by 2035, a 2 percent annual increase. This corresponds to a 43 percent increase over today's demand of 22 million tonnes. We expect a majority of future demand growth to come from China; its per capita consumption of copper, which reached 7.2 kilograms per capita in 2015, could gradually rise to 11 to 12 kg per person by 2035, on a par with the figures for other developed Asian nations. At the same time, the supply outlook is challenging. Declining ore grades and increasingly difficult mining environments could result in supply constraints as ongoing investment becomes more expensive.

Beyond the core mineral resources, the impact of the technological and macroeconomic changes on other, smaller sectors could be significant. Lithium, for example, is already experiencing rapid growth, based on its usage in electric vehicle batteries, which is also driving growing demand for cobalt and nickel. Other resources to watch may include uranium, rare earth metals, and water, which is becoming scarcer around the world because of growing urbanization and economic development.

CAPTURING OPPORTUNITIES IN A NEW ERA OF TECHNOLOGY DISRUPTION

The more subdued outlook for demand and growth in the resource sector, together with a divergence in the prices of commodities and pressure for a substantial increase in the productivity of the resource sector itself, is creating a complex and competitive environment both for resource companies and for countries that depend on resource exports. Policy makers in resource-producing nations face pressure to diversify their economies and capture new growth opportunities, including from domestic demand rather than traditional exports. For resource-consuming nations, the challenge is to lock in the benefits a low-price commodities era has to offer households, industry, and society at large. In the resource sector, incumbent resource producers are under pressure to reverse the trend of declining productivity, while fending off possible attacks from more agile technology-enabled entrants. The prospect of more productive supply combined with potentially reduced demand will influence the decisions of both governments and companies about whether to devote tax dollars or shareholder capital to the development of new resources.[28]

Policy makers: Fostering the resource revolution payoff

Capturing the potential savings and productivity gains of the technological transformation of the resource sector will likely require some trade-offs. Policy makers will need to allow a nation's energy mix to shift and enable rapid technological changes throughout the economy, even as they recognize and account for the social and economic impact of these changes. Regardless of their resource exposure, all nations share the opportunity to invest savings from avoided resource spending into productive parts of the economy. We see three main priorities:

- **Taking a portfolio approach to national energy policy.** Policy makers could support market mechanisms that allow capital to flow in ways that enable resource productivity, while addressing market failures. They could also help companies develop their digital capacity by addressing digital infrastructure and interoperability issues. At a city and regional level, governments will need to ensure that energy-related infrastructure and regulatory choices work together, for example to support changing mobility trends that can reduce traffic congestion and pollution as well as energy demand.[29]

- **Developing the skills needed for the future.** To capture the benefits of the resource revolution, policy makers will need to invest in upgrading the skills of the workforce. Mining and oil and gas operations have a high technical potential for automation, especially occupations that involve sometimes dangerous physical activities.[30] Demand for new job classes such as data scientists, statisticians, and machine-learning specialists is already on the rise among resource producers. Within ten years, oil and gas companies could employ more PhD-level data scientists than geologists.[31] Wind-turbine service technician is the fastest-growing job category in the United States, according to the US Bureau of Labor Statistics.[32] Meanwhile, existing roles will be redefined. To meet the growing demand for skilled workers, policy makers should start by ensuring that education is well funded, retraining programs are effective, more students enter science, engineering, and other technical fields, and secondary and vocational training is upgraded to reflect changing skill requirements.[33]

- **Managing transitions efficiently and effectively.** All countries, regardless of where they are on the spectrum of exporting or importing resources, will have to manage transitions. For nations whose governments are highly dependent on resources as a source of government revenue, economic diversification is a pressing priority. Yet wherever core markets decline, policy makers may need to find ways to mitigate the externalities of shutdowns that arise. This includes addressing the long-term liability and remediation costs of resource assets and putting displaced people back to work. This reality is already playing out in the US coal market, where total coal demand could decline by 2020 by almost 40 percent from 2008 levels. According to McKinsey analysis,

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28 In this report we focus primarily on the impact on resource industries. We looked more extensively at users of resources in previous research. See, *Resource Revolution: Meeting the world's energy, materials, food, and water needs*, McKinsey Global Institute, November 2011.

29 *Game changes in the energy system: Emerging themes reshaping the energy landscape*, World Economic Forum, January 2017.

30 See Michael Chui, James Manyika, and Mehdi Miremadi, "Four fundamentals of workplace automation," *McKinsey Quarterly*, November 2015, and *A future that works: Automation, employment, and productivity*, McKinsey Global Institute, January 2017.

31 Christopher Handscomb, Scott Sharabura, and Jannik Woxhol, "The oil and gas organization of the future," *McKinsey Quarterly*, September 2016.

32 Jennifer Oldham, "Nation's fastest growing job—only for those who like to get high," *Bloomberg*, May 12, 2016.

33 *The world at work: Jobs, pay, and skills for 3.5 billion people*, McKinsey Global Institute, June 2012.

the entire US coal industry had liabilities of close to $100 billion in 2014, which will need to be addressed.[34]

Resource companies: Making the transformation from dig and deliver to technology-enabled productivity

As they adapt to the new realities of changing supply and demand, resource producers, especially incumbents, may need to become leaner and more agile by revisiting their strategy, improving capital allocation practices, and more fundamentally by infusing technology throughout the business.[35] By harnessing new technology, tomorrow's resource leader could derive its advantage from doing more with less, moving faster, thinking differently, and incorporating the best practices from other industries like manufacturing, services, venture capital, and consumer products. Possible steps could include:

- **Developing a more active approach to strategy and growth.** In order to embrace a future with greater uncertainty and fewer sources of growth, resource producers may need to think of themselves more like nimble portfolio managers and less like asset-heavy, "dig and deliver" businesses. As growth opportunities are harder to come by, companies may need to search and find resource-related business opportunities outside their core business and consider joint ventures, as well as mergers and acquisitions, which can lower risk, especially when entering an unfamiliar market. Harnessing technologies including data analytics and robotics can help producers identify and extract resources from areas that are especially remote and inaccessible.

- **Focusing on productivity to create value.** By incorporating technology, resource producers can build a more comprehensive understanding of the resource base, optimize material and equipment flow, improve anticipation of failures, increase safety, and monitor performance in real time. Alone, each of these opportunities has real potential; together, they will go a long way in reversing the trend of declining productivity. They will not be enough, however. By focusing on the fundamentals—driving up throughput and driving down capital costs, spending, and labor costs—resource producers can become productivity leaders. Innovative capital project design and delivery can reduce capital spending by 40 percent.[36] Reshaping workflows and improving collaboration with suppliers can cut operating costs and boost productivity. Those companies able to drive out the most waste from their operations and create a culture that prioritizes continuous improvement stand a better chance of success.

- **Adopting a digital mindset.** Barriers to technology adoption are not only physical, financial, and legal—they can also be cultural. Companies may need to address their own willingness to embrace change, akin to the mindset shifts that were needed in the early days of lean manufacturing, and embrace digitization and automation in a holistic manner, restructuring their organization and providing incentives to maximize adoption of these technologies. Fundamentally, resource producers need to develop the capability and talent of their workforce. This requires recruiting new talent and training existing talent but also putting in place systems for ongoing skills development. A significant challenge for resource producers will be to attract the next generation of talent.

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[34] *Downsizing the US coal industry: Can a slow-motion train wreck be avoided?* McKinsey Metals and Mining Practice, November 2015.

[35] *Mining's next performance horizon: Capturing productivity gains from innovation*, McKinsey & Company, September 2015.

[36] *The oil company of the future: From survive to thrive in "the new normal,"* McKinsey & Company, December 2016.

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For resource producers, it may not be easy to capture the full value of advances in technologies from artificial intelligence to robotics. They may face a world with permanent overcapacity, in which competition is driven by productivity rather than investment. Yet for producers who do adjust to this new technology-enabled era, and especially for resource consumers, who will benefit directly from greater efficiencies and innovation, the resource revolution will provide substantial opportunity. To succeed in this new commodities era will require a degree of agility, strategic capability, and resourcefulness, yet the potential opportunities may be large. The accelerated adoption of technology could unlock billions of dollars of value for resource producers from productivity gains and trillions of dollars in savings for the global economy.

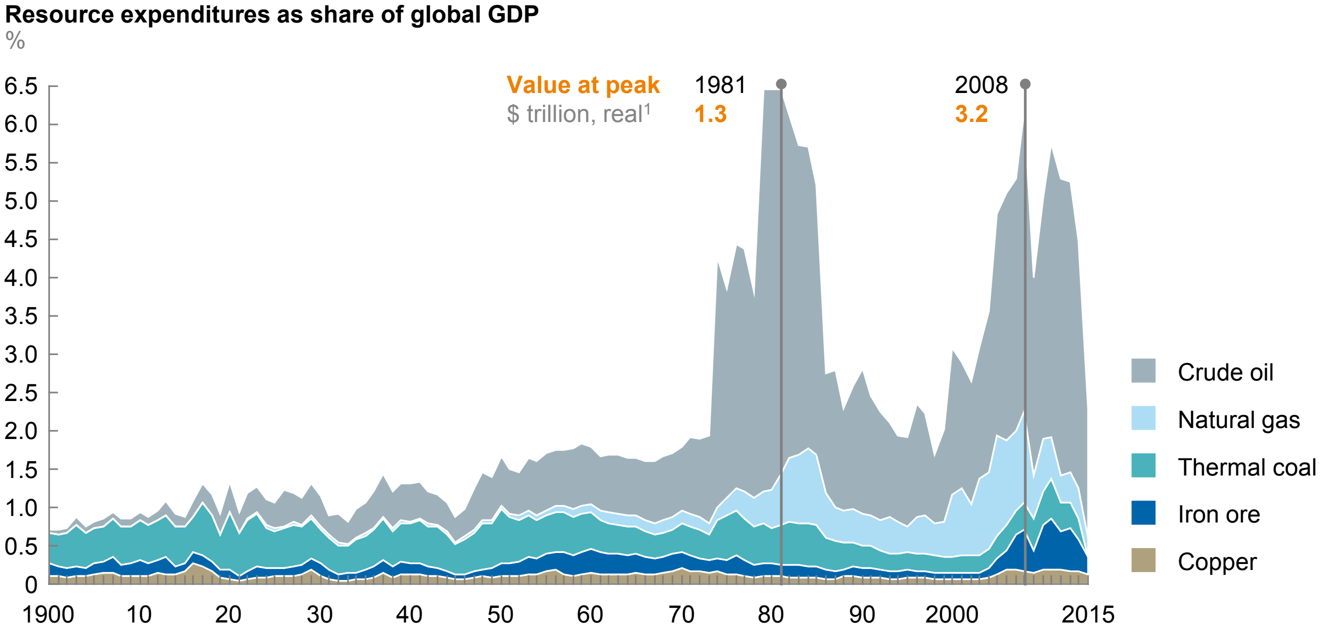
Oil and metals prices rose steeply during the commodity supercycle, only to fall back sharply.

1. AFTER THE SUPERCYCLE

Definitions of what constitutes a "supercycle" can vary, but the commodity boom and bust cycle that roiled the global economy in the past decade largely warranted the superlatives it received (see Box 1, "The 2003–15 supercycle had only one precedent in the past century"). At its peak, spending on mineral resources exceeded 6 percent of global GDP or more than three times the usual proportion (Exhibit 1).[37]

Exhibit 1

Spending on resources during the 2003–15 supercycle exceeded 6 percent of global GDP for only the second time in a century



1 Indexed to 1990 dollar values.

SOURCE: Rystad Energy; *BP statistical review of world energy*, 2015; World Bank; The Madison Project; USGS; McKinsey Global Institute analysis

The combination of rising demand, largely from China, and constrained supply propelled the upswing. In its wake, resource producers and exporting countries have been left weakened. Moreover, the sharp falls in commodity prices since the peaks have not given the global economy the macroeconomic boost many expected. In this chapter, we look at the changed outlook for producers, and examine the global economic and energy trends that will likely affect demand for resources in the next two decades and beyond.

[37] A supercycle, broadly speaking, is a decades-long, above-trend movement in a wide range of commodity prices. See Bilge Erten and José Antonio Ocampo, "Super cycles of commodity prices since the mid-nineteenth century," *World Development*, volume 44, April 2013; Alan Heap, *China—the engine of a commodities super cycle*, Citigroup Smith Barney, March 31, 2005; John T. Cuddington and Daniel Jerrett, "Super cycles in real metals prices?" *IMF Staff Papers*, volume 55, number 4, 2008; Daniel Jerrett and John T. Cuddington, "Broadening the statistical search for metal price super cycles to steels and related metals," *Resources Policy*, volume 33, issue 4, 2008.

Box 1. The 2003–15 supercycle had only one precedent in the past century

Commodity boom and bust cycles are a well-documented phenomenon dating back as far as medieval England, and price volatility is one of the resource industry's hallmarks. Even by those standards, the 2003–15 supercycle was exceptional. It followed a prolonged period of steady or falling prices of resources including energy, food, water, and materials such as steel. Before the supercycle began in 2003, expenditures on mineral resources globally amounted to $1.2 trillion, about 3 percent of the world's GDP. (In this report, we use oil, natural gas, thermal coal, iron ore, and copper as the main examples of mineral resources).[1] At its low point in 1998, spending fell to about 1.7 percent of global GDP. Just ten years later, the world was spending more than $4 trillion annually on mineral resources, or 6.2 percent of global GDP. Even during the recession in advanced economies that followed the 2008 financial crisis, spending on resources barely eased. In 2011, it amounted to 5.9 percent of global GDP.

The only other time in the past century when commodity prices rose as strongly was during the 1970s, when oil producers in OPEC organized an embargo against the United States, the United Kingdom, Japan, and some other countries. The oil embargo sent prices soaring to the then-stratospheric level of $12 a barrel. Mineral resource expenditure in the 1980s rose to an even higher proportion of global GDP, 6.5 percent, than during the most recent supercycle.

There are some significant differences in the nature of these two supercycles. In the 1970s and 1980s, oil was the driver of the upswing, and the global economy reacted to the price shock with a sharp slowdown. Year-on-year global GDP growth fell throughout this period, from a peak of 6.6 percent in 1973 to 1.1 percent in 1982. During the most recent supercycle, however, the global economy remained robust, even as prices climbed, until the 2008 financial crisis, which was not caused by oil. Moreover, after the 2008 financial crisis and recession, the global economy rebounded relatively quickly, driven in large part by emerging economy growth. Global GDP growth exceeded 4 percent in 2005–2007 and rose to 4.7 percent by 2010.[2]

[1] We selected these resources because they are the core of the modern economy and represent a significant amount of the value in the energy and metals sectors. Oil, gas, and coal represent almost 90 percent of all energy consumed on the planet. Iron ore and copper represent 41 percent of the value from mined metals. Gold represents an additional 36 percent of the value from mined metals, but we have excluded it from our analysis since its pricing and value are less driven by economic growth. Other metals were deemed to be too small in value to consider. See *BP statistical review of world energy*, BP, June 2015; *2012 minerals yearbook*, United States Geological Survey.

[2] Data for analysis taken from Rystad Energy; *Mineral Reports 2015*, United States Geological Survey; McKinsey Global Institute Commodity Price Index; IMF; World Bank; and Jutta Bolt and Jan Luiten van Zanden, "The Maddison Project: Collaborative research on historical national accounts," *The Economic History Review*, 2014. For details, see the technical appendix.

More than
50%
of global iron ore and coal supply was consumed by China

THE DEMAND AND SUPPLY FACTORS THAT DROVE THE SUPERCYCLE HAVE SINCE CHANGED

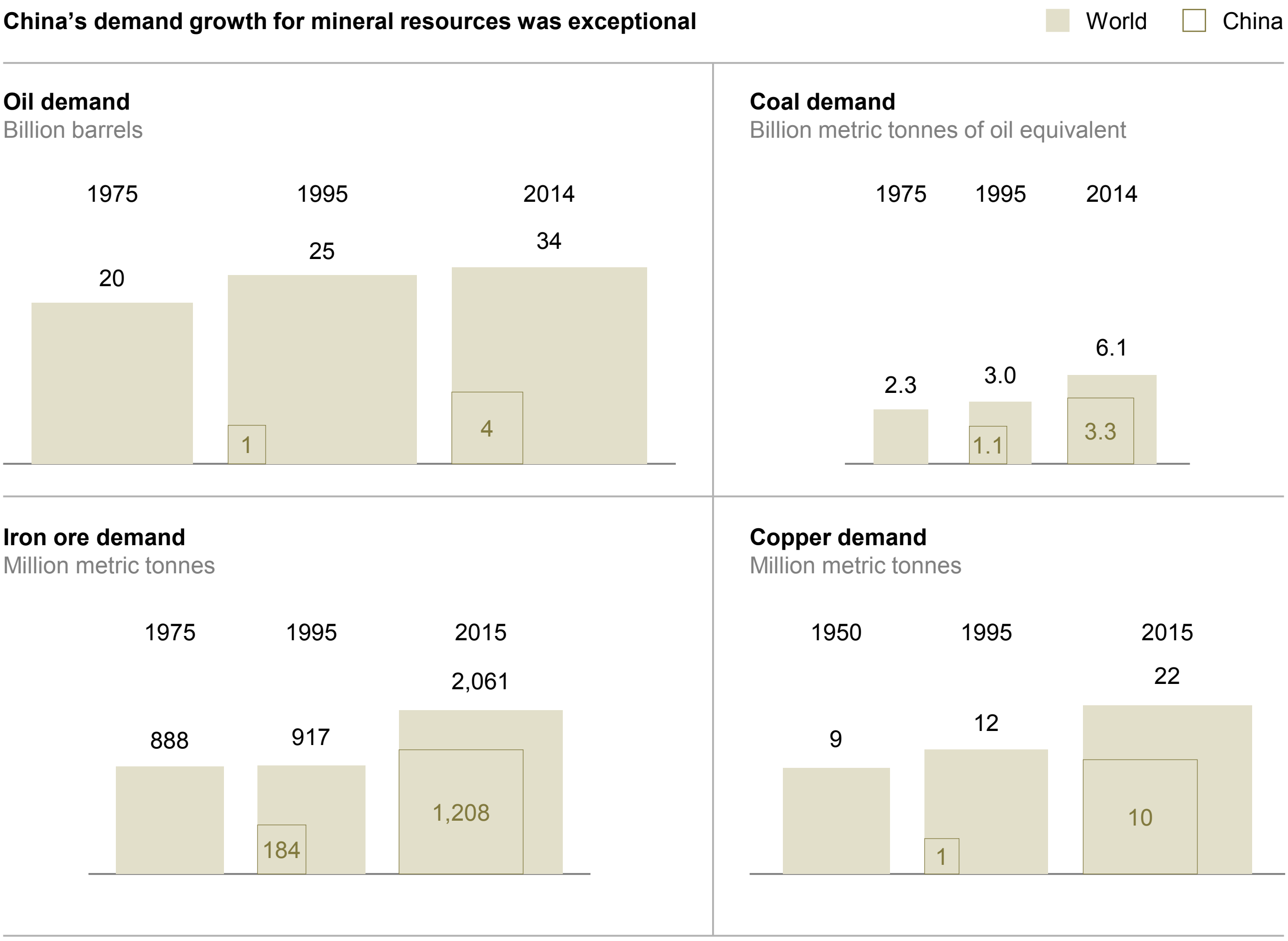
At the core of the supercycle was a textbook case of soaring demand, primarily from China, together with supply constraints. As the pace of its industrialization accelerated, China developed a voracious appetite for natural resources of all types, not just energy but also coal, copper, iron, and other metals. Surging demand caught resource producers unprepared as the industry was in the throes of a prolonged phase of underinvestment. Both of these factors have since changed. Chinese demand has abated as its growth has slowed and its economy shifts from an investment and export-led growth model to a consumer-led one. As prices soared, investment in all resources, including renewable energy, accelerated rapidly, stoking innovation and new competition.

Chinese demand for mineral resources, including metals, in some cases outstripped demand from the rest of the world

China's rapid industrialization and urbanization on a massive scale fueled its voracious appetite for resources. Its urban population surged from 31 percent in 1995 to 56 percent in 2016, generating demand not only for real estate and infrastructure but also for new goods and services for consumption. At the peak of demand in 2015, China consumed more than half of the global supply of iron ore and coal and about 40 percent of the world's copper. Overall, China's demand for thermal coal, iron ore, and copper grew faster in 19 years than the entire world's demand grew in the previous 40 years (Exhibit 2).[38] This growth in demand was coupled with a surge in investment across the country and a build-out of infrastructure, as China doubled the length of its railway system from 59,000 kilometers to 112,000 kilometers and increased the square footage of buildings more than tenfold, from 357 million square meters to 4.2 billion square meters.[39]

Exhibit 2

China's demand growth for mineral resources was exceptional



SOURCE: *BP statistical review of world energy*, 2015; McKinsey Basic Materials Institute; McKinsey Global Institute analysis

Investment in new supply surged after a prolonged period of low prices

Both the oil industry and the mining sector were ill equipped to respond rapidly to Chinese industrialization.[40] The surge in demand followed a prolonged period of declining capital investment in the mining industry: capital spending fell from $96 billion in 1980 to a low of $72 billion in 1999, as weak prices discouraged major investment in new supply. Oil and gas producers in the low price environment of the 1990s were investing about $150 billion per year, far less than the $350 billion per year they had invested in the early 1980s.[41]

With the sudden upswing in demand, capital investment surged across sectors (Exhibit 3). Capital investment by oil and gas companies, which had been $208 billion in 2003, grew to more than $750 billion per year by 2013, reaching a level equivalent to more than 4 percent

[38] *BP statistical review of world energy*, BP, June 2015; United States Geological Survey data January 2015; McKinsey Basic Materials Institute.

[39] *China statistical yearbook*, National Bureau of Statistics, 2015.

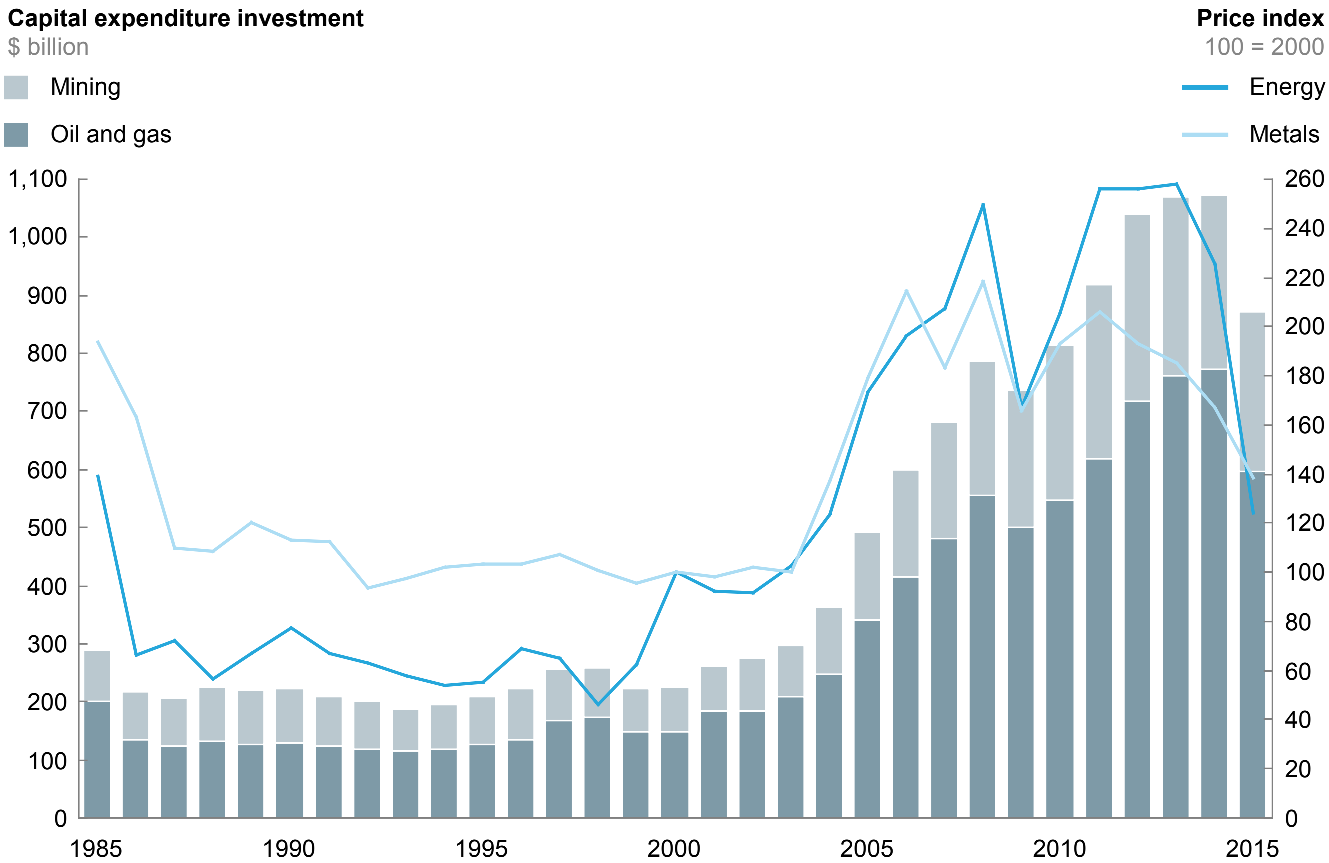
[40] *Energy & Financial Markets*, US Energy Information Administration (EIA).

[41] Based on analysis of data from IHS Markit and Rystad Energy.

of global fixed capital formation.[42] Whereas the industry had previously avoided investment in high-cost and difficult to access resources such as oil sands, deepwater reservoirs, and unconventional oil plays such as light tight oil in shale, companies began investing heavily to develop these pockets of new supply. Oil companies opened up exploration campaigns in the Arctic in the hope of finding new megafields. Mining companies similarly ramped up their capital investment, to a peak of more than $320 billion in 2012, three and a half times the level in 2003.[43] Megamines, such as the copper mine Oyu Tolgoi in Mongolia and the iron ore mines of the Pilbara in Australia, with development costs well over $1 billion per mine, added significant capacity to the global supply base: more than one billion tonnes of production capacity in iron ore mining and, in copper mining capacity, four million tonnes, or a 27 percent increase.[44]

Exhibit 3

The surge in demand overwhelmed what had been limited capital investment for more than a decade



SOURCE: MGI Commodity Price Index; Rystad Energy capital expenditure data; IHS Markit; McKinsey Global Institute analysis

High prices encouraged the development of innovative supply sources including through hydraulic fracturing, speeding the end of the supercycle

Oil demand growth remained near 1 percent annually between 2004 and 2014.[45] However, investment in supply was beginning to catch up with high oil prices. In addition to the build-out of conventional supply sources, high energy prices encouraged expansion of new, more innovative sources of supply. After decades of development, hydraulic fracturing and horizontal drilling became an economically viable extraction technique for hydrocarbons

42 Capital expenditure data from Rystad Energy; global capital formation data from the World Bank.
43 IHS Markit.
44 McKinsey Basic Materials Institute.
45 *BP statistical review of world energy*, BP, June 2015.

trapped in shale deposits. This increase in supply contributed to the driving down of prices and the end of the supercycle.

The change began with natural gas development in North America. By 2011, natural gas hit record low prices of less than $4 per million British thermal units.[46] These low prices resulted in natural gas directly competing with coal as the preferred generation fuel in North America. This in turn led to a collapse of domestic coal prices and put a glut of supply into global markets.

The same fracking technology that was used in natural gas was applied to oil-rich deposits and light tight oil development, enabling US oil production to increase to more than 11 million barrels per day in 2014 from about seven million barrels in 2009.[47] With fundamental supply and demand forces working together, a decision by OPEC in late 2014 not to curtail production in the face of price softening propelled a rapid decline in energy prices. Since 2014, the prices of oil and natural gas have fallen by more than 50 percent. Oil supply outpaced demand by about two million barrels per day in 2015, creating a surplus that only began to rebalance in mid-2016.[48]

RESOURCE PRODUCERS HAVE BEEN WEAKENED BY THE SUPERCYCLE

2x
Price increase for metals between 2004 and 2011

Prices doubled for metals between 2004 and 2011 and rose by 2.6 times for energy between 2004 and 2013, but the upswing masked fundamental weaknesses among resource producers, even as it encouraged stronger competition.[49]

Productivity declined and costs rose during the upturn

For the oil and gas sector, the lifting cost per barrel increased by more than 300 percent, or 11 percent annually, between 2004 and 2014, from about $8 per barrel of oil equivalent to more than $28, a 12 percent annual decline in lifting productivity (Exhibit 4). The return on invested capital for oil companies fell by about 50 percent between 2005 and 2011, and, by the end of 2015, it had deteriorated by 90 percent or in some cases more.[50] The productivity of miners also declined by 6 percent per year between 2004 and 2009, before leveling off and averaging 4 percent from 2004 and 2014 and remaining at 30-year lows.[51]

The rapid decline in productivity was a reversal of many years of productivity improvements across the industry. It was due to a combination of factors, including harder-to-access reserves, increasing service costs as demand for equipment and skilled labor soared, and rising upstream capital costs. At the same time, capital discipline and operational excellence became a secondary focus.[52]

Competition also heated up, including from state-owned enterprises that focused on securing supplies of resources rather than exploiting them.[53] Independent resource producers found themselves facing increasing competition, manifesting itself in the form of higher prices for assets, development inputs, and service costs. The combination of rising capital investment, declining productivity, and higher competition severely weakened the value generation potential of the resource sector. Resource producers' return on invested capital globally declined by about 50 percent for oil and gas companies and by about 10 percent for mining companies even as prices were at all-time highs.

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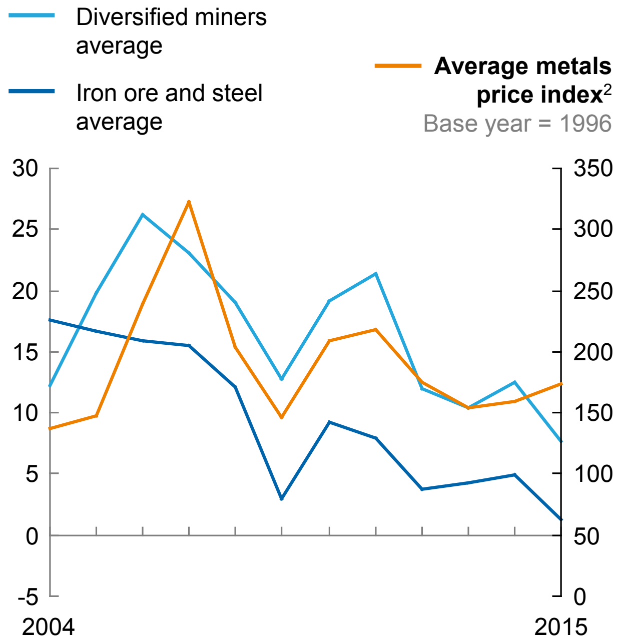
[46] Price data from EIA.
[47] *BP statistical review of world energy*, BP, June 2015.
[48] *Short-term energy outlook*, EIA, July 2016.
[49] McKinsey Global Institute Commodity Price Index.
[50] McGraw Hill Financial S&P Capital IQ.
[51] McKinsey & Company MineLens Productivity Index.
[52] IHS Markit Upstream Capital Costs Index, 2016.
[53] A. Erin Bass and Subrata Chakrabarty, "Resource security: Competition for global resources, strategic intent, and governments as owners," *Journal of International Business Studies*, volume 45, issue 8, October 2014.

Exhibit 4

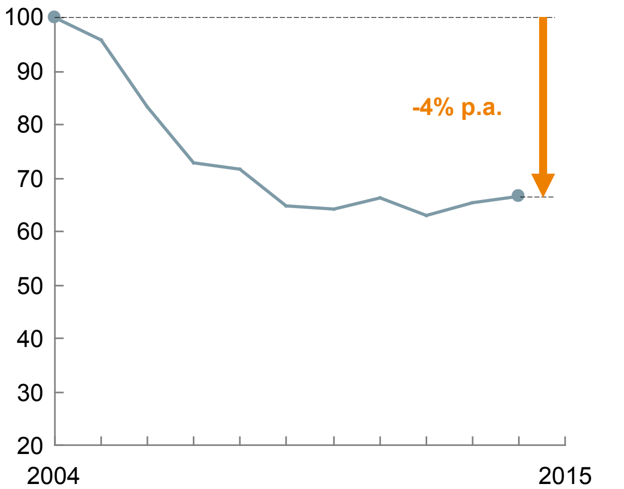
Return on invested capital in the resource sector has declined along with productivity[1]

Mining

Mining companies ROIC
%

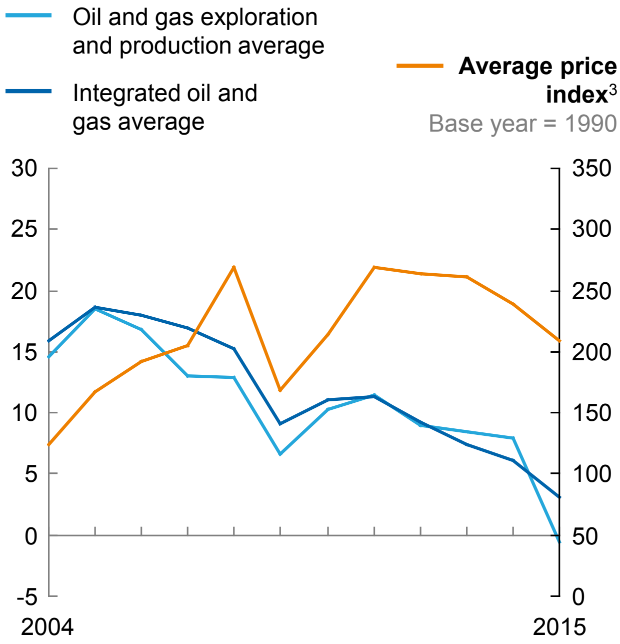


McKinsey MineLens productivity index
100 = 2004

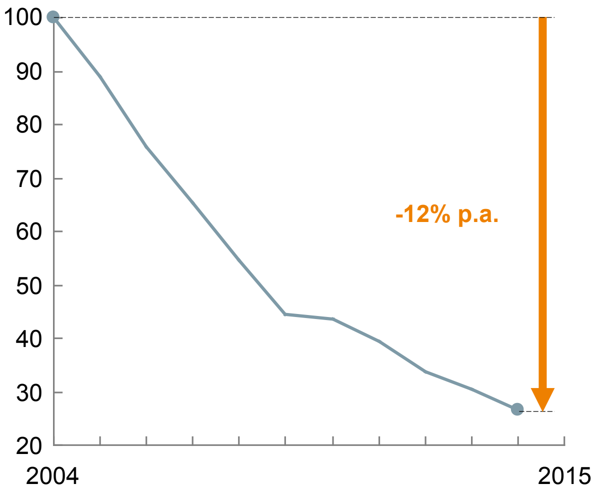


Oil and gas

Oil and gas companies ROIC
%



Oil lifting productivity index
Barrel of oil equivalent per $, 100 = 2004



1 Based on companies with >$5 billion market cap and >$1 billion revenue for oil and gas; >$1 billion market cap and >$0.5 billion revenue for metals.
2 Average of aluminum, thermal coal, copper, iron ore, lead, nickel, and zinc.
3 Average of WTI and Brent.

SOURCE: McGraw-Hill Companies' S&P Capital IQ; MGI Commodity Price Index; McKinsey Global Institute analysis

Resource producers lost $2 trillion in cumulative shareholder value during the downturn

The broad collapse in prices severely damaged the resource industry, and producers lost $2 trillion of cumulative shareholder value.[54] By 2015, price declines had reduced annual global expenditures on resources by about 50 percent compared with 2011.[55] Markets have punished resource producers, with North American and European producers losing 30 to 75 percent of their market capitalization from peaks reached between 2010 and 2013.[56] Resource producers' return on invested capital has deteriorated by an additional 90 percent for diversified miners and integrated oil and gas companies and by about 300 percent for exploration and production companies.[57] In response, the industry has made large cuts to capital spending and to workforces, and redoubled cost-cutting efforts.

CHINA'S CHANGING GROWTH MODEL AND GLOBAL DEMOGRAPHIC AND ENERGY CONSUMPTION TRENDS COULD DAMPEN FUTURE RESOURCE DEMAND

$1T
transfer from importing to exporting countries during the upswing

The steep upturn and the abrupt downturn have affected not just resource producers but the global economy as a whole. The rise in commodity prices, typified by oil peaking at more than $110 a barrel in mid-2014—about $90 a barrel above its price only 11 years earlier—amounted to a $1 trillion transfer from importing nations to exporting nations. When prices started dropping, the transfers went the other way, amounting to a $750 billion flow from exporting to importing countries, an amount larger than the 2016 GDP of Saudi Arabia. As the supercycle changed direction, a number of forecasters expected that falling prices would boost global growth, but the stimulus effect on global GDP has been weaker than expected. Looking forward, even if growth accelerates, the outlook for demand growth could remain restrained, although this will vary according to individual commodities and regions. Overall, demand for resources will be driven by the low likelihood of a country replacing China as a demand engine; demographic shifts in the global economy that are weakening growth; and the ongoing trend toward a less resource-dependent economy.

The decline of resource prices has given only a small bounce to the global economy

When commodity prices, and especially oil prices, began to decline in 2014, a common assumption was that the commodity bust would be a boon for global economic growth.[58] Low prices for raw materials translate into low import prices and subdued inflation, more money in consumers' pockets, and increased spending in more productive areas of the economy. While there has been a stimulus effect in some importing countries, it is less pronounced than some had anticipated.[59] Economic growth in developed countries has remained largely weak, giving rise to some theories that the global economy may be undergoing a phase of "secular stagnation," with the risks of weaker growth scenarios becoming more tangible.[60]

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54 Analysis based on data from Rystad Energy; United States Geological Survey Mineral Commodity Summaries; *World energy outlook*, IEA, 2016; World Bank Pink Sheets 2016; and *BP statistical review of world energy*, BP, June 2015.

55 Ibid.

56 McGraw-Hill Financial S&P Capital IQ.

57 Ibid.

58 See, for example, John Baffes et al., *The great plunge in oil prices: Causes, consequences, and policy responses*, World Bank Group Policy Research Note 15/01, June 2015; Rabah Arezki and Olivier Blanchard, *Seven questions about the recent oil price slump*, IMFdirect, December 2014; and Aasim M. Husain et al., *Global implications of lower oil prices*, International Monetary Fund staff discussion note 15/15, July 2015.

59 *Economic Bulletin*, issue number 4 /2016, European Central Bank, June 2016.

60 Lawrence H. Summers, "The age of secular stagnation: What it is and what to do about it," *Foreign Affairs*, March/April 2016; *World economic outlook*, IMF, April 2016.

A number of circumstances could be depressing the expected benefit of low commodity prices. Although assessing the net effect of these countervailing forces is beyond the scope of this report, we highlight a few reasons that the expected causal relationship between commodity prices and economic growth may be less evident.

The belief that low oil prices would lead to improved economic activity is based on the assumption that consumers in oil-importing regions such as Europe would have a higher marginal propensity to consume out of income than exporters such as Saudi Arabia.[61] The consensus is that the trend in the opposite direction, where high oil prices hurt economic growth, does hold true.[62] However, there could be reasons that this relationship is breaking down in the current situation, as importers and exporters change spending habits in reaction to low commodity prices.

Consumer spending in advanced economies may not be receiving as big a boost as expected; savings and deleveraging are increasing concerns for many, and industrial consumers are returning value to shareholders. A study by Chase has shown that US consumers are spending only 81 cents of every dollar saved because of lower gas prices. Since this represents between 0.5 percent and 1.6 percent of total consumer spending in the United States, the effect could be washed out by other changes.[63] In other markets, energy subsidies and similar measures have been rolled back to strengthen governments' fiscal position, limiting the pass-through effect to consumers.[64] Among industries, downstream users of commodities, including airlines and manufacturers, should be feeling the lower commodity prices on their top and bottom lines. For some manufacturers, however, lower costs for raw materials are being offset by lower demand for products, including from China. Recent work has highlighted how capital investment in the OECD has slowed because of sluggish demand after the 2008 financial crisis.[65] Furthermore, the outlook for investment remains muted as the economic transition in China worries some investors.[66]

At the same time, the decline in resource prices is reducing spending by exporters and producers. Prior to the price decline, oil-exporting countries were spending close to every dollar they received through taxes and royalties.[67] The sudden decrease in revenues is now forcing sharp spending cuts in many economies. For Gulf countries and Algeria, spending fell by $60 billion in 2015, and in Caucasus and Central Asian countries, public expenditure fell by more than $10 billion in 2015.[68] At the same time as exporters rein in spending, corporate resource producers are pulling back on investment. Millions of workers are being displaced from the workforce. Suppliers and service providers are seeing demand fall, creating a ripple effect of layoffs and deferred spending. Investment in the oil sector fell by an estimated $215 billion between 2014 and 2015, about 1.2 percent of global fixed capital formation, or almost 0.3 percent of global GDP.[69] Furthermore, the capital investment taken

61 Maurice Obstfeld, Gian Maria Milesi-Ferretti, and Rabah Arezki, *Oil prices and the global economy: It's complicated*, IMFdirect, March 24, 2016.

62 James D. Hamilton, *Causes and consequences of the oil shock of 2007–08*, National Bureau of Economic Research working paper number 15002, May 2009.

63 *How falling gas prices fuel the consumer*, JPMorgan Chase Institute, October 2015.

64 Ferdinando Giugliano, "World Bank says fall in oil price is chance to cut fuel subsidies," *Financial Times*, January 7, 2015.

65 Patrice Ollivaud, Yvan Guillemette, and David Turner, *Links between weak investment and the slowdown in productivity and potential output growth across the OECD*, OECD Economics Department Working Papers number 1304, June 8, 2016.

66 *World Economic Outlook*, IMF, April 2016.

67 Based on analysis of data from the World Bank, IMF, and WMM.

68 Martin Sommer et al., *Learning to live with cheaper oil: Policy adjustment in oil-exporting countries in the Middle East and Central Asia*, IMF, 2016.

69 Maurice Obstfeld, Gian Maria Milesi-Ferretti, and Rabah Arezki, *Oil prices and the global economy: It's complicated*, IMFdirect, March 24, 2016.

out of the resource sector may have limited redeployment opportunities in the face of an uncertain economic outlook.

Deflationary pressure from sharply lower oil prices has hit the global economy at a time when central bank interest rates are at record lows. Europe and Japan are both trying to revive growth and stave off deflation through aggressive monetary policy while the US Federal Reserve is only gradually raising interest rates. The decline in inflation, actual and expected, owing to lower production costs raises the real rate of interest, which tempers demand growth. Unlike past oil price declines, monetary policy may actually be driving consumers to save more of the windfall from the resource price decline as they search for security and yield to combat long-term trends of low global interest rates.[70]

A new supercycle appears unlikely as other industrializing countries lack China's scale and resource intensity improves globally

One major question in the aftermath of the supercycle is whether it could happen again. China may be changing its economic development model, but other emerging markets including India continue to focus on rapid industrialization as a path to prosperity. Yet for the resource sector, another surge in demand similar to the one unleashed by China seems unlikely. No other country is expected to undergo industrial growth at the same scale or pace as China. Furthermore, ongoing trends of efficiency together with a shift to service-sector economic activity mean the resource intensity of global growth is likely to be lower.

Beyond technology, the other major factor that will dictate the outlook for resource demand is the development path of the global economy. The two most important factors are the pace of growth and the resource intensity of that growth. As noted, the rapid industrialization and investment-focused growth of China drove the surge in resources such as iron ore and coal. If other emerging economies were to proceed along similar paths at a similar pace in their development, it is possible to imagine a 20-year outlook with continued bouts of rapid expansion in demand and severe supply stress. However, developments in China and other emerging markets suggest that such an outlook is unlikely.

The global economy as a whole faces some significant challenges in maintaining its historic growth rate over the past 50 years of 3.5 percent annually.[71] Prior MGI research has shown that a "demographic dividend" that helped to fuel global growth in the past half century has ended and in some countries it has reversed course, becoming a "demographic deficit." Fertility rates have declined, and in many countries they have fallen below the replacement threshold needed to keep the population steady. Over the next half century, the working-age population is expected to fall in all G20 countries; it is already doing so in Germany, Italy, Japan, and Russia. China's working-age population has also been in decline, since 2012, and is forecast to fall by 23 percent by 2050.[72] Taking all of these factors into account, average employment growth will decline to 0.3 percent per year over the next 50 years, less than one-fifth of the 1.7 percent growth that we experienced between 1964 and 2014. Given these demographic trends, the onus for continued global growth will fall far more heavily on productivity gains.

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[70] For a discussion of the underlying drivers of interest rate declines and prospects going forward, see Lukasz Rachel and Thomas D. Smith, *Secular drivers of the global real interest rate*, Bank of England, staff working paper 571, December 2015, and IMF, *World economic outlook*, April 2015, Chapter 3. See also Charles Evans, *The implications of slow growth for monetary policy*, speech delivered at Credit Suisse Asian Investment Conference in Hong Kong, April 5, 2016.

[71] The Maddison-Project, www.ggdc.net/maddison/maddison-project/home.htm, 2013 version, and International Monetary Fund Data.

[72] Joe Myers, *China's working-age population will fall 23% by 2050*, World Economic Forum, July 25, 2016.

If global productivity growth continued to rise over the next 50 years at its average rate between 1964 and 2014, the rate of global GDP growth would decline by 40 percent in the G19 and Nigeria, from 3.6 percent a year to only 2.1 percent.[73]

Beyond the decline of top-line growth, the resource intensity of growth is likely to continue its declining trend of the past few decades. The mid-20th-century development of OECD countries saw the intensity of metal usage peak in the late 1950s. China's industrialization disturbed this long-term global trend for iron ore in the past 15 years, but the declining trend is likely to reestablish itself. Energy intensity peaked in the 1970s, and even the recent rise of China has not disturbed this trend. Recent research has shown that the long-term trend of OECD country energy use decoupling from GDP is mirrored in non-OECD countries, where the decoupling is taking place at a faster rate than in OECD economies.[74] Indeed, while China's economy increased 18-fold from 1980 to 2010, energy consumption increased only fivefold. Energy intensity per unit of Chinese GDP declined by about 70 percent during the same period.[75]

Since then, China's transition from investment-led to service- and consumption-led growth is further reducing resource intensity. The government is aiming to reduce energy intensity by 15 percent in its 13th five-year plan, from 2016 to 2020, after targeting a 20 percent reduction in 2006—2010 and a 12 percent reduction in 2011—2015. The Chinese government is also focusing on overcapacity in both the steel and coal sectors, with layoffs of hundreds of thousands of workers already under way. Industrial electricity consumption, which grew by 7 percent annually between 2010 and 2014, actually declined by 2 percent in 2015. Meanwhile, the service sector has been growing rapidly, from 44 percent of GDP in 2010 to 52 percent in 2016. Consumption contributed about 65 percent of GDP growth in 2016. In other fast-growing emerging economies such as India, considerable infrastructure investment is expected, but the pace of investment could be slower than in China because of differences in market structure and governance. Finally, demand for resources in developed countries could continue a long-term trend of delinking from GDP growth, and the concept of "peak stuff" may be within reach in these markets. Peak material consumption in Britain is well documented, and the concept has begun to permeate the strategy of many companies.[76] Assuming that such shifts take place, the resource intensity of future economic development will decline, flatten, or peak at lower levels.

•••

The supercycle that blew through the global economy was an extraordinary event, even for the resource industry, which is used to boom and bust cycles. Producers in a range of resource industries are in a challenging position after a heavy period of investment that took a toll on productivity. For all its force and impact, however, the supercycle merely masked from view a more deep-seated and permanent shift that will affect commodities in the future. Powerful new technologies are increasingly changing the supply and demand equation for resources, with very substantial implications for all stakeholders and for the global economy as a whole. In the next chapter, we focus on these technologies and how they are bringing about a revolution in resources.

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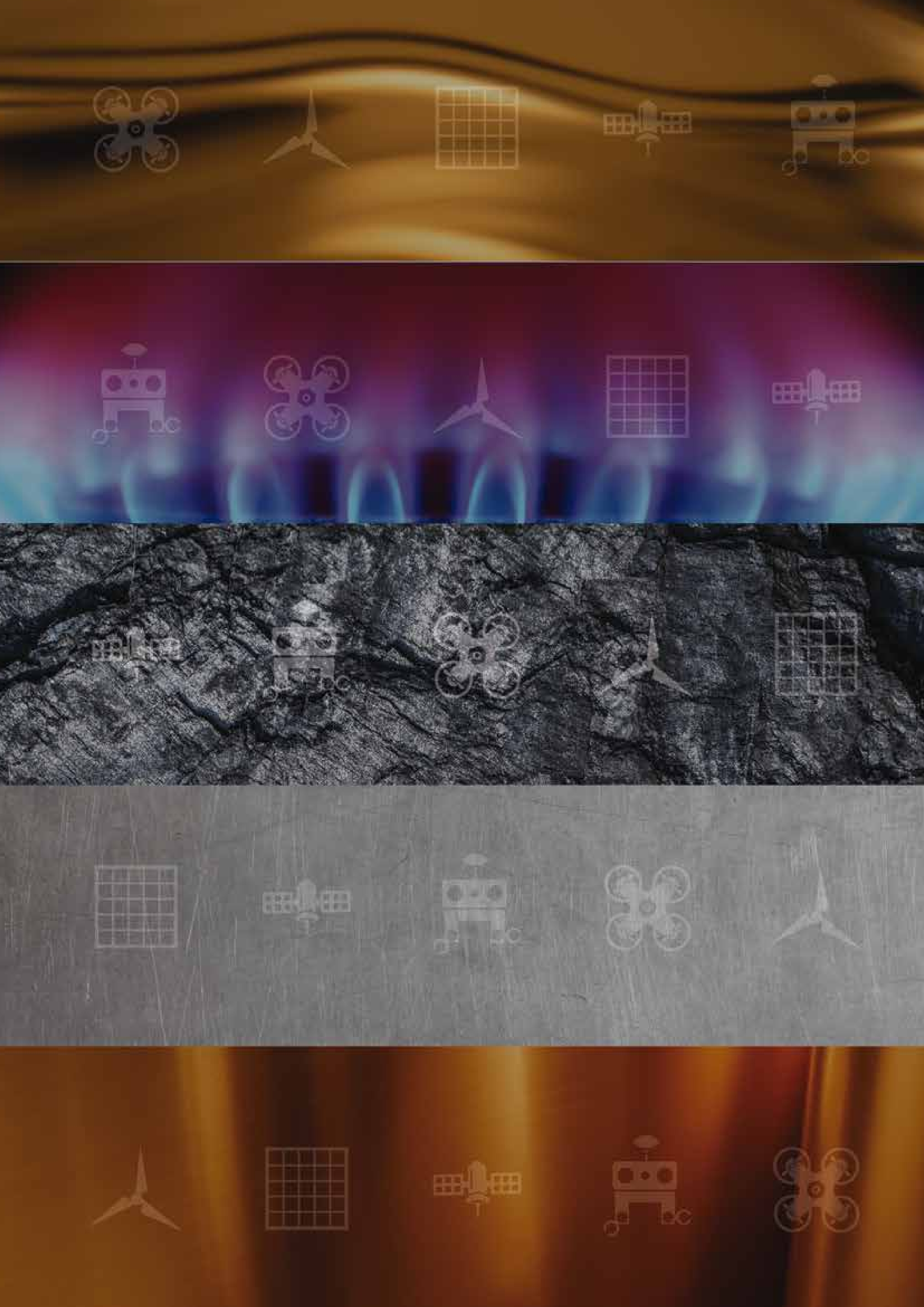
73 *Global growth: Can productivity save the day in an aging world?* McKinsey Global Institute, January 2015.

74 Ari Kahan, *Global energy intensity continues to decline*, US Energy Information Administration, July 2016.

75 *Bringing China's energy efficiency experience to the world: Knowledge exchange with Asian countries*, World Bank, June 27, 2014.

76 Duncan Clark, "Why is our consumption falling?" *The Guardian*, November 1, 2011; Kaye Wiggins, "The companies preparing for sustainable life after 'peak stuff,'" *Financial Times*, June 6, 2016.




Workers installing solar panels on the roof of a house in Germany.

2. THE $1 TRILLION TECHNOLOGY OPPORTUNITY FOR RESOURCES

In the past, changes in the resource sector have often come about as a result of regulation. Over the next two decades, however, we expect technology and its effect on costs will be the main drivers of change. The adoption of a wide range of technologies, from robotics to the Internet of Things and big data, will have substantial effects on the demand and supply of resources, reducing spending on resources by consumers and also reducing the costs associated with extracting and producing them. We estimate the potential savings opportunity for the global economy in 2035 to be between $900 billion and $1.6 trillion, depending on the pace and extent of the technology adoption. This opportunity comes from three likely shifts that we discuss in this chapter:

- Consumption of energy will become less intense and more efficient as people use less energy to live their lives, and as energy-efficient technologies become more integrated in homes, businesses, and transportation. We see a substantially larger potential for demand savings than we did even five years ago (see Box 2, "Changes in the energy demand outlook from our 2011 research").

- Technological advances will continue to bring down the cost of renewable energies such as solar and wind energy, as well as the cost of storing them. This will hand renewables a greater role in the global economy's energy mix, with significant first- and second-order effects on producers and consumers of fossil fuels.

- Resource producers will be able to deploy a range of technologies in their operations, putting mines and wells that were once inaccessible within reach, using robotics to access resources more efficiently and safely, shifting to predictive maintenance, which is considerably less expensive than reactive maintenance, and using sophisticated data analysis to identify, extract, and manage resources.

Box 2. Changes in the energy demand outlook from our 2011 research

Our 2011 "Resource Revolution" report made a number of projections for resource demand that we have updated in this research.[1] Overall, we have increased our estimates for the size of the demand reduction that is possible.

In 2011, we estimated that energy efficiency opportunities could reduce demand by more than 20 percent, or 150 million terajoules, by 2030. In this report, after reviewing and stress-testing our demand assumptions, we estimate the potential for a 20 percent reduction in global primary energy demand by 2035 compared to a baseline with the same level of technology adoption (efficiency, transport, and renewables) as today. If technology is adopted to its full potential, a further 10 percent reduction could be achieved.

In 2011, we anticipated that at least some of the savings would be driven by behavioral changes among consumers. Since then, technology has made major advances, and we have revised our projections to take into account the increased adoption and penetration of automation, advanced analytics, and the Internet of Things. These three technologies are already in the marketplace or close to commercialization, and our research suggests that they will develop rapidly with significant consequences for business and the economy.[2] These technologies alone could accelerate the shift to greater energy efficiency by increasing awareness of energy usage and by quickly identifying solutions to reduce consumption.

1 *Resource Revolution: Meeting the world's energy, materials, food, and water needs*, McKinsey Global Institute, November 2011.

2 Recent McKinsey Global Institute reports that address technological advances and their consequences include *A future that works: Automation, employment, and productivity*, January 2017; *Digital globalization: The new era of global flows*, February 2016; *Digital America: A tale of the haves and have-mores*, December 2015; *The Internet of Things: Mapping the value beyond the hype*, June 2015; and *Disruptive technologies: Advances that will transform life, business, and the global economy*, May 2013.

$1.6T

Potential value to the global economy in 2035 from our accelerated technology adoption scenario

TWO SCENARIOS FOR THE PACE AND EXTENT OF TECHNOLOGY ADOPTION

The $900 billion to $1.6 trillion estimate of the total value to the global economy in 2035 from the technological transformation of the resource sector is based on our modeling of two technology adoption scenarios for both resource demand and resource supply. The first is a "moderate" technology adoption case, which assumes improved energy productivity from the greater deployment of technology to support energy efficiency and reduce the cost of renewables, along with improved productivity of resource extraction from deployment of technologies by producers. The second scenario, which we call a "tech acceleration" case, assumes a faster rate of adoption of technologies and therefore greater energy and resource productivity.[77] For both of these scenarios, we assume that the productivity of resource extraction for our five focus commodities (oil, natural gas, thermal coal, iron ore, and copper) will improve as oil and gas and mining companies deploy automation, analytics, and other technologies. The main difference between the two scenarios is the pace and extent of technological adoption by both producers and consumers.

The largest opportunity from technology is on the demand side, as a result of increased energy productivity from transportation, overall efficiency measures, and renewables (see illustration, "Technology will change the ways consumers live and reduce resource consumption"). The value to the global economy amounts to $600 billion in the moderate case, and almost $1.2 trillion in the tech acceleration case. For producers of our five focus commodities, productivity gains could reach $290 billion annually in the moderate adoption scenario, and $390 billion annually in the tech acceleration case. This amounts to an increase in productivity among producers of 20 percent from current levels in the moderate case and 30 percent in the tech acceleration case (Exhibit 5).[78]

The largest opportunity from technology is on the demand side, as a result of increased energy productivity from transportation, overall efficiency measures, and renewables. On the supply side, resource producers could benefit from a significant increase in technology-enabled productivity.

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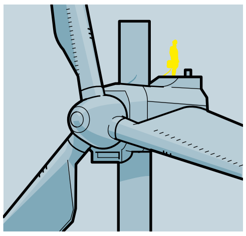
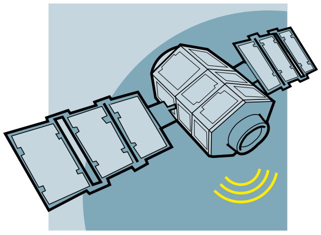
[77] We developed our models with help from our colleagues at McKinsey & Company Energy Insights and the McKinsey Basic Materials Institute. See the technical appendix for details of our methodology.

[78] All figures are in 2015 dollars. We define energy productivity as GDP per terajoule of energy consumed.

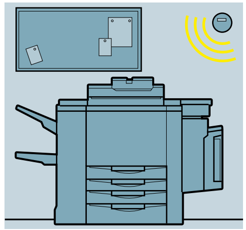
Technology will change the ways consumers live and reduce resource consumption



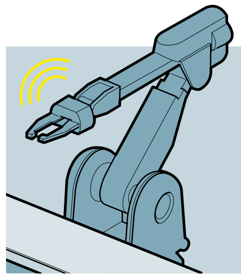
1. Renewable energy may become the cheapest form of power, used in a combination of decentralized and centralized sources.



2. Long-haul transportation adopts greater levels of autonomy as **telematics of travel patterns**, platooning, and analytics enable greater fuel economy.

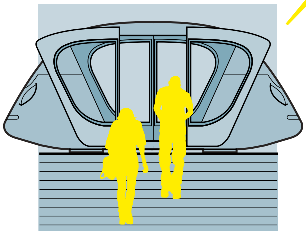


3. Electrical sensors in the office and home enable optimization of heat and light based on usage, weather, and occupancy data.

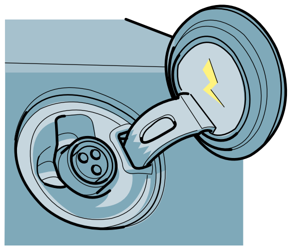


4. Industrial sites capture efficiency improvements with sensors, analytics, and automation, improving overall productivity and safety.

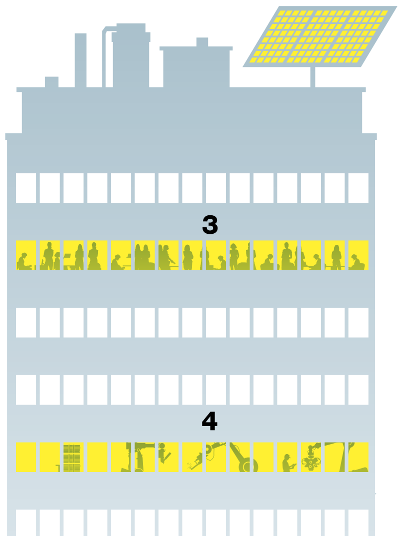
5. Utilities communicate with users and devices to identify optimization opportunities like retrofits or upgrades to new appliances.



6. Autonomous ride sharing services collect passengers at their homes, optimizing route and picking up other commuters to carpool, reducing number of vehicles on the roads.



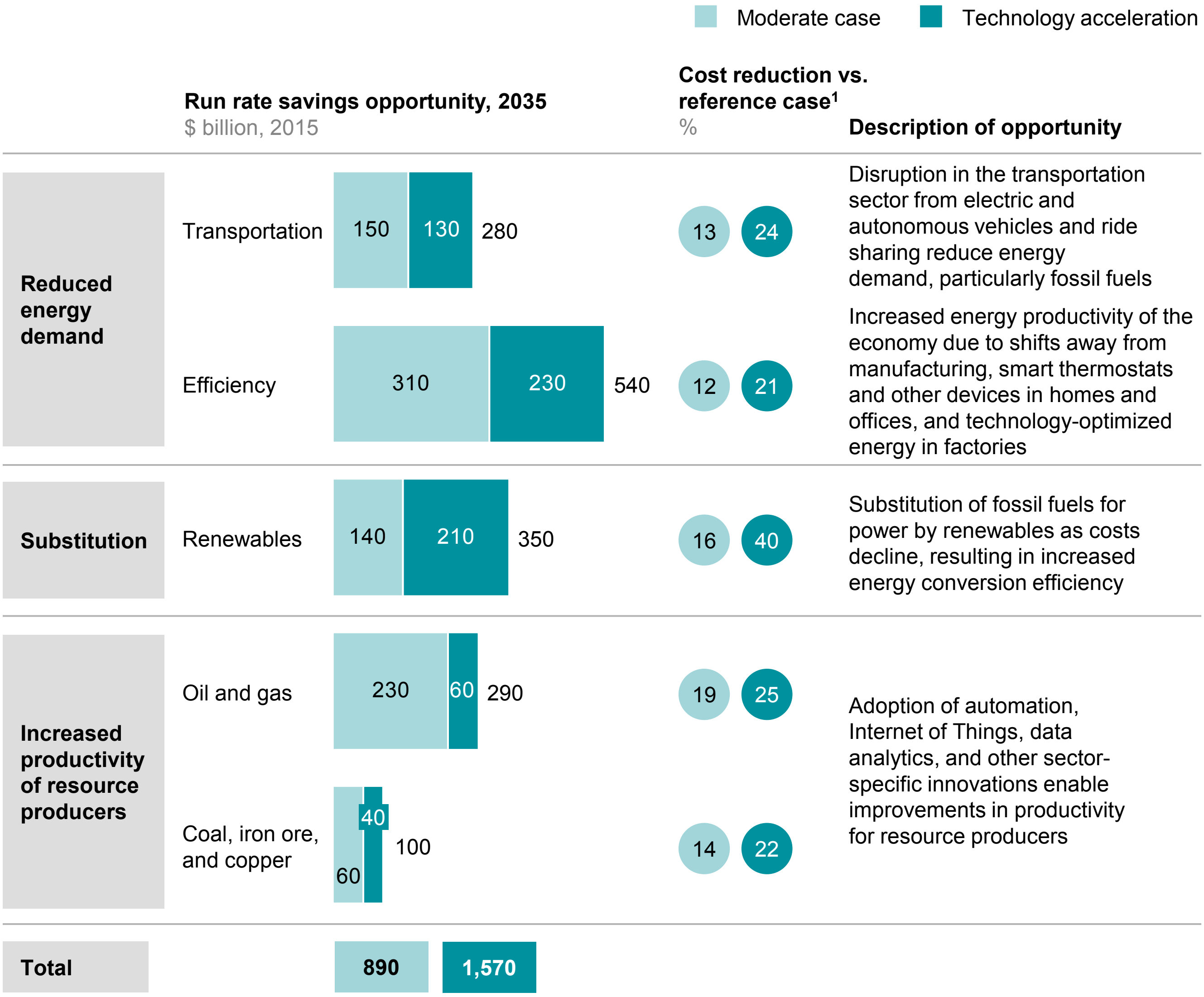
7. Electric vehicles may account for the majority of new car sales, taking advantage of their lower total cost of ownership.



McKinsey&Company | Source: McKinsey Global Institute analysis

Exhibit 5

Technology will create opportunities for increased productivity



1 The reference case used the same macroeconomic assumptions but assumed no further technology adoption beyond current levels

NOTE: Numbers may not sum due to rounding

SOURCE: Energy demand based on demand scenarios from *Global energy perspective*, McKinsey Energy Insights; resource productivity based on McKinsey Basic Materials Institute; additional analysis by McKinsey Global Institute.

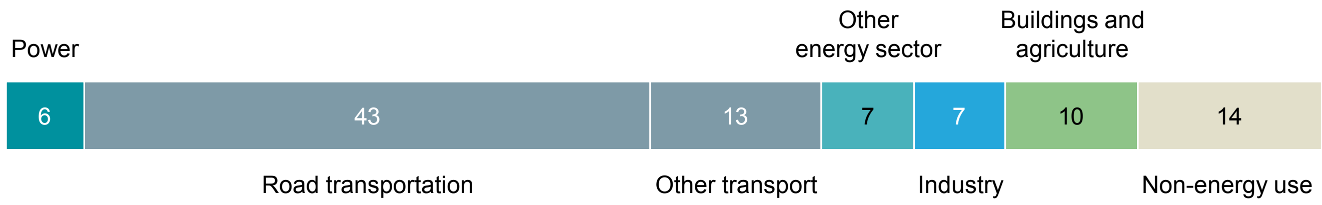
REDUCING ENERGY DEMAND FROM TRANSPORTATION, GREATER ENERGY EFFICIENCY, AND INCREASED USE OF RENEWABLES

Exhibit 6 highlights the key uses of the five resources that we focus on in this report: oil, natural gas, thermal coal, iron ore, and copper. Improving energy efficiency remains one of the fastest and most cost-effective ways to reduce energy consumption and therefore global demand for resources. In 2013, global primary energy demand was 561 million terajoules (TJ). Of this total, transportation accounted for about 18 percent of primary energy demand, power and heat for 38 percent; the remaining 44 percent was used directly in industry or by residential and commercial buildings.

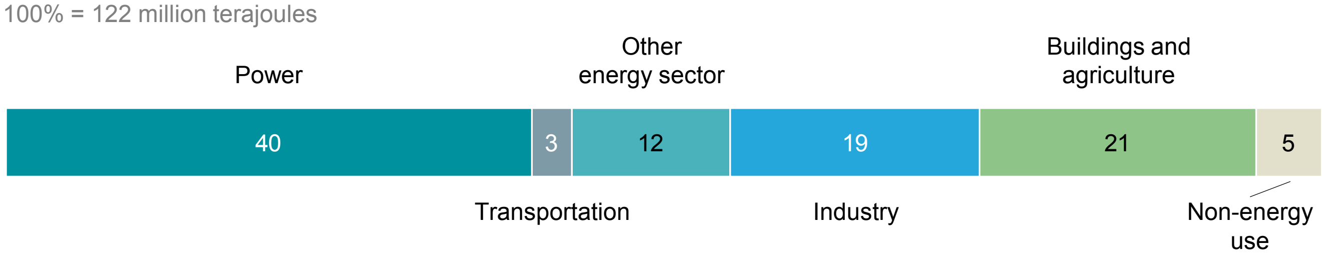
Exhibit 6

Main uses of focus commodities

Oil primary demand, 2014
100% = 181 million terajoules

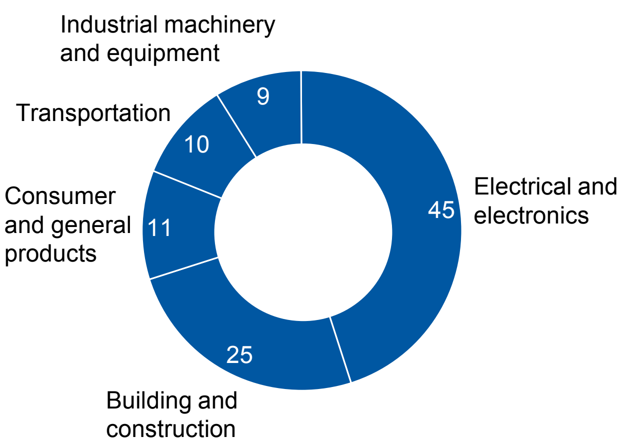


Natural gas primary demand, 2014
100% = 122 million terajoules

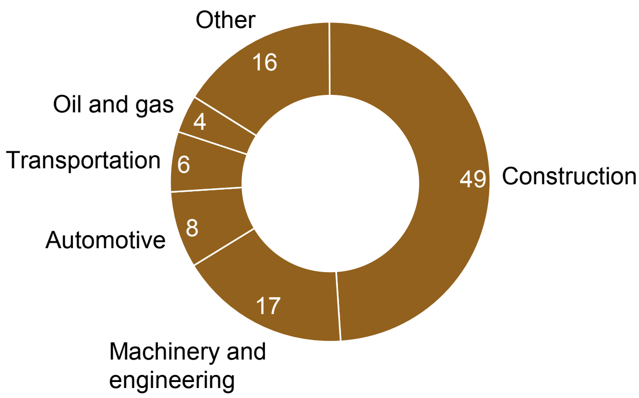


Thermal coal primary demand, 2014
100% = 143 million terajoules

Copper end use, 2015
%



Iron ore end use, 2013
%



NOTE: Numbers may not sum due to rounding.

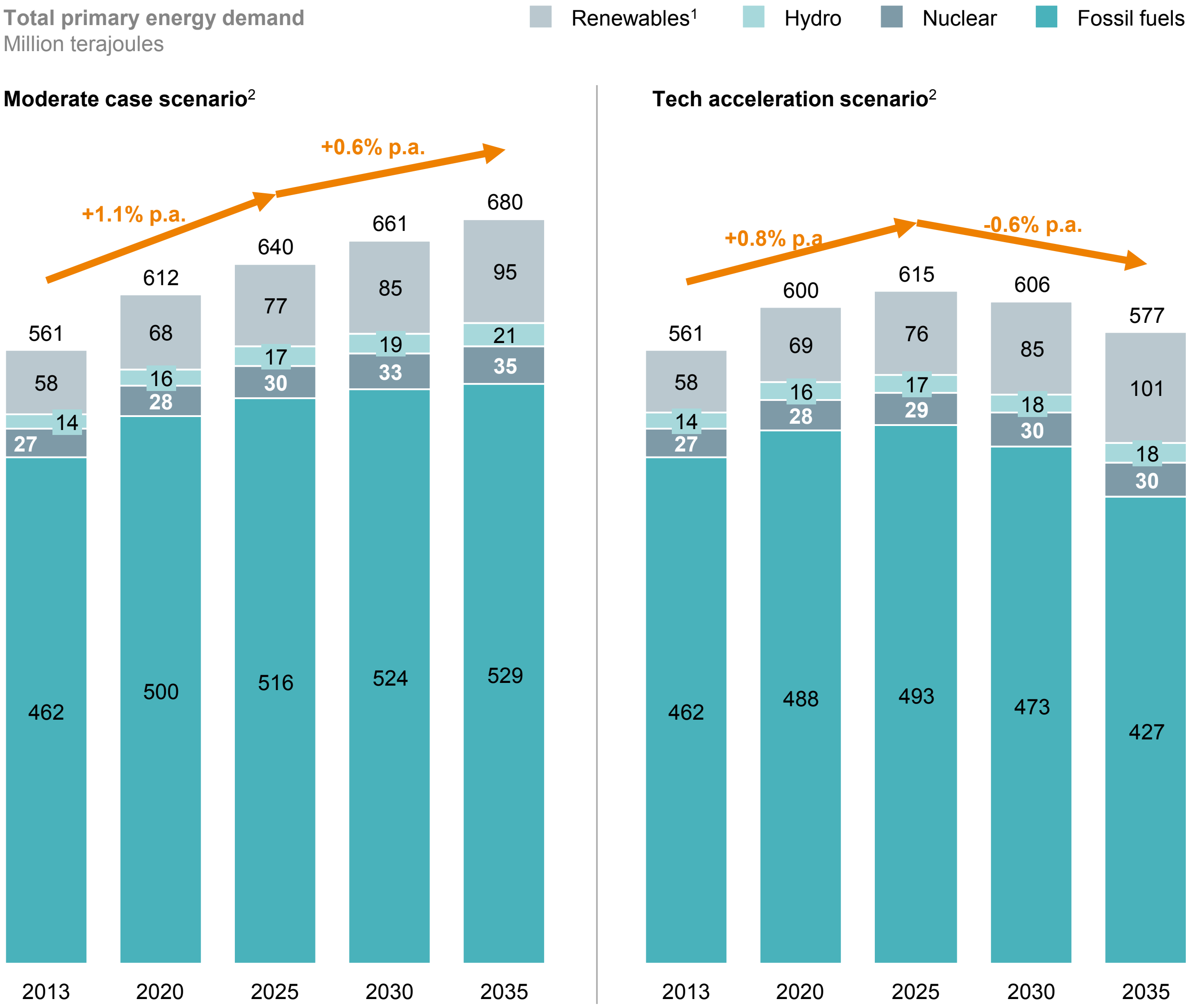
SOURCE: Based on IEA data from *World energy balances*, ©OECD/IEA, IEA Publishing, modified by McKinsey Global Institute; World Steel Association; J. F. King; IEA; McKinsey Global Institute analysis

While total primary energy demand could decline, electricity generation and consumption will likely continue to rise

We expect global energy consumption to decrease due to reduced demand from transportation, increased energy efficiency in residential, industrial, and commercial buildings, and greater use of renewables to generate power. In our moderate case, we expect a reduction in consumption of fossil fuels of 140 million terajoules, compared to a reference case with the same level of technology usage as today. This would mean that total primary energy demand plateaus by 2035 despite growth in global GDP. In our tech acceleration scenario, annual consumption of fossil fuels would decline by a further 100 million terajoules, with total energy demand declining from 2025. By 2035, total energy demand would reach the same value as in 2015. Compared to the moderate scenario, total primary demand for energy in 2035 could be 15 percent lower in our tech acceleration scenario (Exhibit 7).

Exhibit 7

Primary energy demand could peak in 2025 as a result of efficiency improvements, changes in the transport sector, and the shift to renewables



1 Includes biomass and geothermal as well as solar and wind.
2 Both scenarios assume annual average global GDP growth of 2.7%.
NOTE: Numbers may not sum due to rounding.

SOURCE: *Global energy perspective*, McKinsey Energy Insights; McKinsey Global Institute analysis

Another way of understanding the benefits from the accelerated adoption of renewables and demand efficiency technology is to examine energy productivity. The global economy currently produces about $127,000 of GDP per TJ of primary energy demand. In a moderate case scenario, energy productivity increases by 43 percent to $182,000 of GDP per TJ in 2035. This is due to a combination of macroeconomic factors such as industrial sector shifts which reduce the energy intensity of the economy and the aging population, as well as technology advances that improve energy efficiency, reduce the number of miles driven using conventional vehicles, and increase substitution of renewables. In a tech acceleration scenario, by 2035, the energy productivity of the global economy could increase to about $215,000 GDP per TJ of primary energy demand. Therefore, energy productivity in 2035 could increase by 43 percent relative to today in the moderate case scenario and by 70 percent relative to today in the tech acceleration case. At today's prices, this translates to an opportunity of $600 billion in the moderate case scenario. In a tech acceleration scenario, the total opportunity could be as high as $1.2 trillion, a $600 billion benefit from the faster adoption of technology.

Energy productivity in the global economy could increase by 43 percent in 2035 as a result of lower energy intensity and technological advances that improve efficiency.

The outlook for electricity generation and consumption differs from that of total primary energy demand. While the latter starts to decline after 2025 in our tech acceleration case, electricity generation and consumption continue to rise (Exhibit 8). Our analysis suggests that electricity consumption grows at about 1.5 percent annually while total primary energy demand in the power sector declines by 0.5 percent annually. This decoupling between primary energy demand and electricity generation is due to the growth of solar and wind as power sources. Sunlight and wind are free resources, so the effective efficiency of fuel-to-electricity conversion is 100 percent, and the uncaptured sunlight or wind has a marginal cost close to zero. In fossil fuel combustion, by comparison, significant amounts of energy are lost as heat in the transformation process. More efficient conversion means that electricity generation can continue to grow while primary energy demand falls.

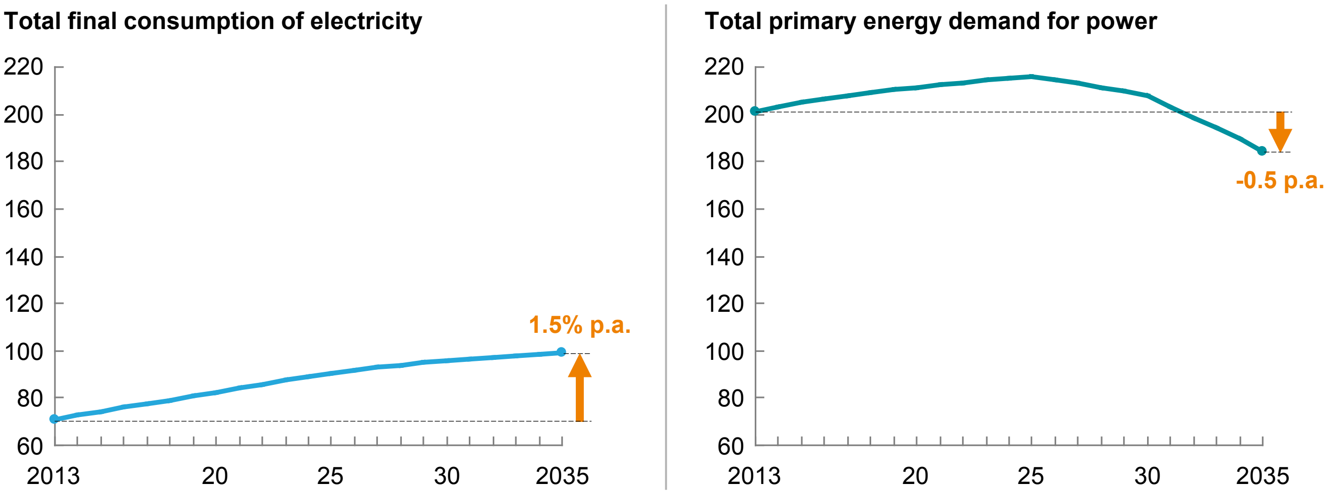
Take, for example, the levelized cost of electricity of a natural gas-fired advanced combined cycle and that of an onshore wind turbine. According to the US Energy Information Administration, the levelized cost of a newly built advanced combined cycle plant being commissioned in 2022 is forecast to be $56.4/MWh, while the estimate for an onshore wind turbine is $58.5/MWh (not including any possible tax credit). However, the variable operating costs for the advanced combined cycle plant amount to 73 percent of the cost, while the wind turbine variable operating costs are zero. The cost of fuel is dominant for the gas plant, while for the wind turbine, capital costs are dominant. Hence, the wind turbine is the more resource productive source of generation.[79]

[79] *Annual energy outlook 2017*, US Energy Information Administration, January 2017.

Exhibit 8

While total final consumption of electricity increases through 2035, total primary energy demand declines as use of renewables increases

Million terajoules[1]



1 Technology acceleration scenario

SOURCE: *Global energy perspective*, McKinsey Energy Insights; McKinsey Global Institute analysis

Autonomous and electric cars, ride sharing, and other technological innovation in transportation could substantially reduce oil demand

Changing patterns in transportation play a major role in our technology-enabled demand reduction scenarios for energy. Light vehicles account for half of all energy demand in transportation, or 9 percent of global demand, and shifts to electric and self-driving automobiles could transform energy consumption, especially of oil. Technological advances are also likely to contribute to reduced demand for oil by heavy-duty vehicles and aviation.

Three technology-driven trends could significantly reduce oil demand for transport

Over the next two decades, continuing improvements in fuel efficiency of engines will improve the energy productivity of transportation. Policy makers in many parts of the world have set stricter emissions standards for light vehicles in the near future; for example, in the United States, minimum standards for new passenger vehicles are set to increase fuel economy from 36.7 mpg in 2017 to almost 51.3 mpg by 2025.[80] On top of these fuel efficiency improvements, three technology-driven trends in transportation may become game-changers, with significant repercussions on the resource consumption of light vehicles. The three are the falling costs of electric vehicles, the increasing use of ride sharing, and the rise of autonomous vehicles. The car of the future could be very different, changing driving behavior and vehicle use, and fundamentally affecting fuel consumption.

As the electric vehicle industry has grown, battery costs and performance have improved substantially and costs have fallen, from $1,000 per kWh in 2008 to $268 per kWh in 2015. Many producers are targeting battery costs below $100/kWh in the next five years.[81] At the same time, energy density has improved dramatically, increasing from 60 Wh per liter to 295 Wh per liter, greatly improving the range potential of electric vehicles.[82]

[80] *2017 and later model year light-duty vehicle greenhouse gas emissions and corporate average fuel economy standards*, US Federal Register, volume 77, number 199, October 2012.

[81] Ibid.

[82] *Global EV outlook*, IEA, 2016.

The rise of electric vehicles is occurring while car sharing and ride-hailing services such as BlaBlaCar are gaining popularity in both developed and developing markets. Car- and ride-sharing apps combined with growing urbanization in emerging markets have the potential to reduce the total distance traveled. While car sharing alone will not necessarily reduce fuel consumption, it marks the beginning of a trend away from private ownership of vehicles, which could reduce the demand for vehicles and thereby reduce energy demand.[83]

15%
of new cars sold in 2030 could be fully autonomous

Autonomous vehicles are currently being tested in the United States and Europe, and McKinsey has estimated that 15 percent of new cars sold in 2030 could be fully autonomous.[84] Assuming they overcome technical and regulatory challenges, these autonomous vehicles will reduce the costs of e-hailing and carpooling services and may become the most cost-effective option for more than 80 percent of urban residents, according to our analysis. Cost savings arise from lower labor costs and higher vehicle utilization rates, defraying capital costs over more kilometers early in the life of the vehicle. The rise of autonomous vehicles could make car-sharing services easier to use and encourage more carpooling options by enabling automatic pick-ups. Companies including Ford have already announced plans to release specially designed cars for just that purpose in five years' time.[85] As a result of these technology-enabled trends, we expect demand for new cars to be about 10 percent lower in the tech acceleration case than in the moderate case in 2035.

Such trends will affect global consumption of oil. The net effect is that in our moderate scenario, oil demand in the light vehicle segment peaks and starts to decline slightly between 2015 and 2035.[86] In the tech acceleration case we forecast that oil demand for light vehicles will fall by 4.5 million barrels per day in 2035 compared with the moderate case.[87] The total energy savings in 2035 from these technology-driven changes in transportation amount to $150 billion for our moderate adoption case, and $280 billion for the tech acceleration case.

To realize the potential that we outline will require overcoming a number of regulatory and social acceptance barriers, as well as technical ones. Ride-sharing services are fighting litigation in a number of cities and countries including the United States and Germany as concerns about safety and labor rights are increasing. For autonomous vehicles, regulatory issues include insurance standards and liability requirements. Policy makers are moving to confront these issues, with countries including the United Kingdom establishing rules for insurance coverage of autonomous vehicles.[88] China is setting up a comprehensive regulatory framework for autonomous vehicles this year, while Dubai and Singapore have announced ambitious goals for autonomous vehicles.[89]

Consumers will also need to be won over and reassured about safety. Recent surveys of American drivers reveal that only one in five trust autonomous vehicles, although most drivers appear open to some form of autonomy.[90]

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83 *Urban mobility at a tipping point*, McKinsey & Company, September 2015.
84 Paul Gao, Hans-Werner Kaas, Detlev Mohr, and Dominik Wee, "Disruptive trends that will transform the auto industry," *McKinsey Quarterly*, January 2016.
85 "Ford targets fully autonomous vehicle for ride sharing in 2021; invests in new tech companies, doubles Silicon Valley team," Ford Motor Company, August 16, 2016.
86 *Global energy perspective 2016*, McKinsey & Company Energy Insights.
87 These projections are constructed on modeling of aggressive assumptions about the total cost of ownership and its impact on adoption rates of technology, estimates of impact from proven deployments or pilots of technology, and current policy initiatives. For details see technical appendix.
88 Oliver Ralph, "Insurance industry welcomes proposals for driverless cars cover," *Financial Times*, May 2016.
89 "China bans highway testing of autonomous cars pending regulation," *Bloomberg News*, July 2016.
90 AAA survey, March 2016; Hillary Abraham et al., *Autonomous vehicles, trust, and driving alternatives: A survey of consumer preferences*, MIT AgeLab, June 2016.

In addition to reducing oil consumption, technological advances in vehicles could produce second-order effects for the resource sector. Reduced auto sales and sales of vehicles made with lightweight materials could lower demand for steel and therefore iron ore. Carpooling, which would reduce the volume of vehicles on the road, would decrease the need for new road construction and regular maintenance and upgrades. Less traffic would also lead to less wear and tear on roads, potentially reducing demand for steel, cement, and other infrastructure materials including petroleum. Land requirements for parking could also be reduced, saving steel and concrete used in parking garages, although this would also increase the availability of land for development of housing in urban settings. However, as a result of electrification of light vehicles, electricity consumption could increase by about 500 terawatt hours in 2035 vs. the moderate case scenario. Moreover, the trend toward lighter vehicles could create new demand for plastics as a structural material, potentially creating additional demand for petrochemicals.

Technological advances could reduce fuel consumption by trucks and aircraft

While light vehicles are the major source of demand in transportation, trucking and aviation are other transportation sub-sectors that could experience technology disruption. Heavy-duty vehicles and trucks could improve fuel economy by more than 2 percent per year over the next two decades in a tech acceleration scenario, through vehicle performance enhancements, automation, and telematics. Technologies that improve engine performance such as friction reduction, engine downsizing, and turbocharging, could reduce fuel consumption by as much as 15 percent. Improved aerodynamic design of the vehicle shell and reduction of tire-rolling resistance could reduce fuel use by an additional 12 percent. Automation could optimize trucking fuel use through predictive powertrain control and vehicle-to-vehicle communication, which would allow increased "platooning" (where a line of vehicles closely follow one another to reduce drag). Telematics, with real-time monitoring of fleet operations and optimized route plans, can decrease distances traveled. Taken together, these technologies could reduce oil consumption in trucking by almost four million barrels per day in 2035 relative to our moderate technology adoption case. Technology could also improve the fuel efficiency of aviation.[91] Aviation fuels account for about 2 percent of total energy demand and almost 11 percent of the energy demand in the transportation sector. Historically, each generation of aircraft is about 15 percent more fuel efficient than the last due to the inclusion of more advanced propulsion and aerodynamic design features. Looking forward, new technologies could drive further efficiency in a tech acceleration scenario, such as advanced predictive analytics to improve aircraft utilization and automatic surveillance-broadcast avionics combined with satellite data to monitor real-time plane locations, enabling fuel savings from more efficient routing of aircraft.

Greater energy efficiency can be achieved in residential and commercial buildings

Accelerated adoption of end-use efficiency technology in residential and commercial buildings could reduce energy demand by about 12 percent by 2035 compared with the moderate case, which follows today's trends of energy efficiency improvement. Smart thermostats and advanced controls that optimize usage to match user behavior and patterns have the ability to save between 10 percent and 30 percent of heating and cooling energy.[92] Smart lighting controls such as network-connected light bulbs that automatically turn off when users leave buildings can achieve 20 to 30 percent in energy savings.[93] In addition to these direct savings, Internet of Things technology could speed the adoption of more efficient devices and home components by enabling greater awareness of the value

91 *Environmental report 2013: Aviation and climate change*, International Civil Aviation Authority, 2013; Anastasia Kharina and Daniel Rutherford, *Fuel efficiency trends for new commercial jet aircraft: 1960 to 2014*, International Council on Clean Transportation, 2015.

92 *Energy savings from the Nest Learning Thermostat: Energy bill analysis results*, Nest Labs, February 2015; *Reduce energy costs and carbon footprint with smart building management*, Intel, 2015.

93 Alison Williams et al., "Lighting controls in commercial buildings," *Leukos*, volume 8, issue 3, 2012.

of such investments. For instance, OPower, a US-based provider of customer engagement and energy efficiency cloud services to utilities, has been able to help drive reductions in end use of electricity by highlighting how users compare to their neighbors in terms of overall electricity use.[94]

As the technology advances and gains wider adoption, information from electric meters, smart thermostats, smart lighting devices, and some user inputs (the age of the home, the number of windows and doors, and so on) could be combined into a central app. This would provide an energy audit, highlighting opportunities to improve a consumer's energy efficiency and connect him or her with providers of installation and replacement services. Recent research has shown that customers are willing to make sustainable decisions when given the information via online platforms.[95]

The uptake of energy efficiency measures will likely be fastest in developed markets where Internet of Things (IoT) devices are expected to see the most rapid adoption. In emerging markets, the potential is lower for a number of reasons, including the ongoing dependence on biofeedstock and lack of access to reliable electricity. However, in urban settings where more modern homes are being built, the uptake of such technologies will likely occur as costs continue to fall. The combined effect of IoT and other efficiency measures would be an improvement in energy productivity across buildings, accelerating trends in OECD markets and slowing the consumption ramp-up in developing markets.

Automation and analytics could reduce energy demand in industry by as much as 30 percent

For industrial sectors, the combination of advanced sensors, control systems, analytics, and modeling could reduce energy demand at existing production levels by 10 to 30 percent based on a current range of proven improvements in facilities that adopted the technology. Many manufacturing plants are already seeing significant reductions in energy demand through retrofit efforts. A chemical company that improved sensors and modeling at a hydrogen production plant reduced energy consumption by 10 to 20 percent.[96] Optimization algorithms for robotic movements in an advanced manufacturing environment have been shown to reduce energy consumption by 10 to 30 percent. A cement grinding plant reduced energy consumption by as much as 5 percent with a customized model-predictive control approach.[97] In addition to energy savings, advanced control systems can prevent inefficient operations by limiting variation and improving safety and quality. We expect industrial companies to adopt such technologies over the next 20 years with the potential to improve overall energy productivity by 45 percent in the moderate case compared to 2015 levels, and by a further 10 percent in the tech acceleration case.

ADVANCES IN RENEWABLES TECHNOLOGY ARE LIKELY TO INCREASE SUBSTITUTION POTENTIAL OF CURRENT RESOURCES

30%
reduction in energy demand in industry is possible with deployment of new technologies

Renewable energy, particularly solar and wind, grew rapidly during the supercycle as people searched for alternatives to high-priced oil and gas. Policy accelerated the adoption of renewables in some markets such as Europe and the United States, and Chinese manufacturers invested at scale to lower costs. Renewable power has the potential to

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94 Stefan Heck et al., *Resource Revolution: How to capture the biggest business opportunity in a century*, Houghton Mifflin Harcourt, 2014.

95 Steven C. Isley et al., "Online purchasing creates opportunities to lower the life cycle carbon footprints of consumer products," *Proceedings of the National Academy of Sciences*, August 15, 2016.

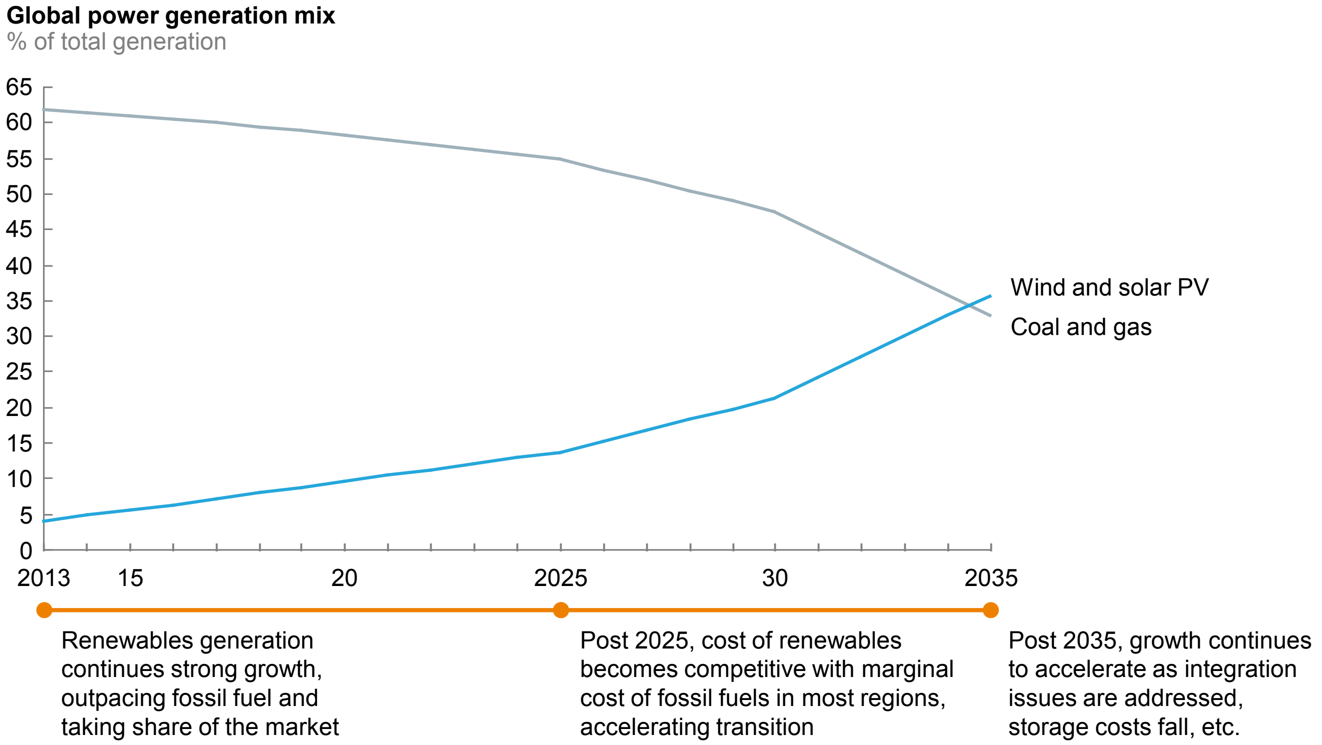
96 *Quadrennial technology review 2015*, US Department of Energy, 2015.

97 Ibid.

reshape the global electricity markets, and our scenarios suggest that a tipping point could be reached by around 2025 as a result of technological progress (Exhibit 9).[98]

Exhibit 9

Cost of renewables could reach a tipping point around 2025, increasing penetration rapidly thereafter



SOURCE: McKinsey Global Institute analysis

Solar and wind energy generation is becoming cost competitive

Since 2001, total solar generation has grown 50 percent annually while wind power generation has grown at an annual rate of 24 percent.[99] While government policy to diversify energy sources has driven much of this near-term growth, a sharp fall in costs has also facilitated the deployment of these technologies. The cost of solar modules has fallen 80 percent since 2008, and the levelized cost of energy for wind has fallen 50 percent since 2009.[100] In recent power auctions for new construction, solar photovoltaic (PV) installations have come in at below $0.03/kWh unsubsidized—about one-tenth the cost of solar plants six years ago.[101] Newly built wind farms in Texas can generate electricity at below $0.05/kWh.[102]

98 Our scenarios assume that market forces would shift rapidly to installing new renewable generation and retire less efficient fossil fuel generation if it becomes cheaper to run new solar and wind power than existing fossil fuel plants. For example, merchant power operators may outbid fossil fuel plants in power markets, and public power utilities could shift their electricity generation portfolios to provide a more cost effective source of power for their customers. See technical appendix for details of our assumptions.

99 *Electricity power and generation figures*, GlobalData, 2016.

100 Bloomberg New Energy Finance presentation, 2016; The levelized cost of electricity is defined as the constant price per unit of energy that causes the investment to just break even and earn a present discounted value equal to zero.

101 Anna Hirtenstein, *New record set for world's cheapest solar, now undercutting coal*, Bloomberg, May 2016; Stephen Lacey, "Jinko and Marubeni bid 2.4 cents to supply solar in Abu Dhabi. How low can solar prices go?" *Greentech Media*, September 20, 2016; *Renewable energy technologies: cost analysis series*, International Renewable Energy Agency, 2012.

102 *2016 sustainable energy in America factbook*, Business Council for Sustainable Energy, 2016.

In our research, we explore what could happen if renewable power continues to realize declining costs and improvements in lifetime and efficiency. Research and development in this sector has found new ways to improve efficiency, including with back contact cells for solar PVs (cells without electric contacts on the light-collecting side), improved thin film materials for solar PVs, and modulating blade position in real time for wind. Efforts are also under way to reduce material costs by creating less waste, for example with kerfless wafers, which require no saw to cut a silicon wafer off a large ingot, and to extend the lifetime of the equipment. This includes efforts to improve manufacturing quality to reduce defects in final solar panels and increase use of predictive maintenance on wind turbines to ensure maximum efficiency for as long as possible.

Soft costs associated with installing panels and turbines are likely to continue falling, too. Installers will continue to develop more efficient methods. Together with the potential for breakthroughs in solar PV technology, such as next-generation thin film materials, and reduced capital intensity of manufacturing capacity, plus continued improvements in the scale and capacity factor of wind technology, the levelized cost of energy could continue to fall.

Our analysis of historic learning curves and expected near-term growth in the industry suggests that, in most regions, power generation from solar PV and wind could become competitive with the marginal cost of power generation from natural gas and coal between 2025 and 2030. Growth rates in renewable power deployment could therefore remain rapid and potentially accelerate in absolute terms until large-scale diurnal storage needs present a new hurdle for the industry to overcome.[103] We have assumed that a tipping point will be reached in 2025 and that the industry will be able to grow to a point where large-scale diurnal storage would likely be needed by 2035. Although there is much debate about the technical limits of intermittent power in the grid—that is, power that cannot be dispatched at will and is not generated in a continuous fashion—and when storage might be needed, we have used the average capacity factor for solar PV or wind technology in a region as a practical limit for penetration without storage.[104] Applying this logic to most regions, we have assumed that in a tech acceleration scenario, solar PV could reach about 10 percent and wind could achieve 26 percent of global electricity generation on a terawatt hour (TWh) basis by 2035, for a total penetration of about 36 percent.[105] This penetration compares with solar and wind power's contribution to global electricity in 2014 of just 4 percent.[106] In a moderate scenario, we expect that solar and wind could account for 22 percent of total electricity generation.

According to our model, solar and wind would need to supply 3,200 and 8,300 TWh of electricity, respectively, by 2035 in the tech acceleration case. This means generation

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103 Our assumptions are determined partly by geography and conditions in local markets. For example, coal usage could increase in India because of the fast-growing energy market there, whereas in the United States coal could lose out to plentiful natural gas. The overall assumption is that renewable power will replace fossil fuel power, and that hydro, nuclear, and other generation will represent the same share of generation in the future as they do currently.

104 Capacity factors indicate an average annual effective utilization of a power source, i.e., what percent of capacity is used. For solar PV and wind power, this is largely driven by the prevailing weather patterns in a region. As penetration rates increase for these resources, major curtailment of the resource happens right around the capacity factor for the technology based on empirical evidence. See MIT's *The Future of Solar* report for curtailment issues. Once enough power capacity is installed to meet total demand on the peak generation day, curtailment becomes a necessity if more power capacity is built. Thus, further value capture on the peak generation day is limited, and the potential value capture of marginal capacity decreases. Hence, marginal renewable power generation becomes more expensive. So even though enough power generating capacity is installed to meet all demand, the power source can only provide the percent of all electric power equal to the capacity factor. We acknowledge that this is a simplistic approach, but it presents a logical upper bound before major trade-offs are required.

105 This assumes no coincidence in solar and wind power, and that the challenges with integration of existing generation sources are overcome. We assume that there will be sufficient integration flexibility in the grid for demand shifting, multipurpose battery systems, and grid interconnection.

106 *World energy outlook 2015*, International Energy Agency, 2015.

capacity of 2.7 TW for solar power and 3.2 TW for wind power would need to be installed, given regional capacity factors. This is a 13-fold increase in solar power and a ninefold increase in wind power over today's installed capacity.[107] By 2035, annual installation of solar would need to reach 185 GW per year, and wind installations would need to be closer to 320 GW per year. That means that roughly 120,000 1.5 MW solar plants would need to be installed in 2035, or about 340 per day. For wind, this would require installing 107,000 3 MW wind turbines per year in 2035, or about 300 per day.

Obstacles to the rapid growth of renewables can be overcome

Renewable power generation will need to overcome substantial challenges if it is to realize its potential growth. Storage is one notable challenge: it could be a key enabler of growth, but it has some limitations (see 3, "The role of storage in the penetration of solar and wind power generation"). Other obstacles include capital investment. A capacity expansion of the size we think possible translates to about $420 billion of capital expenditure for generation assets in 2035, taking into account the cost compression expected. Recent estimates of investment in clean energy assets amount to $286 billion in 2015.[108] Thus, investment in the sector will need to increase by about 47 percent over the next 20 years to hit these penetration levels. While this is a sizable gap, if demand in other sectors such as fossil fuel begins to decline, capital could be available to flow to this sector.

Another challenge is scaling the industry and ensuring that players in the supply chain receive adequate returns to warrant investment. The industry has shown that it can grow very rapidly if there is a driver for supply expansion. For instance, the global PV industry was able to increase PV module production capacity by 17 GW in 2010 and 2011.[109] Delivering on such rates over the next 20 years would grow the PV module market to over 400 GW of production capacity. At current capital costs, this would require cumulative investment of about $340 billion, about half of what the oil and gas industry spent in one year at the peak of the supercycle.[110] However, the solar PV industry has been faced with a glut of capacity over the past five years, with gross margins in the range of zero to 10 percent and earnings before interest and taxes margins that are much lower if not negative. Recent research has highlighted that the industry needs a margin exceeding 15 percent to grow at 19 percent per year.[111] However, supply expansions continue in the face of low prices, indicating that the industry is continuing to find ways to lower costs and increase profitability to warrant new investment.

The industry will also have to overcome the challenges of training a large and geographically disparate labor force to enable cost reductions. Engineering, procurement, and construction firms that are able to standardize the installation process and create effective training programs will be most affected. However, in a time of underemployment in a number of regions, supply of labor is not a primary constraint. Recent research has shown that the retraining of coal industry workers in the US for employment in the solar industry could be accomplished with modest investment.[112] Already, wind-turbine service technician is the fastest-growing job category in the United States, according to the US Bureau of Labor Statistics.[113]

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107 Assumes 10 to 18 percent capacity factor, depending on the region, for solar, and 24 to 33 percent capacity factor for wind. Based on current performance, capacity factor improvements would help lower total generation installation requirements.

108 *Global trends in renewable energy investment 2016*, FS-UNEP Centre, August 26, 2016.

109 *Trends 2015 in photovoltaic application*, International Energy Agency, 2015.

110 Douglas Powell et al., "The capital intensity of photovoltaics manufacturing: barrier to scale and opportunity for innovation," *Energy & Environmental Science*, issue 12, September 2015.

111 Ibid.

112 Edward P. Louie and Joshua M. Pearce, "Retraining investment for US transition from coal to solar photovoltaic employment," *Energy Economics*, volume 57, 2016.

113 Jennifer Oldham, "Nation's fastest growing job—only for those who like to get high," Bloomberg, May 12, 2016.

Box 3. The role of storage in the penetration of solar and wind power generation

One of the biggest issues with wind and solar photovoltaic power sources is their intermittent nature and the fact that they cannot be dispatched when needed. At low levels of penetration, this is typically not an issue, as many grids have some ability to adjust the supply of power from other sources such as conventional power plants, to ramp up or down as needed to match supply and demand. However, as the penetration of solar and wind power sources increases, less conventional electrical generation capacity will likely be available. The effect of this could be an increase in the cost of renewable power as utilization levels drop, reducing the attractiveness of further installations. For this reason, energy storage to shift supply from periods of high generation and low demand to periods of low generation and high demand is an attractive alternative. The challenge becomes the cost of battery storage, which needs to be low relative to the cost of the electricity generated.

Levelized costs of storage have been declining rapidly, and a number of promising technologies are being developed to store energy in a cost-effective manner, such as through grid-scale lithium ion batteries, flow batteries, compressed air systems, and thermal storage. However, there is significant uncertainty around which technology will be successful and how far costs might fall as it scales up. Overall, levelized costs of storage would need to fall to between about $20 and $30 per megawatt hour from their current costs of more than $300 per MWh in order for solar power plus storage to be competitive with the marginal cost of fossil fuels in most regions for load shifting.[1]

The leading technology may be lithium ion batteries, given their ubiquity and the number of high-profile players investing in their development. By our analysis, a 14 percent reduction in capital and operations and maintenance costs for lithium ion batteries would be needed every year to reach the target level by 2035. This assumes that a high level of operational performance is achieved as well, with a depth of discharge of 100 percent, full storage capacity used on every charge-discharge cycle, on a daily basis, with a round-trip efficiency of 85 percent.[2]

The benefit for energy storage in the near term is the large number of additional applications for batteries with higher levels of value generation.[3] Batteries are already being used to stabilize grid operations through frequency regulation of wind and solar PV power. Batteries behind the meter can also generate significant value for commercial and industrial customers by reducing peak power charges, and battery installations can be used by utilities to defer larger-scale capital upgrades. Such value-generating applications will help drive adoption of energy storage solutions and drive down costs as the industry gains experience and scale.

In the longer term, storage will also be important for adjusting to seasonal variations in supply and demand for renewable power—that is, adjusting for the low amount of solar energy available during the winter. Seasonal storage systems would likely need to eschew traditional battery technologies given the low utilization of such systems, with only one cycle per year. Pumped hydro and compressed air systems using caverns could be part of the solution, but their low energy density and the unique geological features that are required pose a challenge to storing large amounts of backup power. Other alternatives could be solar fuels, likely based on hydrogen formation by splitting water. It is unclear at this time what technology will eventually fill this need, but research and development is ongoing.

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1 *Lazard levelized cost of energy version 8.0*, 2014.

2 Ibid.

3 McKinsey & Company, *The new economics of energy storage*, August 2016.

The availability of raw material inputs for solar panels and wind turbines could be a hurdle for achieving cost targets. Large demand for polysilicon for photovoltaics, rare earth elements for advanced wind turbines, and silver for solar PV contacts could drive up the costs of the technology. However, a number of companies are focused on reducing the material intensity of manufacturing and looking for cheaper substitutes.[114]

As the proportion of renewables in the generation mix grows, effectively integrating power becomes increasingly difficult. Investment in the grid will be required to enable renewables growth, whether it is increased interconnectivity between regions to aid in smoothing wind power, introducing frequency-stabilizing components, or scaling up demand response technology. Recent reports have indicated that the cost of effective integration of renewable energy in the United States could be as low as a 3 percent increase over a baseline scenario dominated by fossil fuel sources.[115] Similar work that estimated integration costs for Germany found integration costs of €5 to €20 per megawatt hour (MWh), or roughly $0.006 to $ 0.023 per kWh.[116]

TECHNOLOGY COULD ENABLE SUBSTANTIAL PRODUCTIVITY GAINS FOR PRODUCERS OF NON-RENEWABLE RESOURCES

Technology adoption could raise productivity of iron ore mining by

60%

Resource producers face a significant productivity challenge, particularly as reserves become more difficult to access, but also to reverse a long-term decline in overall productivity. In mining, recent expansions in the copper industry are tapping reserves with an average ore grade of less than 1 percent copper.[117] In oil and gas, the most recent deepwater exploration is accessing reservoirs at depths of more than 8,000 meters four times deeper than the deepest developments in the 1980s.[118] As noted in the previous chapter, mining productivity has fallen by 4 percent per year since 2004, and oil lifting productivity has fallen by 12 percent per year. Without an increase in productivity, the cost of resource supply will increase rapidly over the next 20 years. This is where technological innovation comes in. Technology has delivered productivity gains in the past, for example when oil faced the threat of hitting peak supply, by opening up access to new reserves.[119] Today, once again, technological progress could play a key role in lifting the resource sector's productivity. We project that the adaption and adoption of existing technologies could substantially increase the productivity of the oil and gas and mining sectors, with gains in the technology acceleration scenario ranging between almost 20 percent for coal and more than 60 percent for iron ore.[120] In all, these productivity improvements could unlock between $290 billion and $390 billion in annual value for resource producers in 2035 (Exhibit 10).

In assessing the impact of technology on productivity, we focus on currently available technologies that have been tested in the field, even if their adoption is not commonplace. We then assess each technology for its ability to reduce costs on a category-by-category basis—for example, labor or fuel—or by increasing throughput and uptime. Our assessment

[114] For example, 1366 Technologies is developing new ways to manufacture silicon wafers with less material losses while Enercon is building wind turbines that do not have permanent magnets and therefore do not rely on neodymium, a rare metal.

[115] Trieu Mai et al., "Envisioning a renewable electricity future for the United States," *Energy*, volume 65, February 2014.

[116] *The integration cost of wind and solar power*, Agora Energiewende, 2015.

[117] McKinsey Basic Materials Institute; McKinsey MineLens.

[118] *A brief history of offshore oil drilling*, National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, staff working paper number 1, 2010.

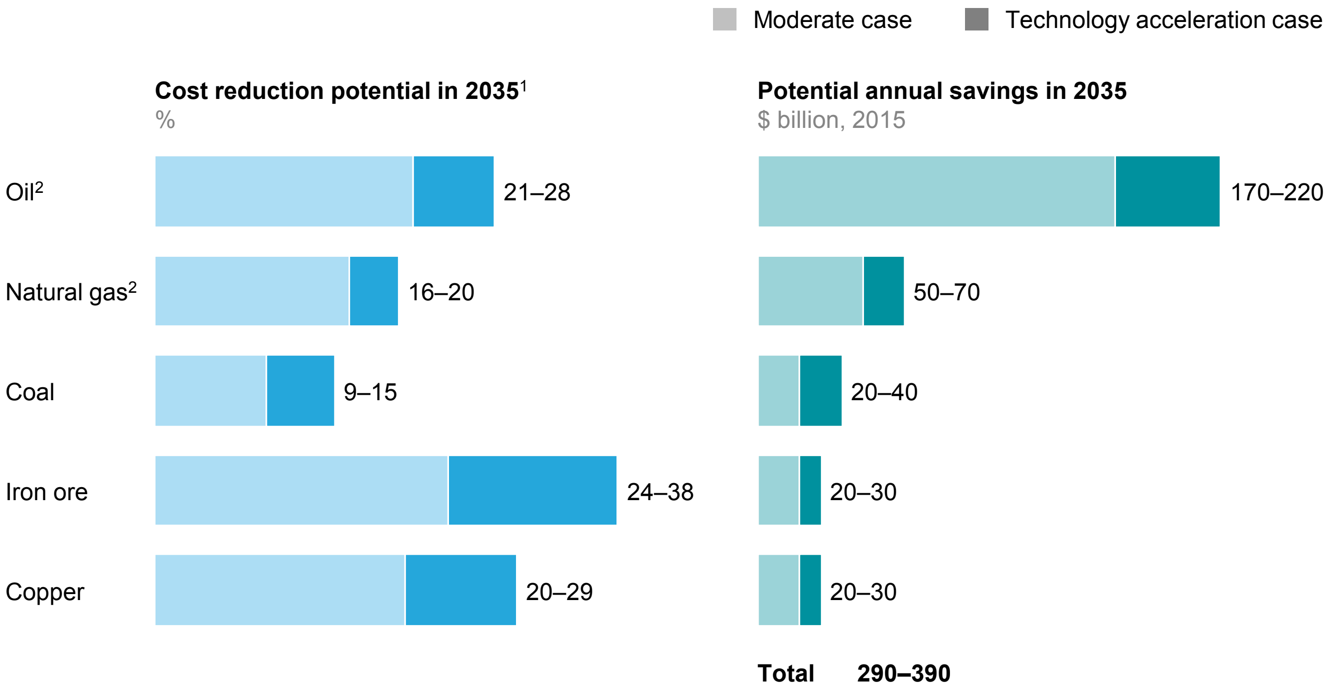
[119] *World energy outlook*, IEA, 2010.

[120] Productivity is defined as tonnes per dollar of production cost. The productivity improvement was calculated by applying each of the technology levers, scaled based on their adoption rates, to the baseline (2015) production cost per tonne. This gave a revised cost per tonne after technology. The inverse of the cost per tonne was calculated to give the productivity (tonnes per dollar). The 60 percent productivity improvement for iron ore was thus calculated as the percentage difference between tonnes per dollar in 2015 and 2035 (after application of technology levers). See technical appendix.

is informed by case studies from the field and interviews with practitioners who have seen the technology and its impact firsthand. We apply the impact assessment to a detailed global cost structure for the individual subsector.

Exhibit 10

Technology could unlock up to $400 billion in annual value for resource producers by 2035



1 Difference between total cost per output unit (tonne, barrel) in 2035 and 2015.
2 Only upstream operations considered.
NOTE: Numbers may not sum due to rounding.

SOURCE: McKinsey Global Institute analysis

We used two scenarios of technology adoption, as we did for energy demand. The moderate case scenario assumes that technologies are adopted conservatively and follow current trends. The more aggressive tech acceleration scenario assumes that technologies are adopted wherever it makes financial, operational, and geological sense to do so. Overall, we judge that technologies that require relatively limited investment, such as Internet of Things sensors, will be adopted more widely than technologies that require significant investment and changing structures of operational sites, as is the case for many of the new extractive technologies. We also took a sector-specific view, judging that growth commodities such as copper were more likely to invest in new technologies across the board than commodities with a softer outlook, such as coal.

Each sector has specific technologies with specific uses that will help bring about a productivity boost. However, across all sectors, automation, the Internet of Things, and advanced analytics will play a significant role. This group of technologies is leveraging the emergence of low-cost computing power, increased connectivity, and the ubiquity of data-collection devices. The technology we refer to here includes things as simple as sensors at the tips of drill bits that measure ore grade in real time, and crawling drill rigs that move between drill sites automatically. Exhibits that illustrate the individual sector discussion of technologies are emblematic of the sort of changes that could be made but are not exhaustive. Other technologies could transform resource supply in unpredictable ways (see Box 4, "Futuristic technologies that could revolutionize the resource sector").

Box 4. Futuristic technologies that could revolutionize the resource sector

Technological innovation over the next two decades is likely to transform industries in ways that are difficult to predict. Some to keep an eye on include:

- **Synthetic biology: Biofuels and microbial leaching in mining.** A number of companies are already leveraging enhanced microorganisms such as bacteria and yeast to create new or difficult-to-synthesize products at much lower costs than traditional chemical industry methods. If technology could be harnessed to make liquid hydrocarbon fuels from inputs such as biomass of the sun, oil's dominance in long-distance transportation could quickly disappear. In mining, some companies are augmenting existing leaching strategies with designed microorganisms to help improve recovery and release of desired metals from ore bodies. If this potential is fulfilled, metals in the future could be extracted from ore bodies in a manner very similar to fracking in oil and gas today.
- **Graphene and nanotubes: Superconductors, ultracapacitor applications, improved battery technologies, and next-generation electronics.** Carbon materials are already used in a number of electronic devices and energy storage solutions. As the cost of these materials continues to fall, new applications could become commercially viable. They may range from new generations of batteries to new electronics, displacing the silicon-based systems we use today.
- **Traveling wave reactors, thorium reactors, and other nuclear fission innovations.** Technology that can provide cheap nuclear energy with reduced waste disposal issues could potentially bring about a nuclear renaissance around the globe. Traveling wave reactors could provide greater power with lower fuel consumption and reduced waste production over their lifetime. Thorium reactors could take advantage of more abundant materials without the risk of the technology being used to make weapons.
- **Bioplastics.** Demand for chemicals and plastics is expected to grow strongly in the coming decades as emerging economies raise consumption. If the cost of producing functional plastics from a renewable biomass source falls significantly below that of traditional petroleum-based plastics, and the technology is scaled up efficiently, demand for petroleum feedstock could decline.
- **Nuclear fusion.** With significant research currently under way in this field, a breakthrough in nuclear fusion could change the energy landscape entirely. Although costs would be significant early on, once proven as viable for commercial-scale electricity generation, nuclear fusion could represent a source of energy with an abundant supply of fuel, namely hydrogen from water.

Box 4. Futuristic technologies that could revolutionize the resource sector (continued)

- **Undersea mining and asteroid mining.** As ore bodies of many base metals face declines in ore grades, more exotic sources of these minerals with higher ore grades become increasingly attractive. A number of companies are raising capital and exploring how to commercialize known deposits undersea and in space.

- **Hyperloop transportation.** The realization of electric-powered ground-based transportation that moves people and freight at very high speeds could radically change long-distance transportation, including by competing with air travel. It could also represent a step change in cargo costs, potentially transforming logistics.

- **High-temperature superconducting materials.** Interconnecting electric grids over long distances is hindered by losses incurred through the cables. A breakthrough in superconducting materials could mean that solar power from the Sahara or other deserts could be readily consumed anywhere in the world.

- **Super fracking.** Currently, fracking recovers at best 10 percent of the oil in a shale deposit. If methods could be found to move that figure closer to standard 50 to 70 percent recovery rates, the resulting supply could enable oil to remain low cost for decades to come.

- **Methane hydrates.** Methane hydrates are reserves of methane trapped at low temperatures and high pressures, typically in permafrost or the seabed. Estimates vary widely, but reserves of methane hydrates could be larger than known reserves of all other fossil fuels combined.

- **Next-generation solar PV.** A breakthrough in solar PV that achieves a step-change improvement both in efficiency and in the cost and capital intensity of manufacturing could greatly accelerate the industry's growth. Thin film and solution-processable materials such as perovskites are receiving attention because of efficiency levels well above those of the current silicon technology deployed in most solar modules.

- **Hydrogen economy.** A breakthrough in the ability to convert renewable electricity into hydrogen from water at scale and at low cost could be the long-term solution to the intermittent issue associated with wind and solar power. It also could mean a transition toward hydrogen fuel cell vehicles and devices rather than fossil fuel–based ones.

In oil and gas, technology can make the workplace safer and more productive

Increased use of robotics in the oil and gas sector could automate many activities that are currently high risk for humans, reducing variability in outcomes as well as making the workplace safer (see illustration, "Technology will make the oil field of the future more productive and safer"). Examples include the use of underwater robots to repair pipelines in subsea locations and of drones to inspect towers on offshore oil rigs. Statoil has developed an underwater robot system for pipeline repairs that is reducing repair times.[121] Drones rather than people can conduct pipeline inspections and real-time constant site surveys in oil field development.

Automation is also being explored for highly repetitive activities including unconventional well development, such as pad drilling, where multiple wells are drilled in a single reservoir using a single drilling pad. New products such as crawling well-drilling machines take this manufacturing approach to another level by creating a moving assembly line of all equipment to drill multiple wells quickly one after another.

Analytics and the Internet of Things technologies build on the decreasing size and cost of sensors and the falling price of data collection to help improve multiple operations in the oil and gas sector. The oil and gas industry has long been an avid user of data for exploration, from earlier innovations in seismic imaging to use of supercomputers to process multiple forms of geological data. The Internet of Things opens the gates to a flood of new data, only a fraction of which is currently being used. By our estimates, less than 1 percent of all data from an oil rig reaches decision makers.[122] If used to its fullest potential, this information could help lower maintenance costs by moving from time-based to predictive-based maintenance routines, thus reducing the frequency of repairs, and by ensuring that the right repairs are done at the right time through improved diagnosis. Increased use of sensors and data could also drive improvements in recovery and reservoir development. The information collected from improved geo-sensing, 4D seismic monitoring, and downhole fiber optic monitoring over the life of a well and reservoir could provide better upfront design of future field development. In other words, it could ensure that the right number of wells go into the right number of places to maximize recovery and reduce costs. This technology would also enable ongoing adjustments to fields and wells as they age to maximize production through changes to operations.

One innovation with significant promise for the oil and gas sector is increased use of technology to enhance oil recovery from mature fields. Typically, only 20 to 40 percent of oil in most fields can be recovered.[123] The impact of enhanced recovery could be greatest in the area of light tight oil, where the current recovery rate is about 5 percent.[124] We assume recovery increasing by between 10 and 50 percent on average.

Other technology with potential for the sector is related to the treatment and processing phase of extraction. This includes subsea processing in offshore oil fields where the mix of hydrocarbons, sand, water, and other gases can be processed at the sea floor rather than being pumped to the surface. This can reduce rig sizes and energy consumption and help promote higher recovery from a reservoir. Improvements in flow-back water treatment represent another area where technology can help raise productivity, by lowering costs associated with the treatment of water after fracking, potentially eliminating the need for disposal aquifers and reducing transportation costs of the wastewater.

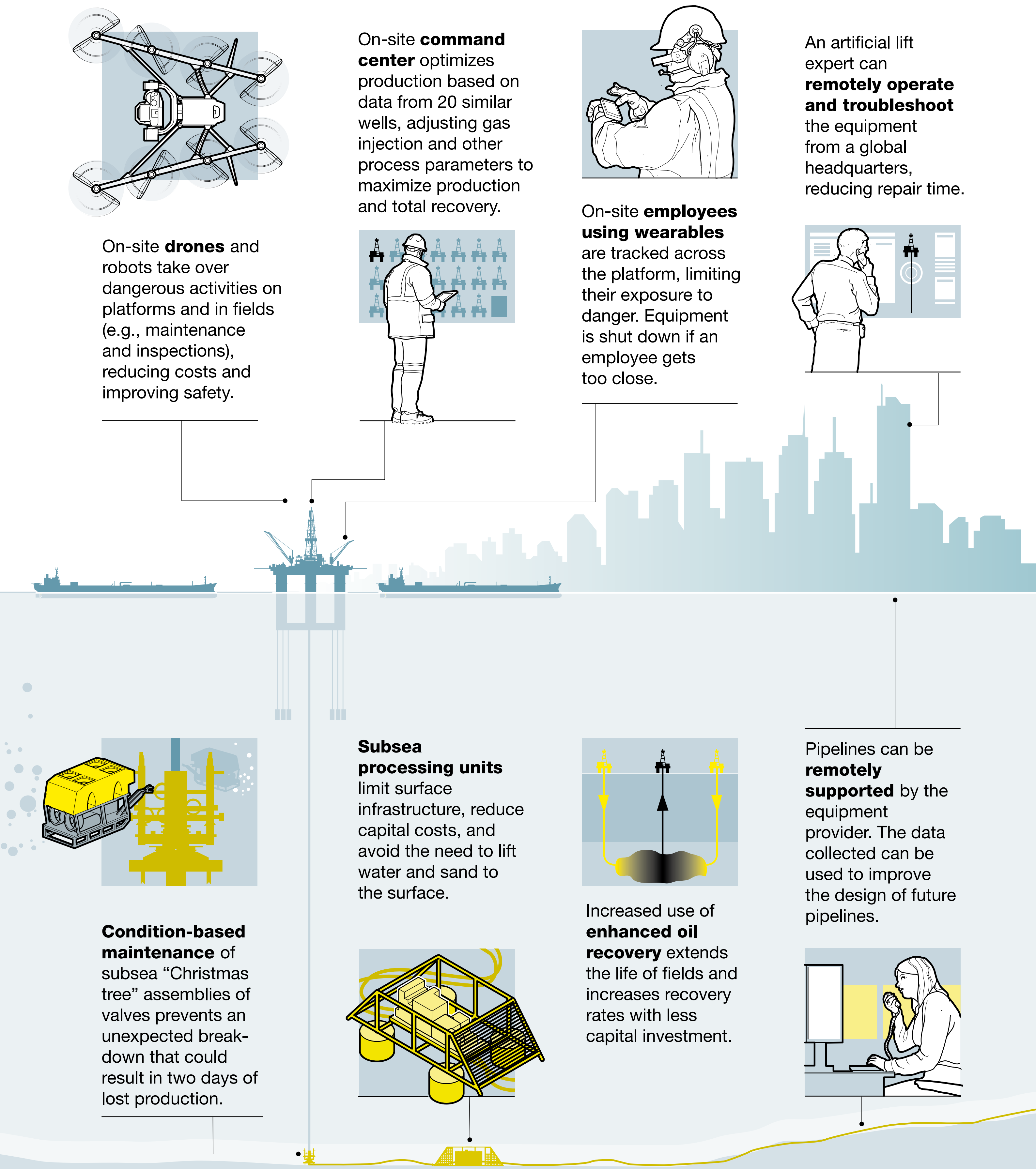
[121] *Remote-controlled welding 1,000 metres below*, Statoil, 2015.

[122] *Unlocking the potential of the Internet of Things*, McKinsey Global Institute, June 2015.

[123] Ann Muggeridge et al., "Recovery rates, enhanced oil recovery and technological limits," *Philosophical Transactions of the Royal Society*, volume 372, issue 2006, January 2014.

[124] Eduardo Jose Manrique et al., *EOR: Current status and opportunities*, Society of Petroleum Engineers Improved Oil Recovery Symposium, 2010.

Technology will make the oil field of the future more productive and safer



McKinsey&Company | Source: McKinsey Global Institute analysis

In mining, automation and analytics can transform production

Automation is gaining traction in mining. Automated haul trucks and drilling machines are being tested in small pilot mines across the world. Rio Tinto's mines using automation technology in the Australian Pilbara are seeing 40 percent increases in utilization of haul trucks, and automated drills are seeing 10 to 15 percent improvements in utilization.[125] Automation has many additional benefits beyond utilization in daily operations: equipment is operated closer to ideal tolerances, limiting wear and tear, and reducing maintenance needs. Energy use is reduced as machines are idled less in order to keep human operators warm or cold. Plans are followed more precisely and compliance can be tracked in real time as the equipment reports back to control on-site or off-site centers. The operations in the field are also safer as interactions between humans and machines are reduced, blast sites are kept clear of humans, and so on (see illustration, "Technology will raise productivity and improve safety in all areas of mining operations").

Other sector-specific technologies could also enhance productivity. For low-grade ores including copper and uranium, advanced leaching techniques could increase recovery as ore grades decline. There is already growing use of leaching methods in the industry from traditional heap leaching, which extracts metals from ore by passing extractive solutions over a heap of ore, to more advanced in situ leaching, in which extractive solutions are injected into the ore body and pumped back to the surface with the desired metals. For many metals, advanced forms of crushing and grinding could result in significant improvements in recovery rates and help reduce costs such as electricity consumption.

In mining, automation will enable equipment to be operated closer to ideal tolerances, limiting wear and tear, and reducing maintenance needs.

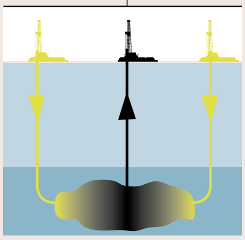
Data analytics are playing an increasingly important role. One example is a gold mine in Red Lake, Ontario, operated by Goldcorp. Seeking to find new deposits of gold in the mine through an unusual crowdsourcing exercise, Goldcorp's CEO published megabytes of geological data about the 55,000-acre site on the company's website with a cash reward for the best answers. The exercise helped the company identify 110 deposits, half of which its own geologists had not known.[126]

Another area with the potential for improvement is the realm of new continuous mining techniques in hard rock settings. In much the same way that coal and similar "soft" materials are mined using long-wall devices or bucket wheels, new approaches to achieve similar continuous extraction in "hard" rock mining could help drive reductions in blasting, increasing equipment utilization time. This technology would take advantage of new materials to develop stronger shearing devices and potentially augment shearing with microwave cracking (pulsing rock faces with microwave radiation) to weaken the rock structure and make it more amenable to shearing. Finally, increasing the adoption of high-angle conveyance equipment in open pit mining or increased use of block caving in underground mining could help drive increased productivity by raising throughput and saving costs.

125 Ibid.; Michael Gollschewski, *Productivity improvements in a changing world*, presented at an Australasian Institute of Mining and Metallurgy iron ore conference in Perth, July 13, 2015.

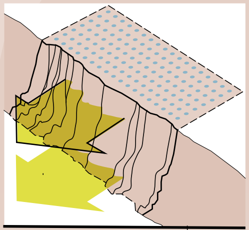
126 *Open innovation: Goldcorp challenge*, Ideaconnection, October 22, 2009.

Technology will raise productivity and improve safety in all areas of mining operations



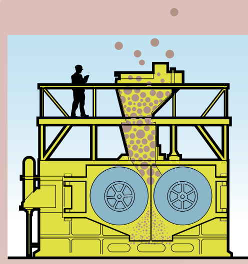
Advanced in situ leaching will open up difficult-to-reach ore bodies at low ore grades, increase reserves, and raise productivity.

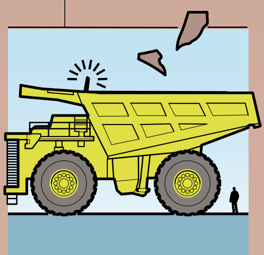
Expanded data collection and analysis of rock fragmentation will inform subsequent blast patterns.



Integrated operating and analytics center remotely monitors site operations, enabling predictive maintenance, real-time collaboration with specialists to reduce downtime.

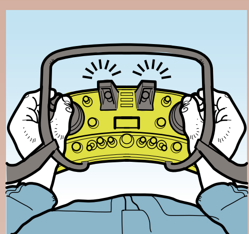
High-pressure grinder rollers will lower electricity consumption and improve recovery rates from ore bodies.

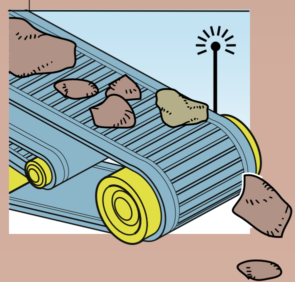




Autonomous vehicles like trucks and drillers will result in less downtime and greater reliability through continuous operations.

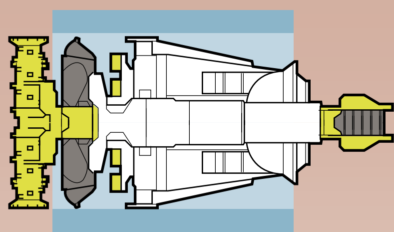
Tele-remote technologies will enable skilled operators to work in areas removed from safety risks.





Processing plant sensors will increase real-time analysis of heat, ore grade, etc., optimizing extraction, lowering energy and consumables costs, and increasing recovery.

Automated continuous hard-rock mining will lead to faster development of underground mines, avoiding the need for drilling and blasting.



McKinsey&Company | Source: McKinsey Global Institute analysis

New technologies are also likely to benefit utilities

Automation, artificial intelligence, and analytics can help utilities shift to predictive maintenance, improving efficiency and process controls with real-time data feedback loops. For wind and solar utilities, these technologies can improve yields and reduce operating and maintenance costs by drone-based surveillance, panel and turbine inspections, and solar panel cleaning (see illustration, "Technology will enable a more resilient grid and more responsive and productive utilities").

For wind utilities, industrial IoT can help optimize the operating pitch and aerodynamic of wind turbines, based on turbine performance, real-time communication with other turbines, other wind farms, grid and wind-speed and -direction changes. Many companies have begun providing drones for inspection of wind turbines, replacing the time-intensive and risky manual inspection of turbines. This reduces turbine downtime because inspections can happen while turbines are running, helping to drive costs lower for wind and solar.

Analytics and artificial intelligence are also useful for transmission and distribution. The "smart grid" of the future will enable real-time monitoring of grid status, tracking residential demand at the minute or second level, dispatching power in an automated manner to enable self-healing, demand management, and so on. Opportunities may be found in grid automation, consumer-end innovations such as advanced metering infrastructure, and the automation and digitization of business processes. Advanced metering infrastructure and demand-response services have helped cut customer service costs from such activities as meter readings and contract changes, have improved customer service, and have reduced power purchase costs for the utility. One European utility has been able to reduce its customer service costs by more than 50 percent through advanced metering infrastructure.

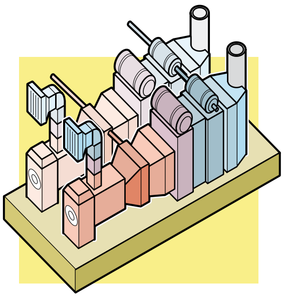
In emerging economies, technological innovation opens up opportunities to reduce electricity thefts. In India, transmission and distribution losses are a major issue, but a number of utilities have begun digital metering of all distribution feeders and consumers to give a heat map of losses at a feeder and regional level.[127] This is followed up with actions including shutting off high-loss feeders, outsourcing collection from high-loss feeders to local entrepreneurs and businesses, and taking legal actions against violators. Yet developing nations have far more ambitious plans. China's State Grid Corporation, for instance, plans to develop a global grid that draws on wind turbines and solar power from all over the world.[128]

For utilities, much of the sector-specific technology is related to improving efficiency in thermal power generation, which will help reduce costs. Closed-cycle gas turbines are typically 40 to 60 percent more efficient than open-cycle systems, and "ultracritical" coal power plants, which operate at temperatures and pressures above the "critical point" of water, could see similar 15 to 25 percent improvements over traditional critical coal power. In addition, application of cogeneration (producing heat and electrical power) and trigeneration (producing heat, cold, and electrical power) where feasible can help drive additional efficiency improvements, reducing fuel consumption by 70 to 80 percent. For pumped hydro plants, retrofits or replacements of existing pumps with variable-speed pumps can improve revenues by 4 percent by providing more flexibility in being used as frequency-stabilizing assets for the grid. Their utility will increase as the penetration of solar and wind increases in the grid.

[127] Distribution feeders are power lines transferring electricity from a distribution substation to distribution transformers.

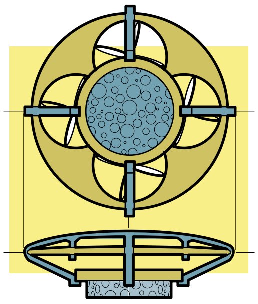
[128] Adam Minter, "China wants to power the world," *Bloomberg View*, April 16, 2016.

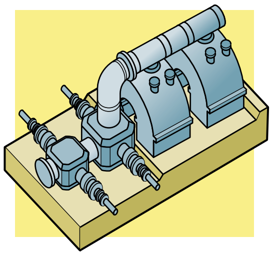
Technology will enable a more resilient grid and more responsive and productive utilities



Cogeneration and combined heat and power systems increase value add of thermal power generation and raise resilience through micro-grid applications

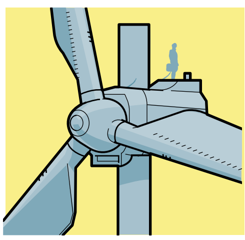
Drones provide remote surveillance and maintenance, including solar panel cleaning, improving safety, and increasing labor productivity





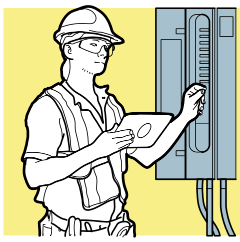
Coal ultracritical plants and natural gas closed-cycle turbines push power generation efficiency closer to theoretical limits, reducing fuel consumption

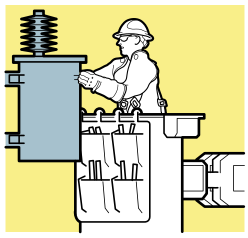
Sensors and real-time data analytics across assets allow for by-the-minute adjustments to maximize power generation efficiency, e.g., communication to adjust to changes in wind conditions automatically



Smart grid meters reporting more data and advanced analytics of customer behavior enable utilities to provide an increased range of services (e.g., efficiency measures) to capture additional value

Smart grid technologies improve grid management, enable faster identification of grid outages causes, reduce thefts, and enable better service to customers.



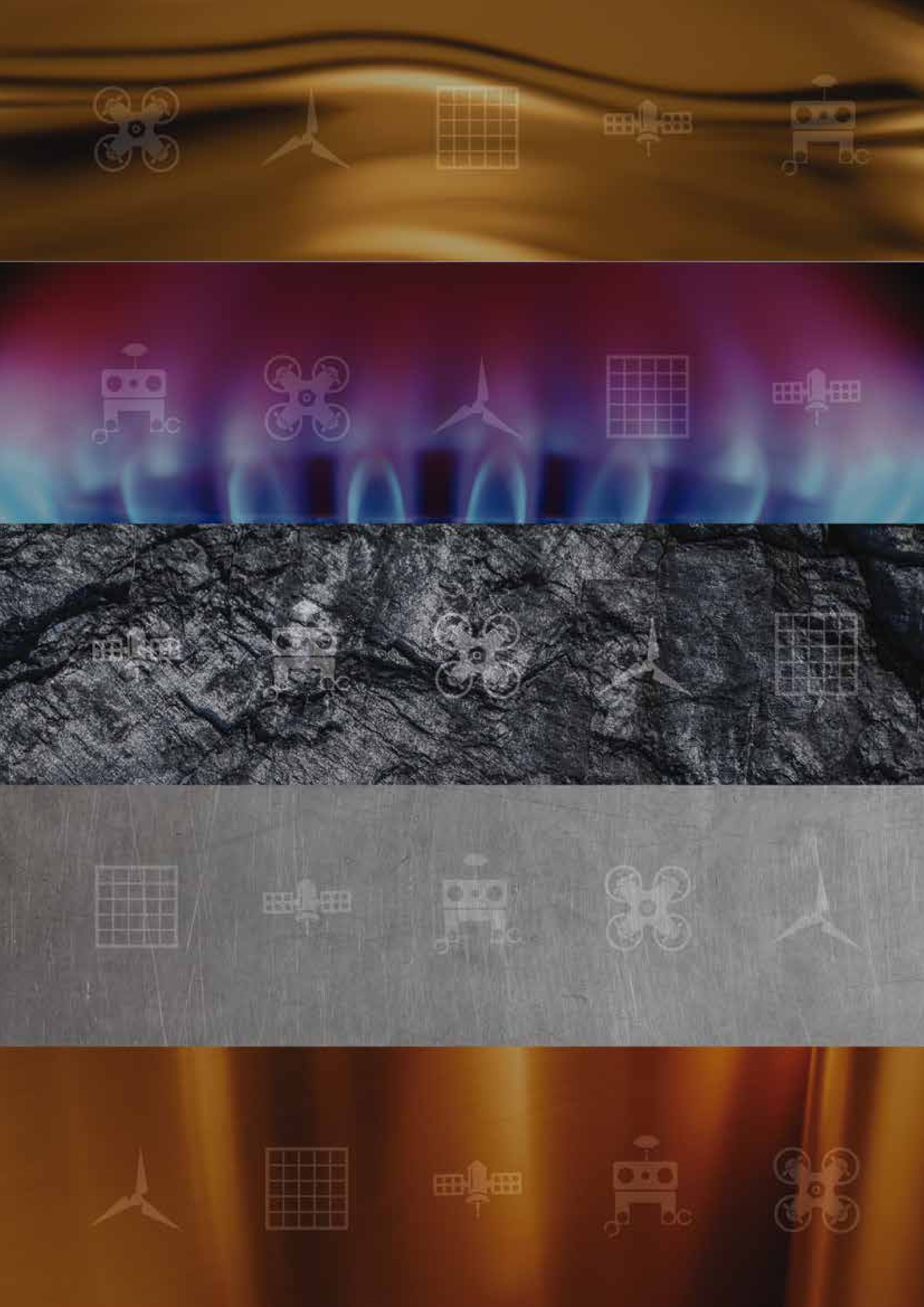


Field workforce receives **real-time network updates**, access to maps and schematic, etc., to decrease response times and reduce the impact of outages

Many companies have begun to use drones to inspect wind turbines, replacing time-intensive and sometimes dangerous manual inspection.

•••

Technology is disrupting numerous industry sectors and companies across the world, and some of the changes it is already bringing, and will surely bring in the next two decades, have direct and indirect implications for the resource sector. Both the demand for resources and the consumption of them stand to be profoundly affected by these shifts. The growth of alternative transportation including ride sharing and electric vehicles, more energy-efficient buildings and factories, and the growth of renewable energies such as solar and wind power have the potential to curb the growth or, in some sectors, even reduce demand from current levels. At the same time, resource producers will be able to harness new technologies to raise the productivity of their mines and wells and to access reserves that were once too remote and too costly even to consider. The implications of these shifts for individual commodities are profound. In the next chapter, we examine key resources in detail.



Cobalt from the Ruashi mine outside Lubumbashi, Democratic Republic of Congo.

3. THE OUTLOOK FOR COMMODITIES IN AN ERA OF TECHNOLOGY DISRUPTION

During the supercycle's downswing, what had been a close correlation between the markets for oil and for other commodities unraveled. We expect this divergence to continue over the next 20 years with widely disparate demand and supply prospects, in part driven by the pace and extent of technology adoption. This will affect not just the five key commodities we focus on in this report—oil, natural gas, thermal coal, iron ore, and copper—but also niche resources such as lithium and rare earth metals, as well as the market for electricity.

Overall, we expect demand for commodities to be muted, especially compared with the exuberant growth during the supercycle (Exhibit 11). Beyond that, the trajectories of different resources could diverge. Copper, which serves multiple purposes in the modern economy, including in a wide range of electronics and infrastructure, could benefit from continued buoyant demand over the next two decades unless cheaper substitutes are found. By contrast, iron ore could follow a downward trajectory due to slowing demand growth for steel as recycling rates of steel increase. Demand for coal, long the dominant fuel for electricity, could also fall as a result of environmental concerns, competition from natural gas in some regions, and the growing cost-competitiveness of renewables over the long term. Demand for both oil and natural gas could undergo a period of tepid growth followed by demand declines if the world focuses on transitioning away from fossil fuels in both transportation and electric power while also embracing improved energy efficiency beyond our moderate case.

Even as price correlations weaken, interplay among commodities should be taken into account. For example, natural gas could benefit from growing decarbonization of the economy, although thermal coal could maintain its competitiveness as a result of falling prices, unless national or global carbon pricing schemes are introduced. The speed and scale of technological adoption is difficult to project; some factors affecting it are technical, whereas others, including labor supply and demand dynamics, are economic.[129] Economic growth in emerging economies remains a wild card. If growth in these economies picks up substantially, the demand for resources could be greater than we project in our tech acceleration scenario (see Box 5, "What if global growth reignites?"). Regional shifts in demand will also come into play. By 2035, according to our moderate case, China could account for 28 percent of the world's primary energy demand, up from 23 percent today, while India would account for 10 percent, up from 6 percent. The figure for the United States would fall to 12 percent from 16 percent.

Our forecasts for each commodity take into account these regional variations and are based on assumptions about technological adoption, the outlook for the global economy, and other shifts, including our estimation of the growth of renewable energy.[130] For investors, producers, and buyers everywhere, it will be critical to understand the unique characteristics of each commodity type and gain insight into the changing context.

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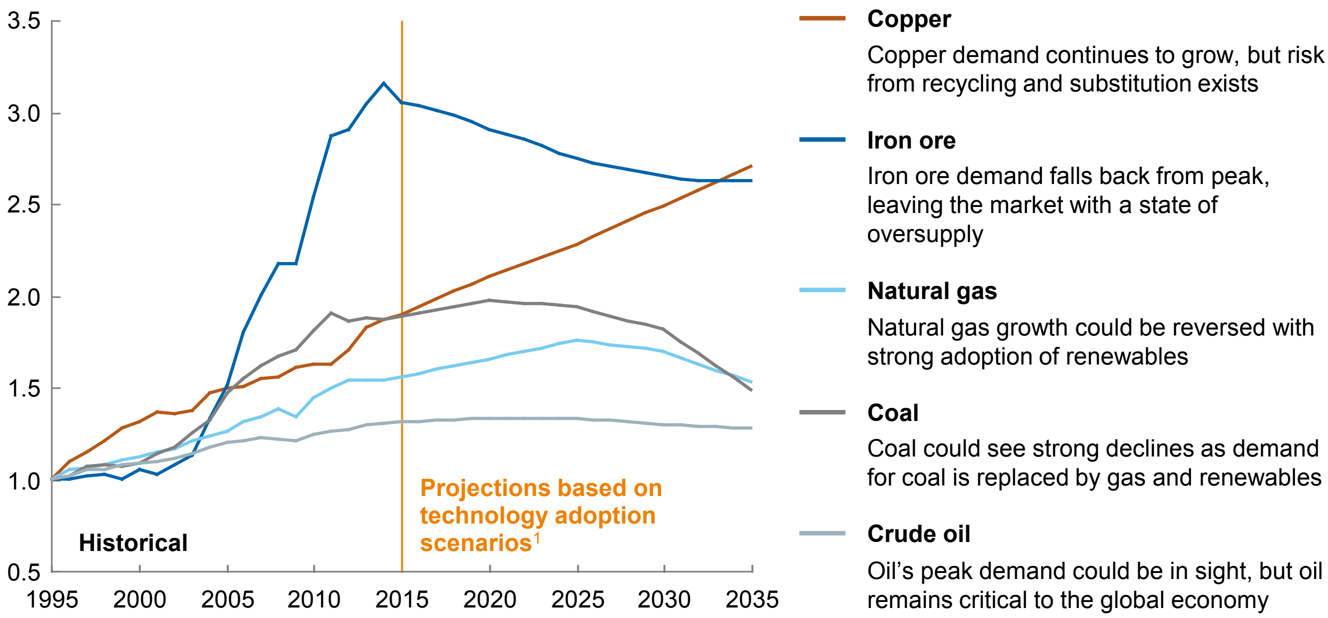
[129] For a detailed discussion of factors affecting the pace and extent of automation adoption, see *A future that works: Automation, employment, and productivity*, McKinsey Global Institute, January 2017.

[130] We construct demand growth projections for individual commodities based on data from McKinsey & Company Energy Insights and McKinsey's Basic Materials Practice, and we explore the impact of different rates of economic growth and technological deployment in our projections. In this chapter, we assume an annual growth rate of 2.7 percent in GDP, although we have also modeled other GDP growth assumptions. For details, see the technical appendix.

Exhibit 11

Demand growth for resources could be muted, with declines a possibility for some commodities

Commodity demand indexes
1 = 1995 demand level



1 Accelerated technology scenario for oil, gas, and thermal coal. Moderate adoption scenario for iron ore and copper. See technical appendix for details.

SOURCE: McKinsey Global Institute analysis

Box 5. What if global growth reignites?

Economic growth is one of the biggest drivers of demand for resources. As discussed previously in this report, an underlying premise in the supercycle was that the rapid growth in emerging markets would continue, pushing demand for resources to much higher levels. Our analysis is based on a conservative annual global growth rate of 2.7 percent over the next 20 years.[1] What if the unexpected happens and growth is much stronger?

It is worth highlighting that even in a more aggressive growth case, technology could have a dramatic effect on curtailing demand for energy resources. Assuming the global economy undergoes a full recovery from the financial crisis, labor productivity growth accelerates, and relatively little turmoil occurs over the next 20 years, we could see a growth rate closer to the historical average of 3.6 percent per year. Applying this 3.6 percent rate of growth to our model, we find that in our tech acceleration case, primary energy demand is 609 million TJ, or 32 million TJ higher than we found with a 2.7 percent annual growth rate. However, primary energy demand in our tech acceleration scenario, at 609 million TJ, is still lower than in our moderate scenario, assuming 2.7 percent annual GDP growth. This indicates the potential impact technology could have to sever the link between economic growth and energy consumption.

1 The 2.7 percent growth rate is based on McKinsey's proprietary Global Growth model. See the technical appendix.

56%

Share of total primary oil demand going to transport

PEAK DEMAND FOR OIL COULD BE IN SIGHT; NEW INVESTMENT ON THE SUPPLY SIDE WOULD STILL BE NEEDED

By far the biggest consumer of oil is the transportation industry, accounting for about 56 percent of total primary oil demand.[131] From a country perspective, the United States, China, Japan, India, and Russia are the major consumers, but trends in demand differ among them. For example, in China and India, demand is growing strongly due to a rapidly emerging middle class that is increasing its demand for mobility as well as plastics and other chemical-derived goods. Yet, as we discussed in the previous chapter, shifts in transportation brought about by technological innovation and new business models, such as the growth of ride sharing and developments in autonomous and electric vehicles, have the potential to change the demand dynamics of the oil market fundamentally over the next two decades. Technological innovation is bringing about significant changes to oil production at the same time, including through hydraulic fracturing, which has shifted the balance among oil producers. Even if oil demand declines in the next 20 years, however, producers will still need to invest in supply capacity because the natural decline rate of existing wells will outpace the decline in demand.

Changes in transportation could sharply reduce demand for oil, which could peak by 2025 in a tech acceleration scenario

Based on our scenarios, global oil demand could decline by 2 percent in 2035 below the demand level registered in 2013 under our accelerated tech scenario. In this scenario, oil demand would peak in 2025. Our moderate tech adoption case sees continued growth in demand throughout the period, but at a declining rate (Exhibit 12).[132]

The tech acceleration scenario is based on a number of factors: an increase in the fuel economy of new vehicles in the future (driven largely by regulatory standards), a greater reduction in the number of kilometers driven as a result of ride sharing and carpooling, an accelerated switch to electric vehicles for many commuters, and faster improvements in fuel economy in the aviation and trucking sectors. As a result, according to our analysis, peak oil demand from light vehicle transportation could occur as early as 2020 at 48 million TJ to 49 million TJ, before falling back to below 2015 consumption levels by 2025 to 2030. Demand for petroleum products for the heavy-duty transportation sector could show similar declines, while demand for aviation fuels is expected to grow steadily at 1 to 1.6 percent per year.

While transport is the main user of oil, power (6 percent) and industry (7 percent) are important minor users. In the tech acceleration scenario, improved energy efficiency in buildings could push demand for oil down by as much as 12 to 17 percent by 2035 compared with 2013 levels. In this scenario, oil demand for power generation would continue its long decline with a 60 percent reduction in demand for oil possible in this sector over the next 20 years.

While oil demand is expected to soften in transportation, buildings, and power generation, it is projected to grow in the chemicals sector as the rapidly emerging middle class in many developing countries increases consumption of plastic-based goods and packaging in goods shipments. In our moderate scenario, oil demand for chemicals can be expected to increase from 35 million TJ to 57 million TJ over the next 20 years. The extent to which this increased demand for plastics manifests itself as demand for oil will depend partly on whether recycling rates increase in both advanced and emerging economies. It has been estimated that recycling and less plastic intensity in packaging have the potential to lower oil consumption by as much as 12.5 percent in the chemicals sector compared with our

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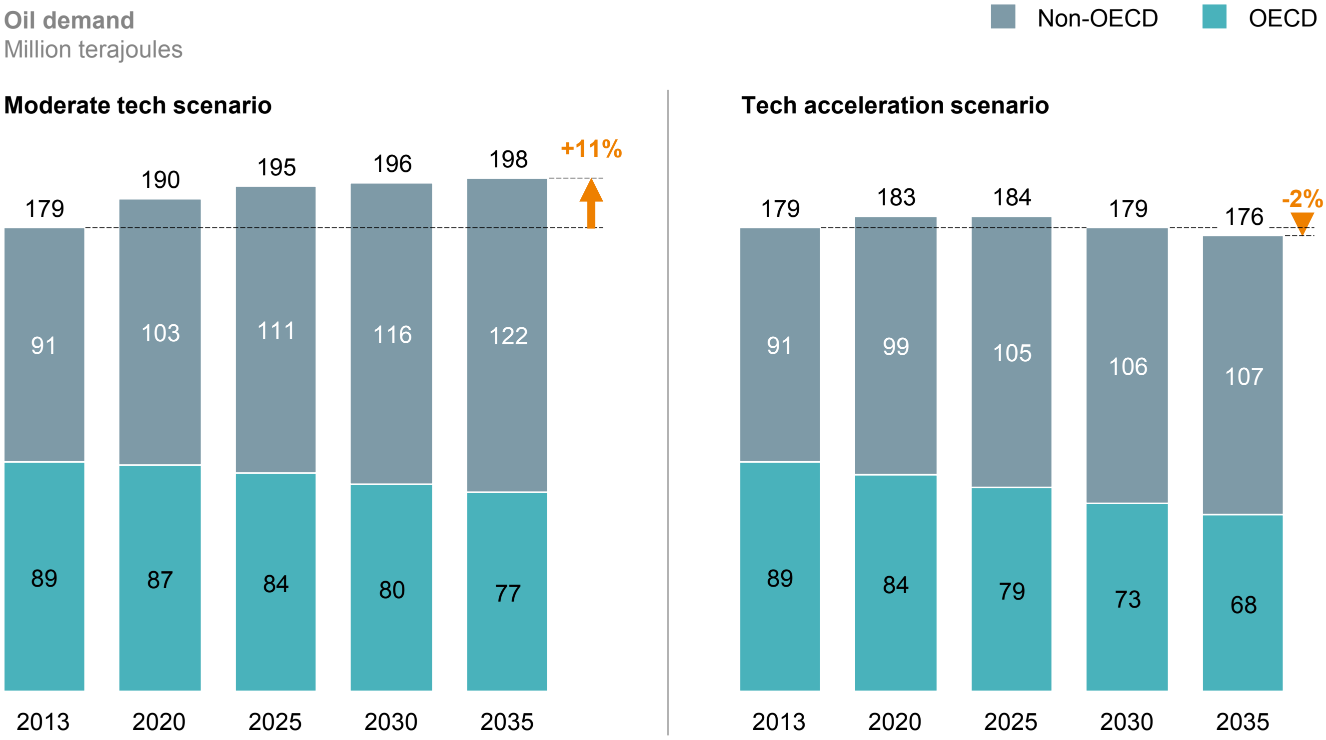
131 *World energy balances*, IEA, 2014.

132 Our forecasts are sensitive to the GDP growth forecast, as outlined in Box 5. In the tech acceleration scenario, under different outlooks for GDP growth that we have modeled, the oil demand decline could range between 1 percent and 8 percent by 2035. See technical appendix.

moderate case, although reaching this level would likely require behavioral or policy changes and is not considered in our tech acceleration scenario.[133]

Exhibit 12

Oil demand could peak by 2025 under a tech acceleration scenario, although demand would continue to grow with moderate adoption



NOTE: Numbers may not sum due to rounding.

SOURCE: *Global energy perspective*, McKinsey Energy Insights; McKinsey Global Institute analysis

Shifting demand for oil will not occur uniformly across countries and regions. For example, OECD nations could experience a faster decline in demand for oil in our tech acceleration case, while non-OECD nations would experience substantial demand growth regardless of the rate of technological adoption. That is not to say that technology will not have an impact on the demand for oil in non-OECD countries. We have found that under our tech acceleration scenario, demand for oil from non-OECD nations would be about 12 percent lower in 2035 than under our moderate scenario.

New investment in oil production will be needed to offset the natural decline of existing fields

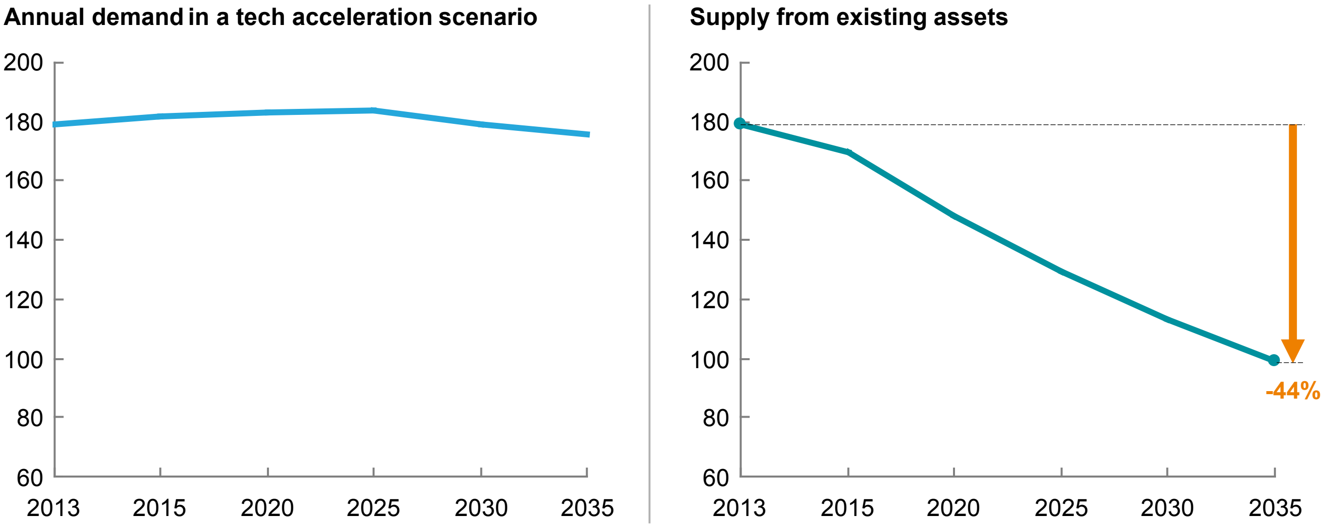
Even in the face of the possible decline in demand for oil to about 176 million TJ, or just over 90 million barrels per day, producers will need to continue investing in new assets because of the natural decline rate of existing oil-producing wells (Exhibit 13). If typical decline rates hold during the next 20 years, existing assets will be able to provide about 36 million barrels of oil per day in 2035, and we expect natural gas liquids and other liquids to reach 21 million barrels per day. Together they meet just over 60 percent of projected liquids demand assuming a 2.7 percent annual rate of GDP growth and a tech acceleration scenario.

[133] Occo Roelofsen, Namit Sharma, Rembrandt Sutorius, and Christer Tryggestad, "Is peak oil demand in sight?" *McKinsey Quarterly*, June 2016.

Exhibit 13

Production declines from existing assets are rapid, meaning significant investment would be needed to close supply-demand gap

Oil supply-demand balance[1]
Million terajoules



1 Assumes annual average global GDP growth of 2.7%.

SOURCE: *Global energy perspective*, McKinsey Energy Insights; McKinsey Global Institute analysis

The industry will need to invest in additional capacity to produce about 35 million barrels per day in new oil production capacity over the next 20 years to meet remaining demand. This amounts to about $5.2 trillion in exploration and production capital spending in the next 20 years. In the moderate scenario, the industry would need to invest $10.2 trillion in cumulative capital expenditure, or almost twice as much as in the tech acceleration scenario. In comparison, between 2004 and 2014, the industry added about $4.2 trillion in cumulative exploration and production capital spending in order to keep up with demand growth and make up for the decline in mature fields. The exact value is highly dependent on the evolution of cost inflation or deflation in the industry. The International Energy Agency expects finding and development costs in the oil industry to be in the range of $15 to $20 per barrel over the next 20 years.[134] However, a number of factors could affect this, including geological challenges, regulation, and competitive intensity for services.

Oil supply could become more elastic as technological innovation gives producers the ability to meet changing demand more rapidly

The future supply of oil could be more agile and elastic as producers respond faster to demand as prices rise and fall. Light tight oil development in North America, built on hydraulic fracturing and horizontal drilling, with its ability to add incremental capacity in a relatively short development cycle, could become the marginal source of supply for the foreseeable future.[135] Large-scale megaprojects, such as oil sands development and deepwater projects, may be less likely to proceed given the long lead times of these projects, high capital costs, and environmental concerns about their impact. As a result, new oil supply could become more elastic in the future. North American light tight oil producers were among the first producers to stop development of new fields because they

[134] *World energy outlook 2015*, International Energy Agency.
[135] *Oil industry drives down global cost curve; US tight oil is the biggest winner*, Wood Mackenzie, July 2016.

could idle drill rigs. They are now among the first producers to return to market as they can bring those same rigs online again in a short period.

Increasing innovation in fracking may also open up previously uneconomic tight oil basins, in North America and elsewhere. Recovery rates are currently low on average for tight oil wells—for example, 5 to 10 percent for a well in the Bakken basin in North Dakota in 2014. That is lower than for conventional wells, whose recovery rates are typically 10 percent to 40 percent, indicating ample room for improvement.[136] Increasing recovery rates could lower the cost of development within North American basins and enable the development of vast shale reserves elsewhere. By some estimates, North America has only 20 percent of unproved technically recoverable reserves of tight oil.[137]

The future supply of oil could be more agile and elastic as producers respond faster to changes in demand.

Together with stagnant or declining global demand for oil, a more elastic source of supply could have a dampening effect on prices. Tight oil production may not be as responsive as OPEC was with its control of excess supply, but it has a shorter development cycle that could help ameliorate sustained price fly-ups in the future, barring major geopolitical events in critical oil exporting regions.

At the same time as the upstream market is adjusting to the new demand outlook, refining will be affected. The transition away from petroleum products for transportation could introduce additional distorting effects to refined product markets depending on how other segments evolve. With less demand likely for gasoline and diesel, other refined products could experience price increases, as there is less ability to capture value from the gasoline and diesel fractions. This could introduce unique strategic opportunities for refiners in the future who are best positioned to meet market needs by being located near demand with good access to best matching petroleum supplies and refining capacity.

NATURAL GAS DEMAND COULD GROW IN THE MEDIUM TERM BUT COULD FACE LONGER-TERM CHALLENGES

40%
Share of natural gas consumed by the power sector

The biggest user of natural gas is the power sector, accounting for about 40 percent of total primary natural gas demand.[138] In the near term, as many economies move to decarbonize, we project that natural gas demand will grow. Recent investment in transportation infrastructure such as pipeline and liquefied natural gas facilities is also likely to promote growth in demand for natural gas. In the longer term, however, natural gas could face increasingly competitive challenges from renewable power sources, decreasing need for gas power generation, and improving efficiency measures limiting demand growth. Natural gas could also face a harder time displacing coal, which may be cheaper in many regions.

Demand for natural gas could peak in the next decade after a short-lived "golden age"

Natural gas demand is widely expected to grow over the next 20 years. In 2013, total demand for natural gas was about 120 million TJ, or roughly 3,200 billion cubic meters (bcm). In our moderate scenario, global demand for natural gas could rise by 39 percent

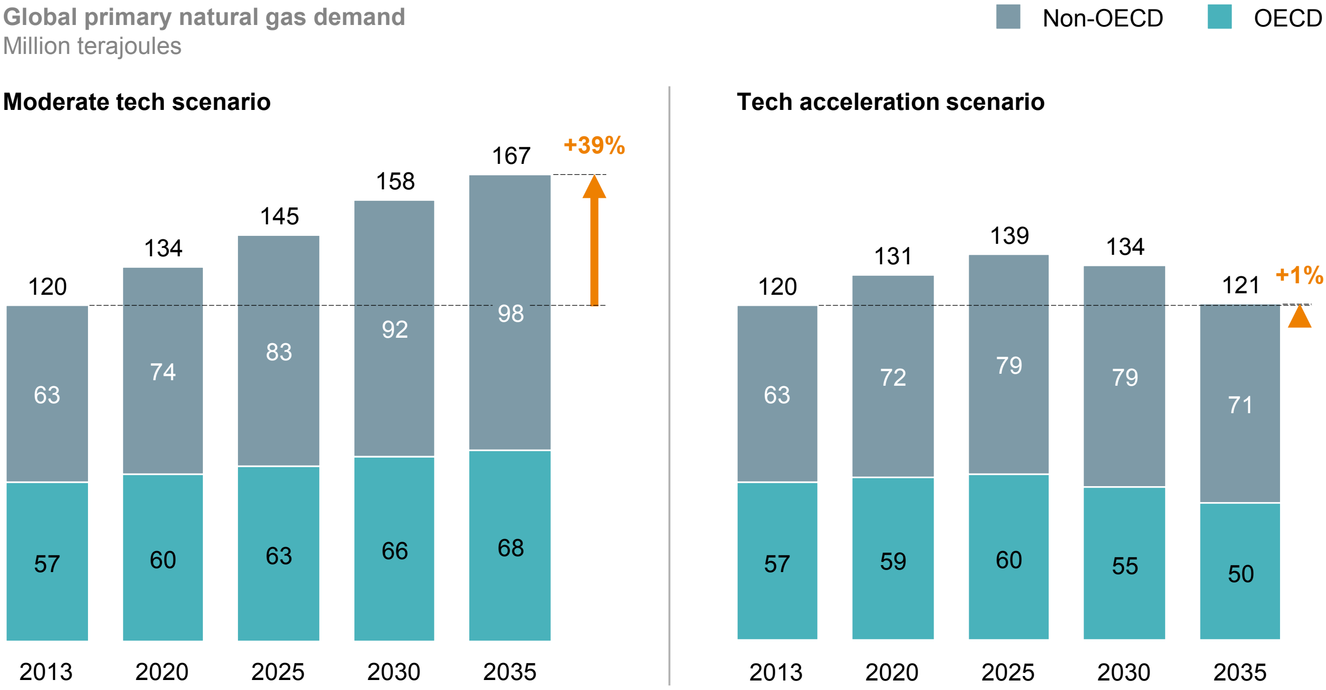
[136] Ibid.; Ann Muggeridge et al., "Recovery rates, enhanced oil recovery and technological limits," *Philosophical Transactions of the Royal Society*, volume 372, issue 2006, January 2014.
[137] *World shale resources assessment*, US Energy Information Administration, September 2015.
[138] *World energy balances*, IEA, 2014.

between 2013 and 2035.[139] According to some estimates, cumulative investment in natural gas infrastructure, such as pipelines and liquefied natural gas (LNG) facilities, would need to reach $8 trillion between 2010 and 2035 in order to capture this "golden age of gas."[140]

In our tech acceleration scenario, which is heavily impacted by the more rapid growth of renewable power generation and high levels of adoption of energy efficiency measures, natural gas demand would grow by 16 percent between 2013 and 2025 but decline thereafter, with the level in 2035 about 1 percent above the level in 2013 (Exhibit 14).[141]

Exhibit 14

Natural gas demand would remain flat vs. 2013 demand under a tech acceleration scenario, but grow rapidly under the moderate adoption case



NOTE: Numbers may not sum due to rounding.

SOURCE: *Global energy perspective*, McKinsey Energy Insights; McKinsey Global Institute analysis

Growth in natural gas demand is likely to remain strong in the near term and in regions such as the United States, Russia, and the Middle East where there is plentiful, low-cost gas. In the United States, natural gas has already replaced coal as the largest source for electric power, with 100 million kWh of electricity from natural gas vs. 72 million kWh from coal in April 2016.[142] In other regions, the outlook is more varied. Some, like China, are looking to increase natural gas consumption to help decarbonize their economies by promoting domestic development or importing via pipeline or LNG from neighboring regions. In other countries, including India, investment is limited because of the high cost of imported natural gas compared with local fuel options such as coal. In Europe, meanwhile, efficiency efforts,

[139] Occo Roelofsen, Namit Sharma, Rembrandt Sutorius, and Christer Tryggestad, "Is peak oil demand in sight?" *McKinsey Quarterly*, June 2016.

[140] *World energy outlook—Special report: Are we entering a golden age of gas?* International Energy Agency, 2011.

[141] The GDP outlook has a slight impact on the forecast for natural gas, with demand in 2035 ranging between 117 and 122 million TJs depending on GDP growth scenario. Compared with 2013, this would represent either a decline of 2 percent, or a 2 percent increase. See technical appendix for details of modeling based on alternative outlooks for GDP growth.

[142] *Monthly energy review*, US Energy Information Administration, May 2016.

renewable power growth, and sluggish economic growth are limiting the demand for natural gas.

The projection of a decline in global natural gas consumption after a decade of growth assumes accelerated growth of renewable power generation and increasing end-use efficiency across the global economy. This effect is strongest in non-OECD countries where significant growth in renewables could bring about a sharp reduction in natural gas–powered energy. In addition, without some form of carbon pricing, gas is not cost competitive with coal in many regions because of the high import cost via pipeline or through LNG. This means the use of natural gas may be limited if renewables provide a cheaper form of clean power. Another factor that could constrain demand for natural gas may be concerns about the impact of methane emissions on the environment.

Several factors could counter the outlook for natural gas demand in the longer term. Natural gas power plants may be a cheaper complementary power source for renewables than coal plants, given the ability of gas plants to ramp up and down faster and their lower minimum generation requirements.[143] In addition, as the market share of renewables grows, natural gas could begin replacing coal as a backup power source and the preferred power source for balancing shifts in seasonal supply and demand. Natural gas could also receive a demand boost from transportation, if compressed natural gas and LNG-powered vehicles gain acceptance, and could be used as a feedstock for the petrochemical industry. However, these segments are small. Transportation and petrochemicals each account for 5 percent or less of natural gas demand today.[144]

A longer-term decline in demand for natural gas would alter investor assumptions

Investment in natural gas rose steadily before the price decline, with a cumulative total investment of $3.5 trillion in the period 2000 to 2013. This was split 60 percent on upstream field development and 40 percent on transportation infrastructure.[145] Accessible upstream reserves are abundant, and only limited funding for new exploration may be needed to meet weak demand in the tech acceleration scenario. In North America, reserves are estimated to be about 12,000 bcm, while Russia and Middle Eastern countries including Iran have existing reserves totaling 141,000 bcm.[146] Together, they have enough gas to meet world demand for 44 years at today's consumption levels.[147] As a result, areas adversely affected by a slowdown in demand could include new field development in African nations such as Mozambique, which recently discovered natural gas fields with more than 4,500 bcm.[148]

On the transportation and infrastructure side, if demand weakens and the utilization of natural gas infrastructure declines in the longer term, ongoing upkeep and capital investment would need to be spread out over declining volumes of consumed gas. If this occurs, unless some plans are canceled or rationalized, the LNG market could become oversupplied in the next five to ten years. If many of the planned investments are completed, the potential utilization could be only around 65 to 70 percent in 2035. Currently, there is 335 bcm of LNG capacity in the global market; taking into account current expansion plans, total capacity could increase to about 550 bcm by 2025.[149] However, in our tech acceleration scenario, demand for LNG may amount to only about 400 bcm by 2030 and then

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143 Jason Channell, Timothy Lam, and Shar Pourreza, *Shale and renewables: A symbiotic relationship*, Citi Research Equities Report, September 12, 2012.
144 *World energy balances*, IEA, 2014.
145 *World energy investment outlook*, IEA, 2014.
146 *International energy statistics*, US Energy Information Administration, 2016.
147 *World energy outlook*, IEA, 2015.
148 Andrew England, "Mozambique strives to get liquefied natural gas projects online," *Financial Times*, November 23, 2015.
149 *Global gas supply model*, McKinsey & Company Energy Insights, 2016.

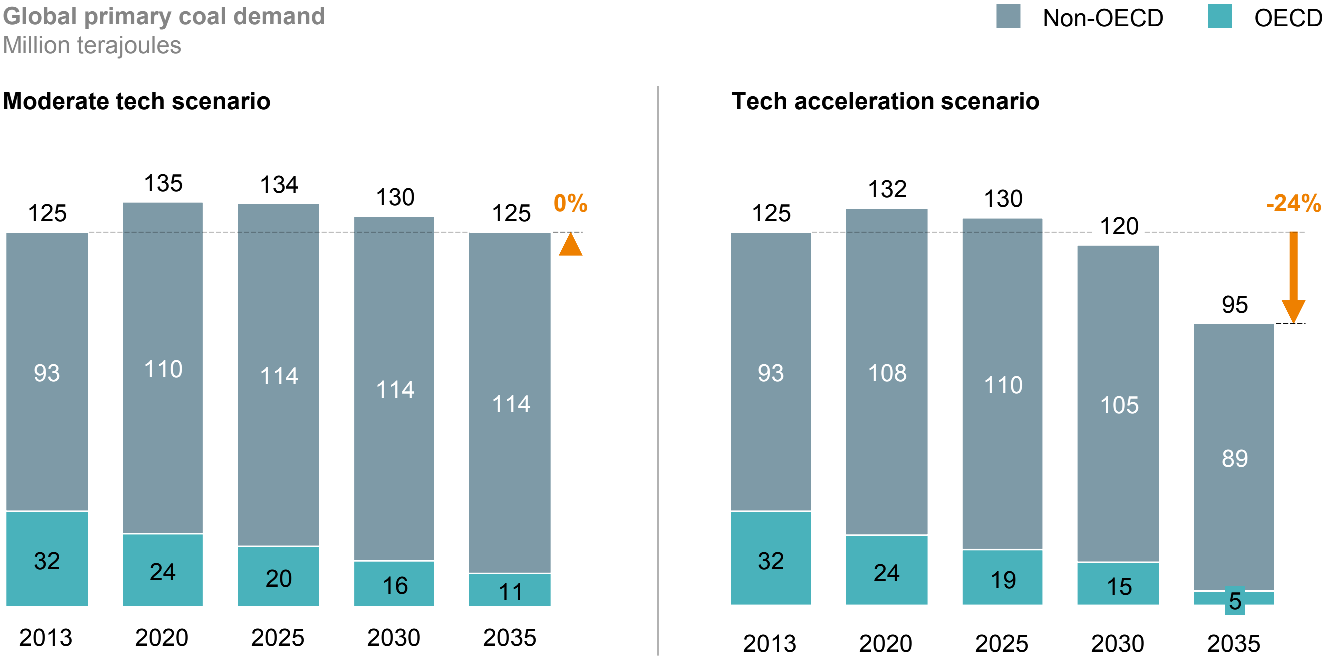
decline. For investors, this would mean changing assumptions about returns on invested infrastructure. In addition, open competition in an oversupplied market is more likely to keep prices subdued until capacity rationalization occurs.

THERMAL COAL DEMAND MAY PEAK AS USE OF NATURAL GAS AND RENEWABLE ENERGY INCREASES

Globally, demand for thermal coal could peak over the next two decades in both of our technology adoption scenarios as a result of environmental constraints and substitution of natural gas for coal (Exhibit 15). Some growth could occur in the next five years as coal consumption in emerging economies rises, but improved efficiency and a shift from coal to natural gas in North America and elsewhere could temper its long-term prospects. In our moderate tech adoption case, coal demand in terajoules would flatten in 2020 and then decline back to 2013 levels by 2035. In our tech acceleration scenario, demand would similarly peak in 2020, but the decline would be much sharper, reaching almost 25 percent by 2035, as coal experiences increased substitution by renewables for power generation and improved thermal efficiency.

Exhibit 15

Coal demand could peak in 2020 and decline thereafter in both of our technology adoption scenarios



NOTE: Numbers may not sum due to rounding.

SOURCE: *Global energy perspective*, McKinsey Energy Insights; McKinsey Global Institute analysis

Thermal coal, or steam coal, is used mostly for power generation, accounting for 70 percent of demand, and for heating applications in industrial settings, representing about 20 percent of demand.[150] Overall, we project that global demand for thermal coal could decline by 24 percent over the next 20 years, from about 126 million TJ or 6 billion tonnes in 2013 to about 96 million TJ or 4.7 billion tonnes in 2035.[151] Not all regions will be affected equally. Overall, demand for coal will remain robust and grow in non-OECD countries. In some

[150] *World energy balances*, IEA, 2014. Thermal coal includes anthracite, sub-bituminous coal, and other bituminous coal.

[151] Depending on the GDP outlook, coal demand could fall between 24 percent to 31 percent in 2035, in the tech acceleration scenario vs 2013 levels. See technical appendix for details of alternative scenarios modeled using different outlooks for GDP growth.

places, such as India, coal demand is still likely to expand even in the face of high adoption of renewable power and subdued global GDP growth, although our analysis suggests that no new coal-fired plants are required in India over the next six years beyond those that already exist or are being built. In contrast, in OECD countries, thermal coal demand could accelerate its decline, amounting to about 3 percent of total primary energy demand compared with 14 percent today. The shift away from coal could even move beyond the level we project if policy measures are enacted that further curb carbon emissions. In a case where natural gas is preferred as a power source over coal for decarbonization policies, thermal coal demand could fall faster.

While demand could drop, the supply of thermal coal is likely to remain high as global production has been ramped up and capital spent on new equipment and mines. In India and China, domestic production increased by 60 percent and 80 percent, respectively, between 2004 and 2014.[152] The potential mismatch between supply and demand may keep prices depressed, potentially at the cash cost for marginal producers, as the industry faces rationalization.

24%
Decline in demand for thermal coal over the next 20 years

A depression of global thermal coal prices will be transmitted by the seaborne coal market, where coal is traded between producers and consumers internationally. In some regions, local coal market dynamics dictate the final price; in other words, it is based on local production and transportation costs, pricing linkages, and netback to the seaborne market. As a result of falling demand, the seaborne market could be adversely affected. At its recent peak in 2014, seaborne thermal coal reached 1 billion tonnes. As demand declines in advanced economies and growth slows in developing markets, seaborne coal providers could be pushed into a fight for survival. India, for example, was long a growth market but has been sharply reducing coal imports. Australian producers have increased production by 425 million metric tonnes since 2005, mostly for the seaborne market.

Coal prices spiked unexpectedly in late 2016, and in the United States, the regulatory environment may become more coal-friendly, with the potential loosening of regulations at the international, national, and state levels. However, even these forces are unlikely to fix the medium-term challenges the industry faces, and we consider it unlikely that coal will see a resurgence. Coal is economically declining, with low costs for natural gas in many regions and declining costs of renewable power generation providing ample competition for coal power going forward. High costs of labor and environmental concerns add to the negative outlook. At the local level, the pollution caused by coal power plants has had dire consequences on the air quality in many cities in the developing world. Countries are actively fighting this pollution by shuttering coal plants near population centers. China's National Energy Administration, for example, in January 2017 announced it is scrapping construction of 85 planned coal plants, and will invest $350 billion in renewable energy sources.[153] Concerns about environmental damage through mining activities and ash waste disposal may further increase local opposition to coal. A leap in technology that increases the efficiency of coal power plants at a much lower cost or a breakthrough resulting in very-low-cost carbon capture and sequestration could reduce carbon emission concerns. However, as it stands today, these would add considerably to the price of coal and make coal even less economically attractive compared to competing power sources.

[152] *BP statistical review of world energy*, BP, June 2015.

[153] Lucy Pasha-Robinson, "China scraps construction of 85 planned coal power plants," *Independent*, January 17, 2017.

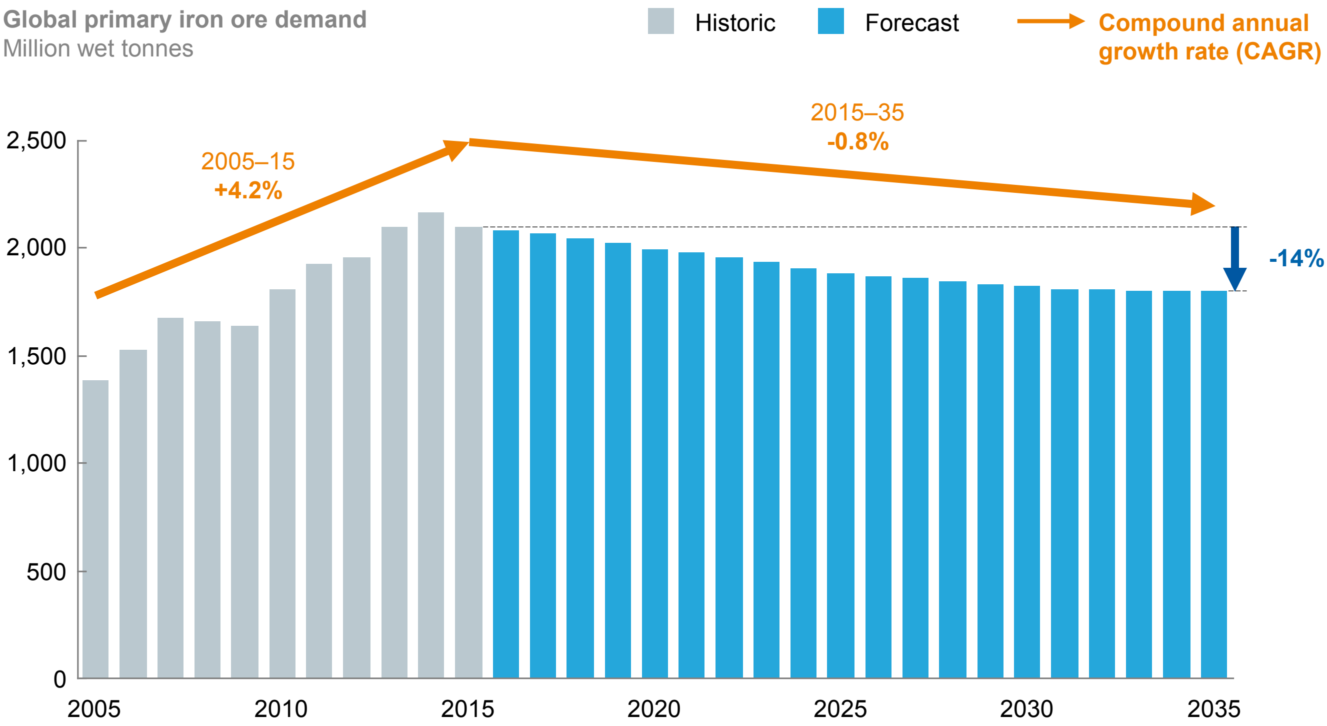
IRON ORE COULD FACE A LONG-TERM STRUCTURAL DECLINE AS A RESULT OF LESS RESOURCE-INTENSIVE GROWTH AND CHANGING STEEL DEMAND

During the supercycle, the supply of iron ore expanded rapidly as investment poured in, on the expectation of continued strong growth in prices. Iron ore is a key input for steel. In Australia and Brazil alone, investment increased iron ore production capacity by 691 million metric tonnes, or the equivalent of about 28 percent of global production capacity.[154]

Today the picture is very different. While large-scale construction continues in both China and India, demand for steel could slow due to widespread use of recycling. Increasing steel recycling rates could bring about a 24 to 32 percent decline in the iron ore intensity of the global steel industry over the next 20 years. This shift is a result of China beginning to recycle steel from buildings and infrastructure that are now at their end of life. Prior to this, China needed to consume more and more iron ore to create a pool of the material from which it could begin to recycle. As a result, we project that iron ore could be in structural decline over the next two decades, with no major investment in supply needed to meet declining demand. By 2035, iron ore demand could decline by 14 percent below 2015 levels under our accelerated technology adoption scenario (Exhibit 16).[155]

Exhibit 16

Demand for iron ore rose strongly in the past decade but could decline by 14 percent by 2035



SOURCE: McKinsey Basic Materials Institute; McKinsey Global Institute analysis

154 McKinsey Basic Materials Institute.

155 The decline could be between 5 percent and 27 percent, depending on the GDP outlook. See technical appendix for details.

Iron ore demand, which hit a peak of 2,200 million tonnes in 2014, dipped back to 2,100 million tonnes in 2015. In the future, demand for iron ore could weaken further if technology-driven changes in transportation gather pace. Other, lighter materials could potentially substitute for steel in automobiles, and fewer roads and bridges will need to be built for a reduced car fleet, for example. By our estimates, the automotive technology disruption discussed in the previous chapter could potentially reduce steel consumption by about 70 million tonnes and affect metallurgical coal in the process (see Box 6, "Metallurgical coal may become a casualty of the oversupplied steel industry"). In the power sector, the electric grid may require less investment in new transmission and distribution lines as distributed generation—that is, decentralized power generation such as rooftop solar panels—takes off. This shift would result in less demand for steel support structures for power lines.

Demand for iron ore could weaken further if technology-driven changes in transportation accelerate. By our estimates, the automotive technology disruption could reduce steel consumption by about 70 million tonnes.

Box 6. Metallurgical coal may become a casualty of the oversupplied steel industry

Metallurgical (met) coal is primarily used to produce coke, which is used in steel making. It is different from thermal coal, which is burned to produce steam used for electricity generation in power plants. Met coal has higher carbon content and lower moisture value, which makes it more suitable for the coking process.

Steel demand has risen at an annual average rate of 3.7 percent over the past ten years, but the pace of growth has slowed, and it is forecast to rise at a more muted rate of between 0.3 and 1.1 percent over the next 20 years.[1] The slowdown is in part a consequence of the changing Chinese industrial sector, but also due to a decreased need for pig iron as a result of higher recycle rates. That slowdown in the growth of steel demand will in turn reduce demand for metallurgical coal by 0.1 to 1.1 percent annually over the next 20 years, likely prompting the industry to rationalize production capacity to balance the market.

The supply overhang on the market is likely to maintain downward pressure on prices, which will in turn limit capital expenditure on new mines. High-cost mines in the United States and Canada may feel the impact more quickly, but even lower-cost mines in China and elsewhere could feel the consequences, as they are not competitive with low-cost imports from Australia and Mozambique. Major players in the industry have embarked on a concentrated effort to boost productivity and expand output from current mines, applying further pressure to high-cost producers.

1 McKinsey Basic Materials Institute.

2%
Annual growth in demand for copper in the next 20 years

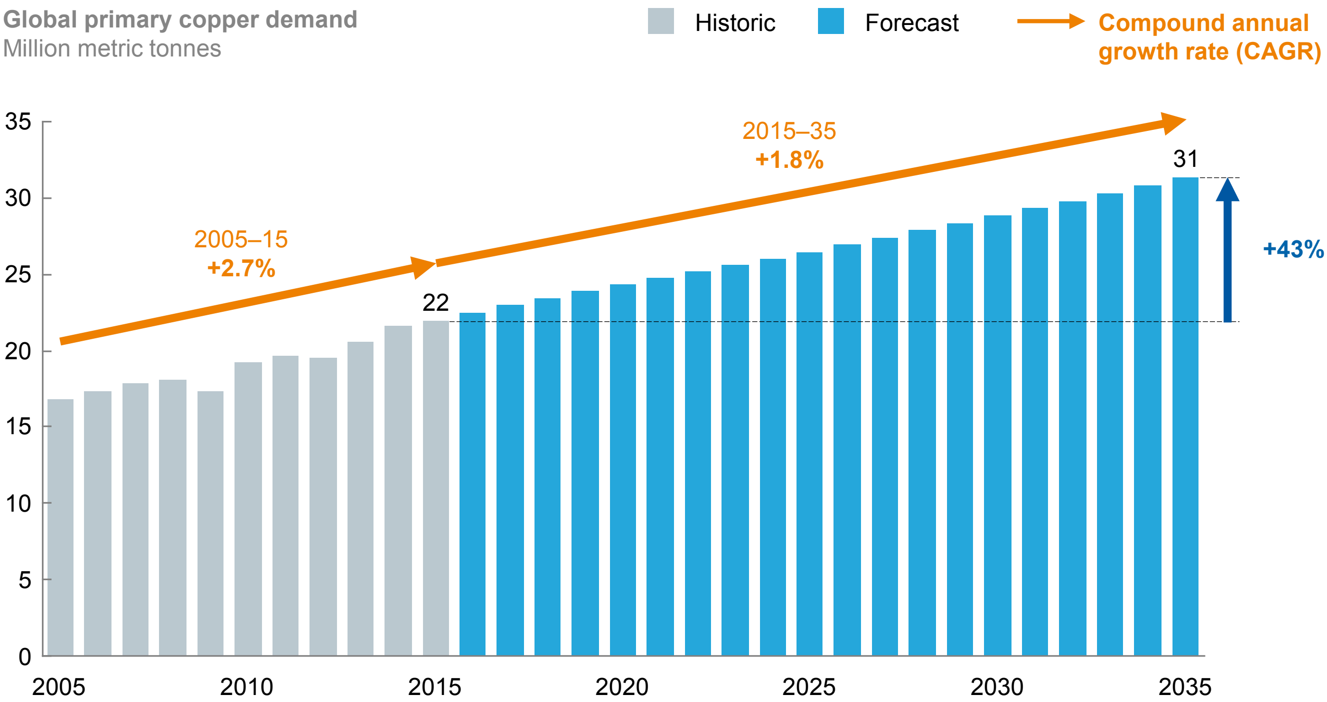
COPPER'S MULTIPLE USES IN THE MODERN ECONOMY COULD BOOST DEMAND

Copper has a wide range of uses in the modern economy, with far more consumer applications than iron ore. Just under half of copper demand is from the electrical and electronics industries and about one quarter is from construction. The remainder feeds a range of industrial machinery, vehicles and consumer products including home appliances. As a result, demand for copper could grow over the next two decades as global consumption drives higher spending on electronics and investment grows in renewables and the electric grid, which are also significant copper consumers.

Primary copper demand could potentially grow by nearly 2 percent annually over the next two decades, reaching 31 million tonnes by 2035. This corresponds to a 43 percent increase vs. today's demand of 22 million tonnes (Exhibit 17).[156] This is a slower pace than the compound annual rate of 2.7 percent of the past decade. A majority of the growth in copper demand will likely continue to come from China. China's consumption of copper, which reached 7.2 kilograms per capita in 2015, could gradually rise to a level of 11 to 12 kg per person by 2035, on a par with other developed Asian nations.

Exhibit 17

Copper demand could grow by 43 percent over the next two decades



SOURCE: McKinsey Basic Materials Institute; McKinsey Global Institute analysis

The accelerated adoption of the technologies outlined earlier in this report is one of the contributing factors to growing demand for copper, creating additional demand of 1 million to 3 million tonnes above the moderate case demand of 31 million tonnes in 2035. Electric vehicles require four times as much copper as internal combustion engines. Solar and wind power generation are also more copper intensive than traditional thermal power. However, although there is growing primary demand for copper and copper-consuming applications, the metal could face competition from other materials that can be used as substitutes,

[156] Depending on the GDP outlook, copper growth could be between 1 and 2 percent compound annual growth rate, reaching between 30 and 33 million tonnes per year in 2035. See technical appendix for details.

such as aluminum. Substitution is already a widely discussed topic in the industry as consumers take advantage of low aluminum prices.[157] We estimate that the potential range of substitution of copper by aluminum, plastics, and fiber optics could decrease demand by one million to four million tonnes in 2035. (For more on how substitution is affecting resources, see Box 7, "The potential impact of substitution: Nickel"). Hence, final demand for copper could be in the range of 29 million to 33 million tonnes after accounting for uncertainty in the pace and extent of technology adoption and the rate of substitution.

On the supply side, there are a number of challenges for the industry to meet future demand needs. Copper supply could increase by two million tonnes per year through 2025. After 2025, a number of countervailing factors will affect the supply side. Ore grade depletion is a perennial challenge for the industry. Ore head grade has declined from 1.5 to 1 percent over the past 25 years. This trend will likely continue to some extent but eventually should stabilize as miners come closer to average ore grade levels. However, between 2025 and 2035, ore depletion could decrease available supply by another one million tonnes per year. On top of this, a number of existing mines will likely reach their end of life. The rate of closures is expected to affect capacity in the range of 2.5 million to 3.5 million tonnes per year. If this were to occur, an additional five million to seven million tonnes of supply could be removed from the global market between 2025 and 2035.

Box 7. The potential impact of substitution: Nickel

Over the past decade, nickel has provided an illustration of how substitution can affect demand for a metal. Nickel is an additive in stainless steel, specifically 300 series stainless steel, which accounted for 68 percent of annual nickel demand in 2014.[1]

Nickel underwent a dramatic run-up in price between 2005 and 2007, propelled by Chinese demand for stainless steel. The price of nickel increased from about $15,000 per tonne in 2005 to more than $35,000 per tonne in 2007. Stainless steel demand grew by 6.2 percent per year between 2005 and 2014, increasing from 22 million tonnes to 32 million. Steel demand helped push nickel demand up from 1.34 million tonnes to 1.93 million tonnes over the same period, a 44 percent increase. With the sharp rise in nickel prices, the metal became about 66 percent of the total cost of some series of steel.

The market subsequently adapted. Stainless steel manufacturers began using alternative, less nickel-dependent classes of stainless steel in a number of new applications. This accelerated a long-term trend of declining share of 300 series steel in the global market. While 300 series stainless steel in 1987 represented 77 percent of the global stainless steel market, it fell to 66 percent by 2005 and dropped to 55 percent by 2014. This long-term trend of substitution continues to challenge the nickel market and prices. By 2015, the price had fallen to about $10,000 per tonne.

Even an export ban on nickel ore by Indonesia in 2014 did little to support prices. Indonesia represented half of the incremental supply that was added to the nickel market between 2000 and 2013. It announced that it would invoke a mineral export ban in 2014, threatening to create a supply deficit in the global market and greatly curtail China's access to the metal.[2] However, after a brief fly-up in early 2014, when the price rose from about $15,000 per tonne to over $20,000 per tonne between January and May, it fell back to $10,000 per tonne by mid-2015 as demand for nickel continued to soften.

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1 McKinsey Basic Materials Institute.
2 Neil Hume and Xan Rice, "Indonesia export ban turns nickel into a star," *Financial Times*, March 20, 2014.

In contrast, secondary and scrap supply could become a larger component of global supply. An increase in recycling could result from a greater push toward recycling electronic waste, and the secondary copper supply pool could grow in China after significant industrialization, as has happened with steel. Increased use of scrap and secondary supply could reduce annual primary copper demand by a further eight million to 11 million tonnes. Another boost to supply might be from the adoption of new technology to improve recovery rates in existing copper mines. Better use of data and analytics could help boost recovery rates by a few percentage points in the mills and beneficiation plants, but the impact could be limited by declining ore grades making recovery harder. We estimate the net effect of improved recovery could be an increase of up to one million tonnes of copper per year. Of course, some mines will be able to boost throughput and recovery at the same time, but this could be offset by accelerations in ore grade depletion and mine closures, so we assume this shift has no net effect on available supply in the future.

Copper has a wide range of uses in the modern economy. Demand could increase as global consumption drives higher spending on electronics and investment grows in renewables and the electric grid, which are significant copper consumers.

As a result of current demand and supply trends, we calculate that annual primary copper supply might need to expand by a further five million to 13 million tonnes between 2025 and 2035. To put this into perspective, annual copper supply grew by about seven million tonnes over the past 15 years. Thus, the upper end of the required supply growth over the next ten years would require an increase in investment over historical rates. Prices will need to rise at some point to encourage investment in existing and new mines, but that will also make copper less attractive against substitutes and encourage increased collection and recycling of scrap copper. The price sensitivity of consumers to copper and the options available to them will dictate which of these forces has a greater impact.

ELECTRIC POWER: RESHAPING THE GLOBAL ENERGY MARKET

40%
Growth of electricity consumption between 2013 and 2035

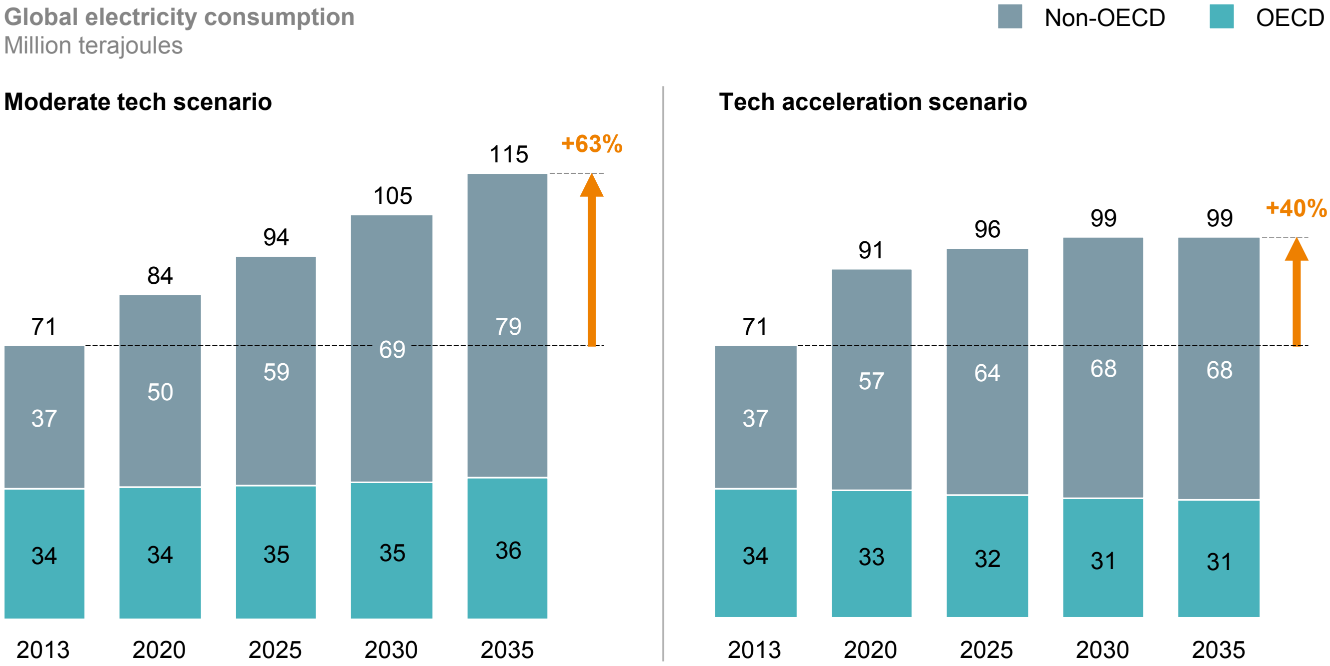
In contrast to demand for many of the energy resources highlighted so far, demand for electric power is expected to grow faster than overall energy demand in the period to 2035. Electricity is not a resource in the traditional sense, but it has significant potential to impact demand for primary resources and the way in which end-use services are delivered. This potential could be realized through higher penetration of renewables in power generation and the availability of more cost-competitive battery technologies, which might enable both grid-scale storage and accelerated use of electric vehicles. Such developments would make electricity a more fungible and valuable resource. For this reason, we have included a brief analysis of the outlook for electric power.

Globally, electricity consumption in our tech acceleration scenario grows by 40 percent from 2013 to 2035 in our tech acceleration scenario.[158] However, this growth is not spread evenly across all countries (Exhibit 18). All of the growth is generated by non-OECD countries, where electricity demand nearly doubles. In OECD countries, electricity consumption declines by almost 10 percent from today's levels.

[158] Depending on the GDP outlook, electricity demand in 2035 could be between 95 and 102 million TJ. This translates to a 34 percent to 44 percent increase on 2013 levels.

Exhibit 18

Electricity consumption is poised to grow strongly in non-OECD countries



NOTE: Numbers may not sum due to rounding.

SOURCE: *Global energy perspective*, McKinsey Energy Insights model; McKinsey Global Institute analysis

In emerging economies, the rise of electricity is driven largely by increasing urbanization, which enables greater access to local electric grids and consumption of electricity. Between 2016 and 2025, the consuming class of emerging-market cities is expected to grow by one billion residents.[159] The shift is coupled with support in many developing countries for increasing access to cleaner forms of energy to capture public health and environmental benefits, and moving away from the use of biofeedstock, for example wood, charcoal, and dung, for heating and cooking purposes. Income growth in emerging economies gives consumers greater buying power, creating demand for additional services such as lighting and cooling as well as appliances, all of which require electricity. As a result of these shifts, in our tech acceleration scenario, we find that electricity consumption in buildings in non-OECD countries rises from 13 million TJ to 32 million TJ, a 240 percent increase over the next 20 years. This is the sector with the biggest potential increases in electricity consumption, surpassing the electricity consumption of OECD countries by 2035.

In advanced economies, increasing end-use energy efficiency will offset growth from new sources of demand. Although electric vehicles grow rapidly in our tech acceleration scenario, electricity consumed in transportation would grow only from 0.3 million TJ to about 2.2 million TJ in 2035, reaching 7 percent of total electricity consumption in the OECD. This increase is more than offset by efficiency gains in industry and buildings in OECD countries, which together are expected to reduce consumption to about 29 million TJ in 2035 from 33 million TJ in 2013 in our tech acceleration scenario.

[159] *Urban world: Cities and the rise of the consuming class*, McKinsey Global Institute, June 2012.

These trends create opportunities and challenges for the electricity sector at large. Globally, electric power generating capacity doubles from about 6 TW in 2016 to almost 12 TW by 2035 in our tech acceleration scenario. Much of this comes from renewable sources; because of their lower capacity factors, power generation capacity growth outpaces electricity consumption. In addition to the investment in generating capacity, substantial investment will also be needed to expand and upgrade electricity transmission and distribution infrastructure, integrate renewables to the grid, and capture energy efficiency gains through demand-side management technologies. The International Energy Agency projects that about $15 trillion in cumulative capital investment will be needed in the electric utility sector in the next 20 years, covering all expansions in power generation capacity, transmission and distribution, replacement of retiring assets, and ongoing maintenance capital.[160] This may be conservative given the scale of renewable power investment that may be needed if the sector experiences accelerated adoption rates.

Globally, electric power generating capacity would nearly double by 2035 in our tech acceleration scenario, from about 6 TW to almost 12 TW.

Electricity markets represent an opportunity for utilities to grow in developing markets but pose a challenge in developed markets, where large capital investment will be needed in a market that could be shrinking on a volume basis. In addition, much of the value in the utility segment is at risk of shifting toward technology and service providers that are able to reduce energy consumption or enable consumers to become producers of their own power. Therefore, utilities may need to radically reconsider their business model in order to adapt.

$1B
Estimate of lithium market based on 2015 average price and production

OTHER MATERIALS AFFECTED BY MAJOR TRENDS IN COMMODITIES

A range of other materials will also be affected by global technological change and macroeconomic trends.

Uranium will see continued demand as nuclear power remains part of the global fuel mix

Increasing demand for nuclear power will result in increased investment in uranium, barring a major technological breakthrough. Although a full-scale global nuclear renaissance does not appear imminent, there are areas where nuclear power is expected to grow. China, the biggest source of growth, has announced plans to increase nuclear power capacity by about 60 GW by 2025.[161] Given this growth, demand for uranium is expected to climb from 160 million pounds in 2015 to over 201 million pounds by 2025. Longer term, we expect nuclear power to potentially grow from about 2,700 TWh of electricity generated globally today to about 3,200 TWh in 2025 and to 3,700 TWh by 2035, a 38 percent increase over the next 20 years. Demand for uranium will likely continue to grow in line with these projections.

As demand continues to grow, the supply of uranium could undergo some important shifts. The supply of uranium in the past has been a mix of primary mined uranium, which accounted for 75 percent of supply in 2012, and secondary supply, including stockpile burn down and underfeeding of reactors since the Fukushima nuclear power plant accident in 2011. In the future, these secondary sources of supply are expected to decline in volume while primary supply increases dramatically. As a result, new uranium mines will be needed

[160] *World energy investment outlook 2014*, International Energy Agency, 2014.

[161] *The nuclear fuel report: Global scenarios for demand and supply availability 2015–2035*, World Nuclear Association, 2014.

to meet demand. Australia and Kazakhstan have the greatest volumes of identified uranium reserves in the world, at 1.8 million tonnes and 900 thousand tonnes, respectively, and will likely be key sources of new supply.[162] Although these reserves are sufficient to meet demand over the next 20 years, within the next 50 years, the discovery of new reserves may be needed. Although exploration spending increased dramatically over the last decade, the discovery rate was well below the historical standard. This presents a major challenge for the uranium industry and nuclear power to overcome in the coming decades.

Lithium is seeing strong demand from electric vehicles

Lithium is already seeing strong demand growth from the increased production of electric vehicles. Spot prices for lithium carbonate jumped to all-time highs in the past year.[163] However, lithium production is still very small, about 33,000 tonnes in 2015 on a lithium content basis, but at the average market price for the year of $6,400 per tonne for battery-grade lithium carbonate, that translates to a market worth just over $1 billion.[164]

If the growth rates of electric vehicles were to achieve the levels assumed in our tech acceleration case, lithium production in 2035 would need to total about 180,000 tonnes to meet the demand of automotive batteries with a storage potential of 2 TWh of energy. This assumes minimal improvements in battery performance to decrease the demand for lithium. At the same time, it does not assume battery size increasing as battery costs fall to increase the range of the vehicle. On top of demand from electric vehicle batteries, there could be increased demand from grid storage batteries and traditional lithium sources of demand, for example from glass manufacturing. However, lithium would still be a relatively small market in 2035 compared to oil today, even under these aggressive assumptions.

Although production will need to ramp up considerably, shortages of lithium are unlikely to limit electric vehicle growth in the 20-year time horizon. Globally, there are proven reserves of lithium to power more than 1 billion electric vehicles with 40 kWh battery packs using current battery materials. Some estimates put global lithium reserves at about 14 million tonnes, more than 420 years at current production levels, with resource estimates more than three times higher.[165] In the longer term, the battery industry may look to circular economy principles in the future design of lithium batteries. At the moment, only a small percentage of all lithium is recycled from batteries.[166]

Rare earth metals: An environmental rather than a supply question

Rare earth metals are a critical component in many modern electronic devices, from batteries to turbines to LEDs. Concerns about availability were raised in 2010 when China moved to limit supply.[167] Since then, supply from the United States and Australia has increased, recycling rates have improved, and manufacturers have looked to decrease the quantities needed or have found substitutes. When China increased supply again, prices dropped sharply—so sharply, in fact, that the only US mine of rare earth metals, Mountain Pass Mine, owned by Molycorp, was made idle indefinitely in October 2015. Given global reserves of 130 million tonnes and annual production of 124 million tonnes in 2015, the roughly 1,000-year supply means that rare earth metals are not all that rare.[168] The biggest uncertainty with rare earth metals is whether environmental concerns could curtail access to supply. Rare earth metals require substantial processing, resulting in large amounts of

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162 *Uranium 2014: Resources, production and demand*, OECD Nuclear Energy Agency, 2014.
163 *Mineral commodities summary*, United States Geological Survey, January 2016.
164 Lower grades of lithium are used for other applications, meaning that this is an overestimate of the true market size.
165 *Mineral commodities summary*, United States Geological Survey, January 2016.
166 Prachi Patel and Linda Gaines, “Recycling Li batteries could soon make economic sense,” *MRS Bulletin*, volume 41, June 2016.
167 Keith Bradsher, “Amid tension, China blocks vital exports to Japan,” *New York Times*, September 22, 2010.
168 Ibid.; *Mineral commodities summary*, United States Geological Survey, January 2016.

waste tailing that are often toxic. How policy makers account for environmental impact will determine how supply and prices evolve.

Other mineral resources that could challenge the global economy

Other, less common resources could find themselves in demand. Three of them are cobalt, potash, and tellurium.

- Cobalt serves as an anode in many lithium ion batteries, especially in consumer appliances. It is rarer than lithium, with most of the world's production coming from the Democratic Republic of Congo, a country with substantial geopolitical risk.

- Potash, a key fertilizer, currently has no substitute. Reserves of potash are limited, with only a 100-year supply available at today's production levels. With the need to increase agricultural output to meet the demands of a growing population, there could be future pressure on the price of potash.[169]

- Tellurium is a vital additive in many semiconductor devices, but it is mined entirely as a by-product of zinc. Whether mining for tellurium could be economically viable by itself has yet to be determined.

Could water be the new oil?

Water is the single most important natural resource for human life after oxygen, and water scarcity is increasing dramatically around the world. In 2030, global water requirements are forecast to be 40 percent greater than current supply and one-third of the world's population, mostly in developing countries, will live in basins where this deficit is larger than 50 percent.[170] Increasing demand from rapid urbanization, economic development, and population growth will strain water supplies, as will the agriculture needed to feed a growing global population. These demands come at a time of shifting water cycle patterns resulting from climate change. Demand for water is expected to grow 55 percent above 2010 levels by 2050.[171] Most of this increase is expected to come from manufacturing, electricity, and domestic uses, with irrigation increasing only slightly.[172]

Water access and supply are intersecting more directly with resource production. Large volumes of water are needed in hydraulic fracturing of shale deposits in oil production, roughly two million to 16 million gallons per well.[173] Mining operations can also be water intensive. In 2014, copper miners in Chile used 12.4 cubic meters of fresh water on average for every tonne of copper produced.[174] Water is key for some renewables as well; for instance, water is used as a coolant in wind turbines. In fact, after agriculture, power generation is the second-largest use of water. But energy, sometimes in large amounts, is required to supply water. For example, the California aqueduct, which brings snowmelt over two mountain ranges, is the biggest energy consumer in the state. Desalination also requires vast amounts of energy. For instance, plans for a desalination plant in San Diego have been under dispute because energy requirements might threaten the city's power supply.[175]

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169 Ibid.

170 *Charting our water future: Economic frameworks to inform decision making*, The 2030 Water Resources Group, 2009.

171 *OECD environmental outlook to 2050: The consequences of inaction*, OECD, March 2012.

172 Ibid.

173 *Facts about fracking: How much water does the typical hydraulically fractured well require?* United States Geological Survey.

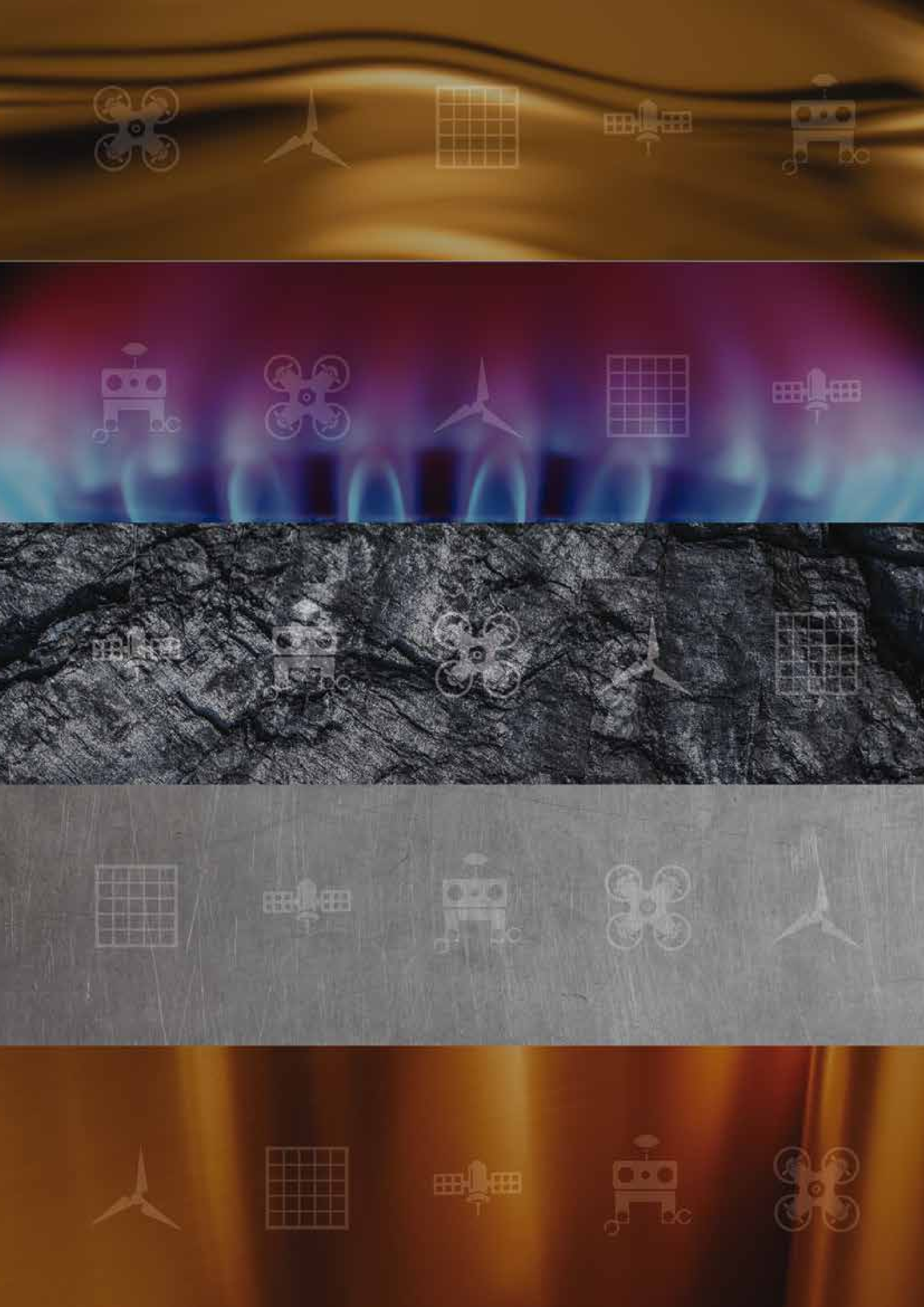
174 Douglas Aitken et al., "Water scarcity and the impact of the mining and agricultural sectors in Chile," *Sustainability*, volume 8, issue 2, 2016.

175 Dana Littlefield, "Concerns rise over the environmental impact of Carlsbad desalination plant," *Los Angeles Times*, July 31, 2015.

Water efficiency is becoming a priority in the resource industry as companies shift to less energy-intensive water treatment and less water-intensive power generation. Power generators may use air-cooled turbines rather than water-cooled ones, and reverse osmosis membranes and energy-recovery systems can help reduce energy demand in desalination processes. As water scarcity increases, technologies that can extract and recycle water could become increasingly valuable, creating new competition. Advanced water management will also become more important with a global imperative of zero waste and maximum recycling and regeneration. The returns on water-conservation efforts become more attractive when companies consider the full economic burden of waste, including disposal costs, water-pumping and heating expenses, and the value of recoverable materials carried off by water. Technological advances could help reduce demand for fresh water sources. The use of sensors and analytics in agriculture could provide real-time feedback to farmers, helping them determine when to irrigate given soil conditions and weather forecasts. Genetically modified, drought-resistant crops also open new avenues for increasing yields while needing less water.

•••

In a new commodities era, overall growth in prices should be more muted with less correlation between commodities. Price fly-ups could come at any time, to any commodity, but they may be fleeting. The broader trend of technology disruption that we have outlined is likely to have a dampening effect on demand for many, if not all, resources, even as it offers the potential for far greater efficiencies in both consumption and production of resources. Under these challenging conditions, how do resource producers capture opportunities for future growth? And given all the uncertainty, how can policy makers manage policies around resources in order to promote growth and stability? We address some of these questions in the following chapter.



Burbo Bank offshore wind farm in the mouth of the River Mersey, United Kingdom.

4. CAPTURING THE OPPORTUNITIES

The productivity performance of the resource sector can have a disproportionate effect on other sectors, on households, and on the economy as a whole. In the United States, for example, the resource sector accounts for only 4 percent of employment and 8 percent of GDP—but it represents one-third of all tangible capital investment by the private sector excluding real estate, and 40 percent of the input costs incurred by food, construction, and transportation firms.[176] Governments as well as resource companies therefore have a major interest in ensuring that the productivity opportunities for the sector are captured. In this final chapter, we highlight some of the implications of the technology-driven transformations we have outlined for both policy makers and business leaders in the resource sector. The prospect of more productive supply combined with potentially reduced demand will influence the decisions of both governments and companies about whether to devote tax dollars or shareholder capital to the development of new resources.

POLICY MAKERS: FOSTERING THE RESOURCE TECHNOLOGY PAYOFF

Capturing the potential productivity gains of the technological transformation of the resource sector will likely require some trade-offs. Policy makers will need to allow a nation's energy mix to shift and enable rapid technological changes throughout the economy even as they recognize and account for the social and economic impact of these changes.

Nations face different pressures. As we outlined in Chapter 1, the supercycle first represented a $1 trillion transfer from importing countries to exporting countries, followed by a $750 billion transfer in the other direction (Exhibit 19). Governments that relied on resource endowments to finance a significant part of their budgets will need to find alternative sources of revenue. For their part, importing nations could stock up their strategic reserves of petroleum and other commodities while prices are low, to safeguard against supply or price disruptions.

Regardless of their resource exposure, all nations share certain opportunities. We see three main priorities for policy makers in this new resource era: taking a portfolio approach to national energy policy, developing skills needed for the future, and effective management of transitions.

Policy makers will need to allow a nation's energy mix to shift and enable rapid technological changes throughout the economy even as they recognize and account for the social and economic impact of these changes.

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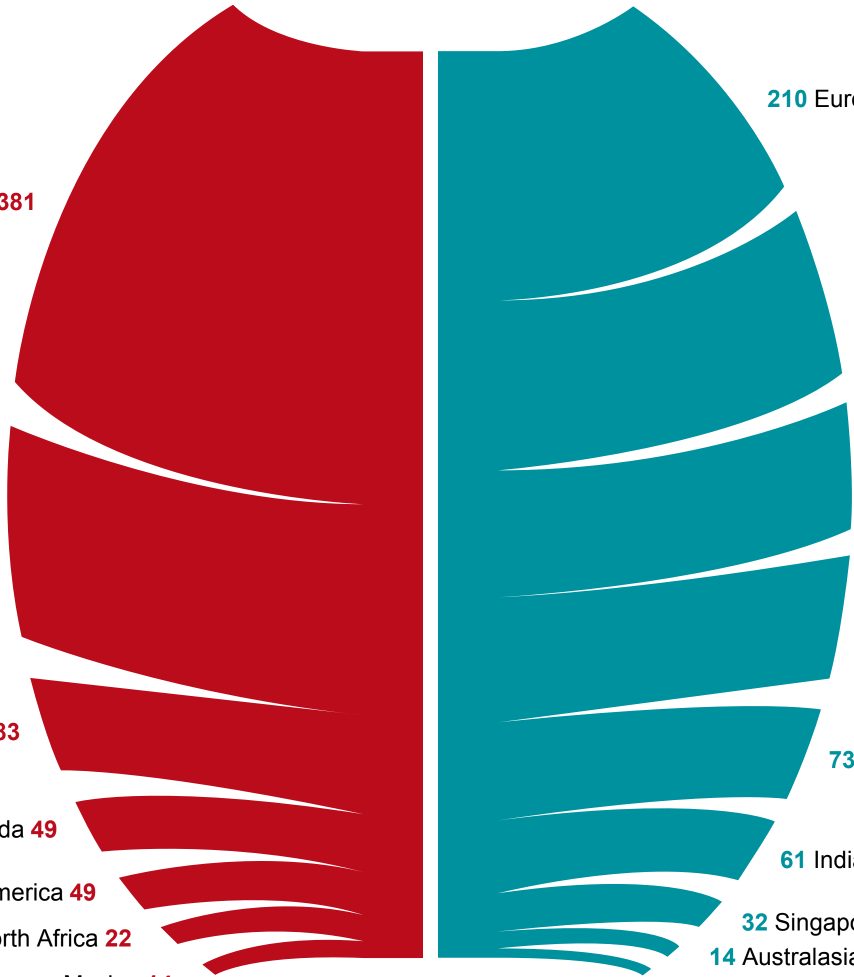
[176] *The US economy: Agenda for inclusive growth*, McKinsey Global Institute, November 2016.

Exhibit 19

The reduction in oil prices from 2013 to 2015 levels amounted to a $750 billion annual transfer from exporters to importers

$ billion per year



SOURCE: *BP statistical review of world energy*, 2015; EIA; McKinsey Global Institute analysis

Taking a portfolio approach to national energy policy

Rather than trying to pick winners and losers in the resource industry, policy makers could focus on providing a regulatory framework that helps all companies develop their digital capacity and move into new markets. This could set the stage for stronger growth from the dividend of falling costs and greater energy efficiency, as well as from resource companies moving into new growth markets. Policy can support innovation by taking a portfolio approach to national energy policy and by ensuring that regulatory bodies are responsive and farsighted about speeding the allocation of capital to the most promising opportunities. Today some of the challenges for policy makers include the difficulty of permitting new energy generation and transmission facilities, misaligned incentives for investment in energy efficiency, and the burdensome wind-down process of inefficient operations that are assuming losses. These barriers contribute to higher costs for consumers and lower returns to the industry.

In terms of broader policy goals, our analysis shows that even rapid technological change may not enable countries to achieve agreed climate change targets. (See Box 8, "Technological change in the resource sector could reduce carbon emissions, but not to the levels needed for countries to reach climate change targets").

Box 8. Technological change in the resource sector could reduce carbon emissions, but not to the levels needed for countries to reach agreed climate change targets

Technology will reduce the resource intensity of the global economy over time and will help countries get closer to meeting agreed global emissions targets. But on their own, the technology-enabled changes we model will not suffice to meet the broad international goals agreed at the Paris COP 21 climate conference in December 2015.

In our analysis, fossil fuel productivity per dollar of GDP would increase by 55 percent in our moderate case from 2013 to 2035, and by 90 percent in our tech acceleration scenario over the same period. As a result, in our tech acceleration scenario, CO2 emissions reach a peak in 2025 and then start to fall. In the moderate case scenario, CO2 emissions peak ten years later, in 2035.

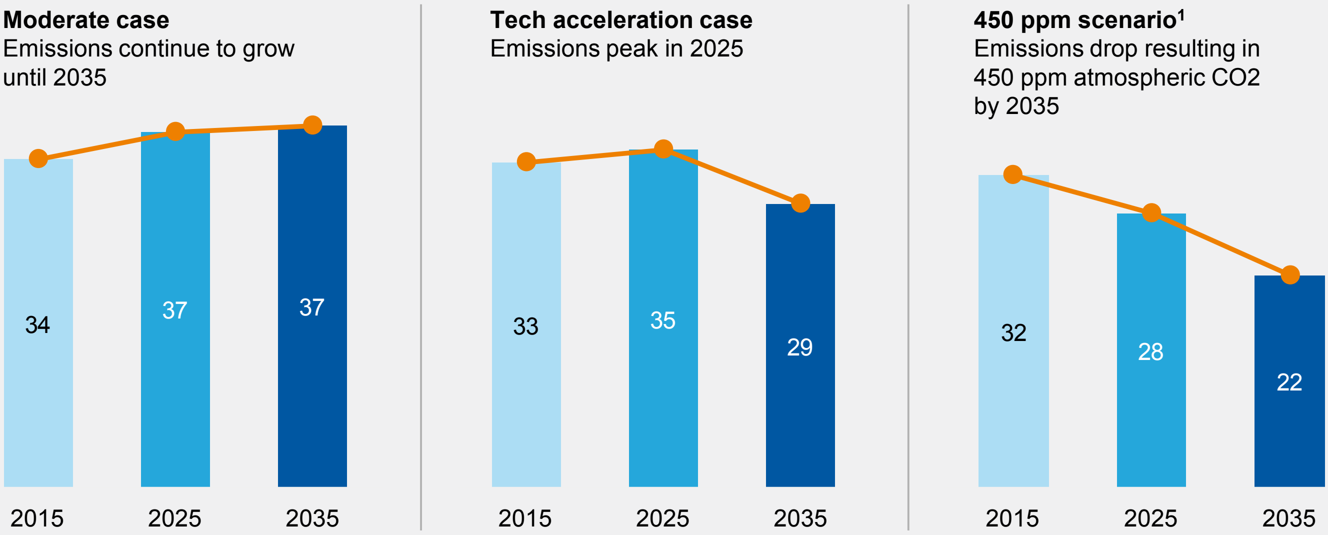
What does this mean for global warming? We compared forecast CO2 emissions in our two scenarios to the levels required to ensure a temperature rise of not more than 2 degrees Celsius (the 450 ppm scenario in Exhibit 20).[1] While CO2 emissions start to flatten out in our moderate case and tech acceleration scenario, this slowdown is insufficient to meet the IEA 450 target. In particular, our aggressive technology adoption scenario by itself would be insufficient to prevent a temperature increase of more than two degrees by 2100.

To be fair, the technologies that we model in this report are only part of the answer to meeting global emissions targets. We have not considered for our analysis other actions that could mitigate climate change, such as carbon capture and storage, a significant shift to nuclear, reducing non-energy-related emissions, reforestation, and the use of additional policy levers. Our analysis nonetheless highlights an important point: we cannot rely on the resource revolution alone to meet global emissions standards.

Exhibit 20

In both our technology adoption scenarios, greenhouse gas emissions will not meet international reduction targets

Greenhouse gas emissions by scenario
Gigatonnes CO2 equivalent



1 This chart has been adapted from IEA data about the levels of CO2 from greenhouse gases required to limit global temperature in 2100 to two degrees Celsius above pre-industrial levels. We took IEA data for 2020, 2030, and 2040 and interpolated midpoints assuming a linear trajectory.

SOURCE: McKinsey Energy Insights; *World energy outlook 2016*, IEA; McKinsey Global Institute analysis

[1] *World energy outlook special report: Energy and climate change*, IEA, 2015.

In a low growth commodities environment, policy makers could help promote an open investment culture that allows companies to capture new growth opportunities. In some countries, this might mean addressing currency risk as well as geopolitical risk. In other countries, it might involve strengthening property rights. For example, a 2011 study found that 35 percent of new mining projects in copper and 30 percent of new projects in iron ore were in countries that had issues related to property rights.[177] Property rights are also an important consideration in renewables like solar and wind power plants that require greater area per power produced than coal or gas power plants. Building support in the community, ensuring that the process to decide on property rights is fair and transparent, and making sure citizens clearly understand the benefits are important steps to avoid conflicts later.

Policy makers could help resource companies capture value from building digital capacity by removing barriers to the adoption of technology. Research has identified $3 trillion in economic value that could be generated each year through enhanced use of open data.[178] For example, in 2011, New York City began releasing detailed information on energy and water consumption for each non-residential building.[179] Building operators now use this data to benchmark their own energy efficiency, prioritize investment to capture savings, and create incentives to promote energy-reducing programs or devices. At a city or regional level, governments will need to ensure that energy-related infrastructure and regulatory choices work together. For example, local choices about which transportation technologies and business models to support, through investment and regulation, will help determine energy use. The greater the interplay between these choices, the larger their impact.[180]

Policy can support innovation by taking a portfolio approach to energy and by ensuring that regulatory bodies are responsive and farsighted about speeding the allocation of capital to the most promising opportunities.

Setting clear efficiency standards is another way policy makers could help promote the adoption of new technology, particularly white goods, consumer electronics products, air-conditioning, lighting, and vehicles. Instead of regulating the use of specific technologies, standards are more effective if they set targets for overall efficiency, leaving the details of how to meet these targets to companies. For example, Japan's Top Runner program mandates that manufacturers improve the energy efficiency of their products to the top level of a benchmark within a specified period, with a benchmark-resetting mechanism for the next period.[181] In Africa, Ghana has established standards for household appliances. Research shows, for instance, that the country's energy efficiency standard on air conditioners will save Ghanaian consumers an average of $64 million per year on their energy bills and reduce carbon dioxide emissions by some 2.8 million tons over 30 years.

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177 Fred McMahon and Miguel Cervantes, *Survey of mining companies*, Fraser Institute, March 2011.

178 *Open data: Unlocking innovation and performance with liquid Information*, McKinsey Global Institute, October 2013.

179 *New York City local law 84 benchmarking report*, New York City Mayor's Office of Long-Term Planning and Sustainability, August 2012.

180 *Game changes in the energy system: Emerging themes reshaping the energy landscape*, World Economic Forum, January 2017.

181 Osamu Kimura, *Japanese top runner approach for energy efficiency standards*, SERC discussion paper number 09035, 2010.

Given uncertainty about the future direction of commodity prices, governments could put in place stable, effective policy regimes that strengthen market signals and recognize environmental and social externalities of production and use. While this involves challenges, there are three areas to consider. First is the removal of fuel subsidies without compromising social welfare objectives. Fuel subsidies can distort market behavior, often promoting the adoption of inferior or inefficient technologies, and can place a burden on government finances. Policies that can achieve social welfare objectives without these problems are worth considering. For example, Indonesia put in place a conditional cash-transfer program to help cushion low-income households from higher prices that arose as a result of the country's reform of kerosene subsidies in 2005 and 2008.[182] Singapore compensated low-income households for increases in water tariffs by providing rebates in the form of "quasi-cash" that households could draw on at any time to pay utility bills, including water.[183]

Second, policy makers may have to reevaluate taxes on the usage of resources as a major source of government revenue. For example, gasoline taxes fund road maintenance in the United States. If the gasoline market for transportation declines with the advent of electric vehicles, the government will need to find alternate ways to raise that revenue, such as by moving from gas taxes to vehicle taxes, tolls, or mileage taxes. Policy makers could aim to create market-based pricing schemes such as time-of-use pricing, enact taxation or regulation to account for externality costs, and take other measures to create a system that reflects the true costs of the resources being consumed.

Third, policy can also address the potential for distortion in the utility markets. Utilities are unique institutions given their role as a "public good" provider, heightened levels of regulation, need to recoup the cost of large capital outlays, and varying levels of ownership including private, quasi-public, and public. Policy makers could work with utilities to facilitate the development of new rate structures and pricing to take into account the changing energy environment. Renewable subsidies may also need to be revised to encourage higher adoption of the most economic solutions.

Growing workforce skills

To help capture the payoff from the resource revolution, policy makers will need to invest in upgrading the skills of the workforce. As more activities become automated, higher-skill workers will be in demand. Recent MGI research has estimated that some 60 percent of occupations in the United States could have 30 percent or more of their activities automated by currently demonstrated technologies.[184]

Demand for new job classes such as data scientists, statisticians, and machine-learning specialists is already on the rise among resource producers. Within ten years, oil and gas companies, for example, could employ more PhD-level data scientists than geologists, either in-house or through partnerships with increasingly sophisticated vendors.[185] Wind-turbine service technician is the fastest-growing job category in the United States, according to the US Bureau of Labor Statistics.[186] Meanwhile, existing roles will be redefined. For instance, the automation of repetitive technical decisions will free up engineers to focus on more difficult analyses.

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[182] Christopher Beaton and Lucky Lontoh, *Lessons learned from Indonesia's attempts to reform fossil-fuel subsidies*, International Institute for Sustainable Development, October 2010.

[183] *Resource Revolution: Meeting the world's energy, materials, food, and water needs*, McKinsey Global Institute, November 2011.

[184] *A future that works: Automation, employment, and productivity*, McKinsey Global Institute, January 2017.

[185] Christopher Handscomb, Scott Sharabura, and Jannik Woxhol, "The oil and gas organization of the future," *McKinsey Quarterly*, September 2016.

[186] Jennifer Oldham, "Nation's fastest growing job—only for those who like to get high," *Bloomberg*, May 12, 2016.

To meet the growing demand for skilled workers, policy makers should start by ensuring that education is well funded and retraining programs are effective.

Countries will need to raise the number of young people earning college degrees in general and find ways to graduate more students in science, engineering, and other technical fields in particular.[187] Secondary and vocational training could be revamped to retrain midcareer workers and to provide job-specific skills to students who will not continue to college. In developing countries, policy must address how to retrain hundreds of millions of adults who have little or no formal education.[188]

Governments can work with companies to develop curriculums especially designed for energy and mining industries. This is particularly effective in countries where resources are a dominant employer and advanced education may not be widespread. For example, in Kazakhstan, oil companies such as Chevron, in conjunction with the government, are developing a curriculum developed by the Society of Petrochemical Engineers to bring the skills of prospective employees in the industry up to world-class standards. In general, there is room for the private sector to play a greater role in educating and training the workforce, both in and out of the classroom, and governments can play a role in convening and mobilizing more of these initiatives.

Managing economies, industries, and communities in transition

Policy can help reduce friction and transaction costs as capital and resources shift to different sources of energy supply. Reducing transaction costs for firms as they open and close plants, acquire the necessary permits, and dispose of hazardous or unneeded materials would allow the sector to become more nimble and innovative. In addition, finding ways to mitigate the impact of shutdowns and transitions on displaced workers and affected communities while also addressing issues of overcapacity, stranded assets, pensions, and other financial and environmental liabilities will be important. All of this may involve additional trade-offs; for instance, speeding up the closure of "zombie mines" may require creative policy solutions to balance short-term financial costs with long-term benefits.

Reducing transaction costs for firms as they open and close plants, and finding ways to mitigate the impact of shutdowns and transitions on displaced workers and communities, will be important.

Managing transitions is a top priority for resource-dependent countries. The first step is to identify sectors to develop based on geographical advantages and natural resource abundance. The next step is identifying and acquiring workforce and infrastructure. After that, policies will need to be put in place to divert resources to the new sector. Successful diversification has a number of characteristics: strong governance, a skilled workforce, effective public spending, and determined effort by policy makers.[189] Some resource-dependent countries are seeking to reposition their national economies and government revenue sources around a broader set of industrial sectors. This requires investing the surplus from resource exports for the development of other sectors and ensuring that spending is well thought through, efficient, and targeted.

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187 *The world at work: Jobs, pay, and skills for 3.5 billion people*, McKinsey Global Institute, June 2012.

188 Ibid.

189 *Reverse the curse: Maximizing the potential of resource-driven economies*, McKinsey Global Institute, December 2013.

Saudi Arabia is an example of diversification at work.[190] Low oil prices forced the oil-dependent nation to accelerate its economic diversification path. Since then, Saudi Arabia has launched a $2 trillion sovereign wealth fund to diversify into non-petroleum assets, thus hedging its almost total dependence on oil. The government plans to raise part of the funds through the sale of a less than 5 percent stake in Saudi Aramco.[191] Chile has developed into a dynamic and more diversified commodity exporter, with an emphasis on high-value primary-based products that draw on its diversified resource base. One key element has been its successful implementation of countercyclical fiscal policy, stabilizing the economy by high savings during the copper boom years and dis-saving when prices began to fall. Chile also offers several examples of successful active vertical public roles in helping to develop the salmon and wine industries.

$100B
Total liabilities of the US coal industry in 2014

Developing a framework and process to help industries in decline is an essential component of policy making today. Policy makers need to think about long-term liability renegotiations, including environmental remediation. Many industries facing a decline have long-term liabilities, which they might not be able to honor given declining revenues and profits. These liabilities include environmental cleanup costs. This reality is already playing out in the United States, where total demand for coal by 2020 could decline by almost 40 percent from 2008 levels. According to a McKinsey analysis, the entire US coal industry had liabilities of close to $100 billion in 2014, which will need to be assumed.[192] These liabilities are for future health-care costs and life insurance benefits for their current and retired employees as well as restoring the land by reclaiming mines, filing them with dirt, and recreating the ecosystem. The government has to work with companies and communities to come up with a solution that is feasible for the company and not a huge burden on taxpayers. One possibility may be to stem the decline of the industry until the liabilities are recovered from the revenues. Another solution could be to decide the priority order of repaying liabilities upfront, especially if the industry is in decline. Smoothing the transition between individual plants and sources of energy would allow for more efficient capital allocation within the energy sector, boost productivity, and support long-term sustainability objectives. Industry, meanwhile, has begun the process of restructuring, with several large players either beginning Chapter 11 bankruptcy processes or emerging from them. This is a necessary first step that will significantly reduce overall liabilities in the industry when these restructurings are complete.

THE RESOURCE COMPANY OF THE FUTURE: WINNING THROUGH TECHNOLOGY

In the new technology-enabled world of resources, competition could come from anywhere, including technology leaders such as Google and Alibaba that have reached "hyper" scale in revenue, assets, customers, workers, and profits, and can move quickly into other industries.[193] Alibaba, for example, recently started an online marketplace for crude oil tracking. To adapt to this new reality, incumbents may need to rethink what it means to be a resource producer.[194] Size may matter less and agility more while future growth may come from non-traditional sources. By harnessing new technology, tomorrow's resource leader could derive its advantage from doing more with less, moving faster, and thinking differently than in the past. It may incorporate best practices from other industries, such as manufacturing, services, venture capital, and even consumer products. Successful companies, whether they are incumbents, renewable energy producers, or utilities, should

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190 *Saudi Arabia beyond oil: The investment and productivity transformation*, McKinsey Global Institute, December 2015.

191 Stefania Bianchi, "The key questions asked about Saudi Arabia's $2 trillion fund," *Bloomberg*, May 25, 2016.

192 *Downsizing the US coal industry: Can a slow-motion train wreck be avoided?* McKinsey Metals and Mining Practice, November 2015.

193 *Playing to win: The new global competition for corporate profits*, McKinsey Global Institute, September 2015.

194 *Mining's next performance horizon: Capturing productivity gains from innovation*, McKinsey & Company, September 2015.

consider developing a more active approach to strategy and growth, making productivity a priority, and digitizing their organizations.

Developing a more active approach to strategy and growth: New markets, new partnerships, and preparing for uncertainties

Resource producers will have to embrace a future with more uncertainty and fewer sources of growth. The future oil and gas or mining company may more closely resemble today's industrial manufacturers by moving away from tactical contractual arrangements and toward long-term strategic partnerships with a network of tier-one and tier-two suppliers.[195] In a world of plentiful resources, access is no longer a key strategic differentiator, and large oil companies may increasingly rely on specialized explorers rather than in-house exploration teams for reserve replacement.[196]

Of course, mining and energy differ from other industries in many ways. They are highly variable, starting with uncertainty about the nature of the resources being mined or extracted. Operations often take place in extreme environments, moving operators to the work site can be time-consuming, and the stresses and strains placed upon equipment can result in frequent breakdowns. Despite obvious differences, resource producers may benefit from borrowing some best practices from other industries.

Resource producers could incorporate more of a private equity or venture capital mindset to discover and evaluate investment prospects. While overall growth in commodities is expected to be muted, in an industry that is no stranger to speculation, the next big thing is almost certainly around the corner. To learn from the private equity or venture capital industry, resource producers may take a structured, data-driven approach to making investment decisions using the latest asset valuation and portfolio techniques. While these are standard practice in finance, resource producers often evaluate new investments on an individual basis and do not take into account the effect of a project on overall cash flow and risk to the firm. Identifying the sources of risk, for example commodity price uncertainty, exchange rate uncertainty, diversification costs vs. benefits, technological adoption rates, and strategic matches, and quantifying the impact on cash flow should enable leaders to make more informed decisions about the trade-offs associated with each decision. Each potential asset could then be evaluated to select a portfolio that delivers the highest risk-adjusted return that the company is confident of delivering, while also matching other company criteria such as strategic fit and shareholder expectations.

Resource companies may consider drawing on alternative models. One example is a service provider. In this case, a distinctive source of value is meeting the needs of the customer, not just selling a commodity on a market. One company that puts its customers ahead of its own needs is Zappos, which helps customers buy from competitors if it cannot find an item in stock. Another is a technology-focused company such as GE, where the distinctive source of value is developing and capitalizing on new technological breakthroughs and ideas. Utility PG&E offers business customers an on-site integrated energy audit, which identifies opportunities in demand response and self-generation as well as energy efficiency for eligible customers. The gold miner Barrick Gold is using digitization to mine lower-grade resources in more challenging locations with greater community oversight and sustainability demands. For example, Barrick's Veladero gold mine in the mountains of Chile and Argentina is in a remote area that creates frequent challenges for maintaining operations and requires strict adherence to oversight by provincial authorities.[197]

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[195] Christopher Handscomb, Scott Sharabura, and Jannik Woxhol, "The oil and gas organization of the future," *McKinsey Quarterly*, September 2016.

[196] Ibid.

[197] *Barrick announces resumption of operations at Veladero*, Barrick Gold, October 4, 2016.

Another model is that of a capital fund where the distinctive source of value is the strength of the firm's balance sheet to put behind the right business opportunities.

To become more agile and better prepared for disruptions, resource producers could strengthen their strategy process. This may include adopting portfolio management techniques, actively reallocating capital, setting shorter strategic horizons, and looking for stage gates or tipping points. Agility combines two distinct concepts: dynamic capabilities, such as the ability to rapidly form cross-functional teams and reprioritize tasks to adapt quickly, and a stable backbone of core value-adding processes and cultural norms that provide resilience, reliability, and relentless efficiency.[198] Some practices that help build agility include fluid teaming, loose hierarchies, rapid prototyping, and instant feedback.

Resource producers could incorporate more of a private equity or venture capital mindset to discover and evaluate investment prospects. While overall growth in commodities is expected to be muted, in an industry that is no stranger to speculation, the next big thing is almost certainly around the corner.

To be better prepared for uncertainty, firms may also consider joint ventures and partnerships as well as mergers and acquisitions, which can lower risk, especially when entering an unfamiliar market. Involvement in research and development partnerships to share costs and risk is another possibility, while small-scale equity stakes may also provide non-operational ownership in segments where a firm's core competencies may not be applicable and create a less risky way to harness fast-growing markets. In addition, companies with strong balance sheets will be in a better position to endure uncertainties while regular strategic reviews will keep management abreast of sudden changes.

Focusing on productivity to capture value

During the supercycle, cost overruns, delays, and decreasing labor productivity became trends throughout the industry. Capital projects of more than $1 billion grew rapidly at a rate of 24 percent per year between 2004 and 2008, but these megaprojects had failure rates on average of 65 percent, with some sectors as high as 75 percent.[199] Resource companies now have an opportunity to reverse the trend of declining productivity by applying new technology throughout the organization.

There are many ways technology can drive productivity improvements, as we outlined in Chapter 2. RFID tracking can be widely used in construction and other remote fields to increase worker productivity and security. In the mine pit, combining traditional dispatching with smart algorithms can optimize the efficiency of machine movements. In processing plants, applying artificial intelligence and new mathematical techniques that look for hidden relationships between second- and third-order variables can improve yields by 3 to 10 percent.[200] Automated haulage and drilling have now been commercialized, while other technologies, such as automated blasting and shoveling, are in testing, making it possible

[198] Christopher Handscomb, Scott Sharabura, and Jannik Woxhol, "The oil and gas organization of the future," *McKinsey Quarterly*, September 2016.

[199] Edward W. Merrow, *Industrial megaprojects: Concepts, strategies, and practices for success*, John Wiley & Sons, April 2011.

[200] *How to address the mining productivity imperative?* McKinsey & Company World Mining Conference, October 20, 2016.

not only to reduce labor costs but also to reduce the number of people working in the most dangerous areas.

By harnessing technology, resource producers can build a more comprehensive understanding of the resource base, optimize material and equipment flow, improve anticipation of failures, and monitor performance in real time. Alone, each of these opportunities has real potential; together, they represent a fundamental shift in both potential safety outcomes and how value can be captured in the mining sector, and they help close part of the productivity gap.

Resource producers will need to do more than digitizing to increase productivity, however.[201] By focusing on the fundamentals—driving up throughput and driving down capital costs, spending, and labor costs—resource producers can become productivity leaders. First, resource producers should consider taking a tight-fisted approach.[202] According to this approach, companies could aggressively lower their operating cost base with deep and targeted cuts in areas of excess spending and focus on achieving operational excellence. Areas of opportunity include reducing external spending through smarter procurement and streamlining support functions. Operational excellence not only implies a sustained focus on cost reduction but also throughput improvement. This will require mining companies to shift away from the traditional approach of making occasional intensive drives for improvement and instead embed manufacturing-type systems and continuous-improvement approaches in their organizations. Particular target areas include elimination of waste, reducing variability, and building individual and organizational capabilities.[203]

Digitizing alone will not increase productivity. By focusing on the fundamentals—driving up throughput and driving down capital costs, spending, and labor costs—resource producers can become productivity leaders.

McKinsey has found that innovative capital project design and delivery in the oil sector can reduce capital expenditure by as much as 40 percent, through compressing the cost of current projects and rethinking future capital project-management systems, taking advantage of collaborative agile delivery and new technologies that have already been pioneered and adopted by other industries. Furthermore, reshaping workflows and improving collaboration with suppliers to share risk and align incentives can reduce operating costs by 20-30 percent.[204]

Another approach to increasing productivity is for companies to embed effective management operating systems, in particular at mines. Establishing such systems will create greater transparency on operations performance and identify areas for improvement. The operating systems should also free people and resources to focus on productivity and operational excellence and should support effective performance management. This approach will help resolve what has been a long-standing challenge for many mining companies: making productivity performance and its measurement a priority. Operators

[201] *Productivity in mining operations: Reversing the downward trend*, McKinsey & Company, May 2015.
[202] *Productivity at the mine: Pointing the way forward*, McKinsey & Company, July 2016.
[203] Ibid.
[204] *The oil company of the future: From survive to thrive in "the new normal"*, McKinsey & Company, December 2016.

have typically concentrated on improving one or two variables, such as reducing costs, lowering capital intensity, or increasing throughput. Many mining companies still consider productivity improvement the domain of a continuous-improvement department or a handful of lean experts rather than a core competence that should be embraced throughout the organization.

Companies could also improve the productivity of their asset base. This means digging and hauling more dirt with each shovel and truck as well as removing bottlenecks from the downstream logistics chain. For example, one Australian miner was able to increase substantially the overall-equipment-effectiveness performance of its pit-to-port system by improving equipment availability, raising utilization through better planning and scheduling, and accelerating the pace of port loading.[205] Finally, focusing on capital productivity is also important. Resource producers could also become more disciplined in capital allocation and increase the productivity of that capital when it is deployed.

Accelerating the future: Adapting the organization and building digital capacity

Resource producers can enable change by adapting their organization to the new reality of a technology-driven resources era (see Box 9, "The challenge of change"). The payoff from building digital capacity is significant. Prior MGI research has shown that the most digitized companies have faster revenue growth and higher productivity and innovation than their less-digitized peers. Their profits and margins can grow up to three times as quickly, and workers within these companies enjoy wage growth that is twice as fast as that of their peers.[206] The resource industry lags behind other industries in terms of digitization, and there are significant opportunities to unlock value, increase productivity and efficiency, and increase health and safety across the mining value chain. While some resource companies are well on their way in this process, others are near the beginning.

Firms may start with appointing a senior executive to drive the entire digital strategy throughout the firm. That chief digital officer would report directly to the CEO and have a high level of business responsibility. The chief digital officer would be responsible for digitizing across functions and departments, overseeing all tech initiatives, guiding process innovations as new technology is adopted, incorporating data into decision making, enhancing customer outreach by creating online user communities and linking with customers through social media, and overseeing the development of tech talent throughout the workforce. Support and commitment from the CEO are also critical.

Creating a digital culture means using technology to push the boundaries, make changes, and innovate. That may be done by gathering market intelligence in different ways, including creating online platforms for bottom-up idea generation, revamping processes to fast-track new opportunities, and via collaborations with startups and other partnerships. For example, utility firms E.ON and Innogy (formerly RWE) have announced investments in Bidgely, a Silicon Valley startup that disaggregates smart meter data into appliance-level consumption, and RWE has also entered into a partnership with Google Nest. ExxonMobil introduced the ExxonMobil Fuel Finder, an app that lets customers easily locate the nearest station.

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205 Ibid.

206 *Digital America: A tale of the haves and have-mores*, McKinsey Global Institute, December 2015; *Digital Europe: Pushing the frontier, capturing the benefit*, McKinsey Global Institute, June 2016.

Box 9. The challenge of change

Digitization is occurring unevenly across the economy, and some resource companies are among the laggards. In an MGI analysis of the state of digitization in the US economy, mining ranks near the bottom of industries. Oil, gas, and utilities rank closer to the top but are still below digital leaders like banking, media, tech, and business services.[1] Industries that are more digitally mature than resource producers can offer clues to how digital entrants can disrupt a marketplace and force incumbents to adapt quickly.

By allowing companies to split their value chains into more specialized activities, digitization creates opportunities for niche companies to capture value in the marketplace. In consumer-facing industries, these niche players can quickly establish their own brands and challenge established incumbents. Retail banks, for instance, that traditionally offer a range of bundled products must now deal with financial technology companies, each one small, agile, and focused on a specific unbundled value proposition such as crowdfunding or personal finance management. To make things more challenging, these niche players can quickly build on their customer-centric success thanks to the network effects inherent in digital platforms and near-zero marginal costs of expansion. These attackers can ride a winner-take-all dynamic to become "hyper" scale companies virtually overnight, upending traditional business models.

While it is hard to predict whether a similar incursion by outsiders may upend the resource sector, especially given its capital intensity, one possibility is that we may see the rise of the integrated energy company.[2] Instead of the traditional oil and gas or mining company that we think of today, technologically driven trends such as electrification in transport and heating may encourage a blurring of boundaries to form highly integrated energy companies with activities spanning from resource extraction all the way through to the supply of consumer products and services.

Incumbent resource producers, renewables, and utilities each face their own set of unique challenges. For incumbents, they must consider whether to stay in current markets, diversify into new markets to capture growth opportunities, or a combination of both. The decision to remain in current markets will depend largely on a resource producer's cost position. If a producer has a low cost structure within the industry, there is little reason to exit a sector, even in the face of potentially declining demand and low prices. For example, BHP announced that it produced a record 257 million metric tons of iron ore from its Australian pits in the year to June 2016 and said it planned to keep increasing production.[3] For large companies, it makes sense to begin investing in new sectors to capture growth in the future. For instance, Total announced plans to invest heavily in renewables and electricity markets, about $500 million per year, with the goal of becoming the top player in 20 years and growing its share of the asset portfolio to 15 to 20 percent by 2035.[4]

For renewable resource producers, agility and intelligence through data analytics will be key to beating the incumbents. A major challenge for the renewable sector will be to keep costs down and deliver higher-value products while moving to scale. Technology will be a key factor here in cost containment and reduction. For utilities, the challenge will be adopting new generation and distribution technology and coping with end-user demand shifts that will require ongoing regulatory dialogue to ensure grid stability, financial viability, and consistent service to all customers. A study by the Lawrence Berkeley National Laboratory, for example, suggests that a 2.5 percent penetration rate of home-installed generation sources would reduce the earnings of a utility by 4 percent.[5] Utilities will have to work closely with policy makers to balance their own interests with the lowest economic cost and highest efficiency of resource use. To address this issue, a number of interventions could be explored. These include redefining rate structures for distributed power, creating a more flexible rate structure such as time-of-use pricing to drive efficiency and demand management, and expanding storage to balance the load and avoid massive spikes in demand.

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1 *Digital America: A tale of the haves and have-mores*, McKinsey Global Institute, December 2015.

2 *Game changers in the energy system: Emerging themes reshaping the energy landscape*, World Economic Forum, white paper, January 2017.

3 *Operational review for the year ended 30 June 2016*, BHP Billiton, 2016.

4 *Growing renewables, in particular solar energy and biomass*, Total SA, September 26, 2015.

5 Andrew Satchwell, Andrew Milles, and Galen Barbose, *Financial impacts of net-metered PV on utilities and ratepayers: A scoping study of two prototypical U.S. utilities*, Lawrence Berkeley National Laboratory, September 2014.

Developing the capability and talent of the workforce will require recruiting new workers and putting in place systems for ongoing skills development. Learning and innovating on the job will be key to harnessing the maximum potential from digitization. Resource companies may try to foster talent across multiple domains—for instance, design, statistics, research and development, and technical know-how—and they may identify talent gaps across domains and levels based on a firm's specific digital strategy. In the recruiting process, firms could identify new sources of talent, such as innovation centers at universities. A new generation of social media and digital recruitment tools is now available, offering human resources departments opportunities to identify and reach out to specific talent.[207] A significant challenge for resource producers will be to attract the next generation of talent to the industry, particularly if operations are based in remote areas of the world. This will mean attracting millennials by designing an environment that meets their expectations, with features such as flexible employment structures, including remote working and alternative career paths with more rapid progress cycles.[208] For now, 14 percent of millennials say they would not want to work in the oil and gas industry because of its negative image, the highest percentage of any industry.[209]

Key decisions will need to be made on new IT that should be introduced and how to integrate it into existing business processes and improve data security. New IT infrastructure might include drones, robotics, and Internet of Things sensors for predictive maintenance or 4D printing for well optimization. For example, Shell has been pushing its reservoirs limits by utilizing 3D/4D seismic imaging to help increase oil recovery in offshore Brazil and Central North Sea fields.

Embedding data analytics into all processes across the enterprise, including operations, can reduce costs, boost revenues, and improve service levels. McKinsey research has found that most companies are still capturing only a fraction of the potential value from data analytics.[210] Leading companies are using their analytics capabilities not only to improve their core operations but also to launch entirely new business models. For resource companies to realize the benefits of data analytics requires installing equipment such as sensors and hardware to collect and store data in real time; acquiring, developing, and installing software to drive analytics and data visualization; and developing processes to incorporate the output of analytics in decision making. Some companies are already reaping the benefits of data analysis. BP has been using data analytics to better understand reservoir activity, increase refinery efficiency, improve biofuels yields, and make better trading choices.[211]

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Policy makers and resource companies face a challenging transition in the post-supercycle era of technological change. New opportunities for growth beckon, but capturing them will be challenging. Instead of size, companies will need to promote speed and agility. Instead of picking winners and losers, policy makers will need to take a portfolio approach to energy policy. The changes are likely to be complex and numerous, yet the rewards of greater productivity, faster growth, and a less resource-intense economy will benefit all.

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207 *A labor market that works: Connecting talent with opportunity in the digital age*, McKinsey Global Institute, June 2015.

208 Christopher Handscomb, Scott Sharabura, and Jannik Woxhol, "The oil and gas organization of the future," *McKinsey Quarterly*, September 2016.

209 Ibid.

210 *The age of analytics: Competing in a data-driven world*, McKinsey Global Institute, December 2016.

211 *Big data analytics for oil and gas: Finding opportunities for success*, Syntelli Solutions, blog, August 28, 2016.

An oil drilling rig in Bakken, North Dakota.

TECHNICAL APPENDIX

This appendix has the following sections:

1. Key assumptions and principal sources for technology adoption scenarios

2. Economic assumptions

3. Calculation of the opportunity from technology adoption

4. Increased productivity of resource producers

5. Calculation of demand outlook for focus commodities

1. KEY ASSUMPTIONS AND PRINCIPAL SOURCES FOR TECHNOLOGY ADOPTION SCENARIOS

For this report, we modeled two principal scenarios to gauge the impact of technology adoption on both supply and demand for resources to 2035. They are a moderate technology adoption scenario, and an accelerated technology adoption scenario.

The moderate technology adoption case captures current trends and expected trajectories of resource intensity and end-use efficiency improvements in the resource sectors. The technology acceleration scenario takes assumptions about the rate of technological adoption in certain sectors and accelerates the adoption of the technology to realize more of the potential of the technology in a shorter amount of time; this affects the end-use efficiency figures, energy mix, and the productivity of resource producers. The assumptions for both scenarios were selected using a combination of primary research from external third party reports and resources with inputs from experts both within and external to McKinsey & Company. In particular, we collaborated extensively with colleagues at McKinsey Energy Insights and McKinsey Basic Materials Institute. Much of the data and assumptions we used comes from their proprietary models. We have detailed external sources in the footnotes to the report. These include the International Energy Agency, the United States Geological Survey, BP's statistical review of world energy, Rystad Energy, and Wood Mackenzie.

We primarily focused on five commodities: oil, natural gas, and thermal coal, iron ore, and copper. For energy commodities, the Energy Insights' Global Energy Perspective model was used. For the basic material commodities, the Basic Materials Institute Global Steel model and the Global Copper model were used. To estimate supply, we constructed our own bespoke models based on McKinsey's analysis of cost structures and assumptions on the impact of technology and adoption rates informed by our own experience and by external experts.

Underlying economic growth was taken as an exogenous variable throughout the report. For our default economic projection, we used the "global downshift" scenario from McKinsey & Company's Global Growth Model. This projects annual average growth in global GDP to 2035 of 2.7 percent. We also conducted sensitivity analyses using two other economic growth cases from the global growth model to provide a range of outcomes.

The scenarios we modeled aim to clarify the potential range of outcomes and assess the potential impact of select drivers on the demand and supply outlooks. They should not be viewed as precise forecasts of commodity prices.

In some cases, because of a scarcity of data about nascent technologies, input assumptions for the potential impact of technology were taken from few data points. In these cases, we also leveraged impact case studies and practitioner assessments. The impact of these technologies will become clearer once they are more widely deployed.

Policy decisions will have a large impact on the adoption rates of the technology highlighted. Throughout the report, we have assumed policy interventions that have been announced will occur, but we do not assume additional policy interventions. While these could accelerate or decelerate the adoption of technology, we did not explicitly test this sensitivity.

2. ECONOMIC ASSUMPTIONS

In this report we assume an average annual global GDP growth rate of 2.7 percent to 2035. This is a projection from McKinsey & Company's proprietary Global Growth Model, which provides complete time-series data for more than 150 concepts and 110 countries over 30 years. It incorporates more than a dozen major international databases from such institutions as the United Nations, the World Bank, the International Monetary Fund, and the Bank for International Settlements.

The 2.7 percent growth scenario corresponds to the global growth model's "global deceleration" scenario. This assumes that major economies converge to lower growth rates. In this scenario, global growth is slightly below the average for the past three decades. The expansion is especially reliant on positive outcomes in emerging markets. Structural challenges remain largely unaddressed but are offset in the near term by partly successful efforts to revive demand. China avoids the worst effects of a "hard landing," but confidence in the financial and fiscal system is shaken, further weighing on growth. China still accounts for nearly 23 percent of global GDP by 2025, however. In the advanced economies, fiscal and monetary buffers to address structural reforms are exhausted. Near-term demand revives globally, creating an opportunity for Europe and the United States to make progress on financial services, privacy, and M&A activity, which becomes a benchmark for global emulation. Trade is a more important driver of growth in this scenario than in the previous one. The lower growth curve is a constraint, but trade still accounts for 27 percent of the global economy. Under this scenario, demand for energy (including oil) revives, but the availability of additional supply keeps prices from recovering more quickly.

We also conducted sensitivity analyses using two other assumptions from the global growth model. These provided a range of outcomes for individual commodities that we have indicated in footnotes in the text in Chapter 3. They are the scenarios known as "Rolling regional crises" and "Pockets of growth". The first describes a world in which structural challenges remain largely unaddressed, and the global economy becomes more vulnerable to regional crises and grows increasingly insular. The second captures the case in which growth accelerates but the major economies diverge. Further details of the global growth model are to be found in *Shifting tides: Global economic scenarios for 2015–25*, McKinsey & Company, September 2015.

3. CALCULATION OF THE OPPORTUNITY FROM TECHNOLOGY ADOPTION

The opportunity from technology adoption is discussed in Chapter 2.

Changes to energy demand and energy mix

Projections of energy demand and energy mix are based on McKinsey Energy Insights' proprietary Global Energy Perspective (GEP). This provides a detailed and flexible outlook on the global energy landscape until 2050. It gives insights on upcoming trends, underlying drivers, and possible discontinuities from the short to the long term. The projections are based on detailed energy demand models for different sectors in the energy system, including light vehicles, medium and heavy-sized vehicles, marine, aviation, chemicals, iron and steel, other industry, buildings (residential and commercial), and a separate module projecting the power generation mix. This leads to projections of energy demand by sector, country and fuel. The methodology for each sector defines how underlying drivers such as GDP and population affect energy demand, also taking into account technological, regulatory and behavioral trends. Details are available at **https://www.mckinseyenergyinsights.com/services/market-intelligence/reports/global-energy-perspective/**

For our demand scenarios, we created scenarios around the efficiency potential of a range of uses. Details of these are as follows.

Impact of technology on transportation

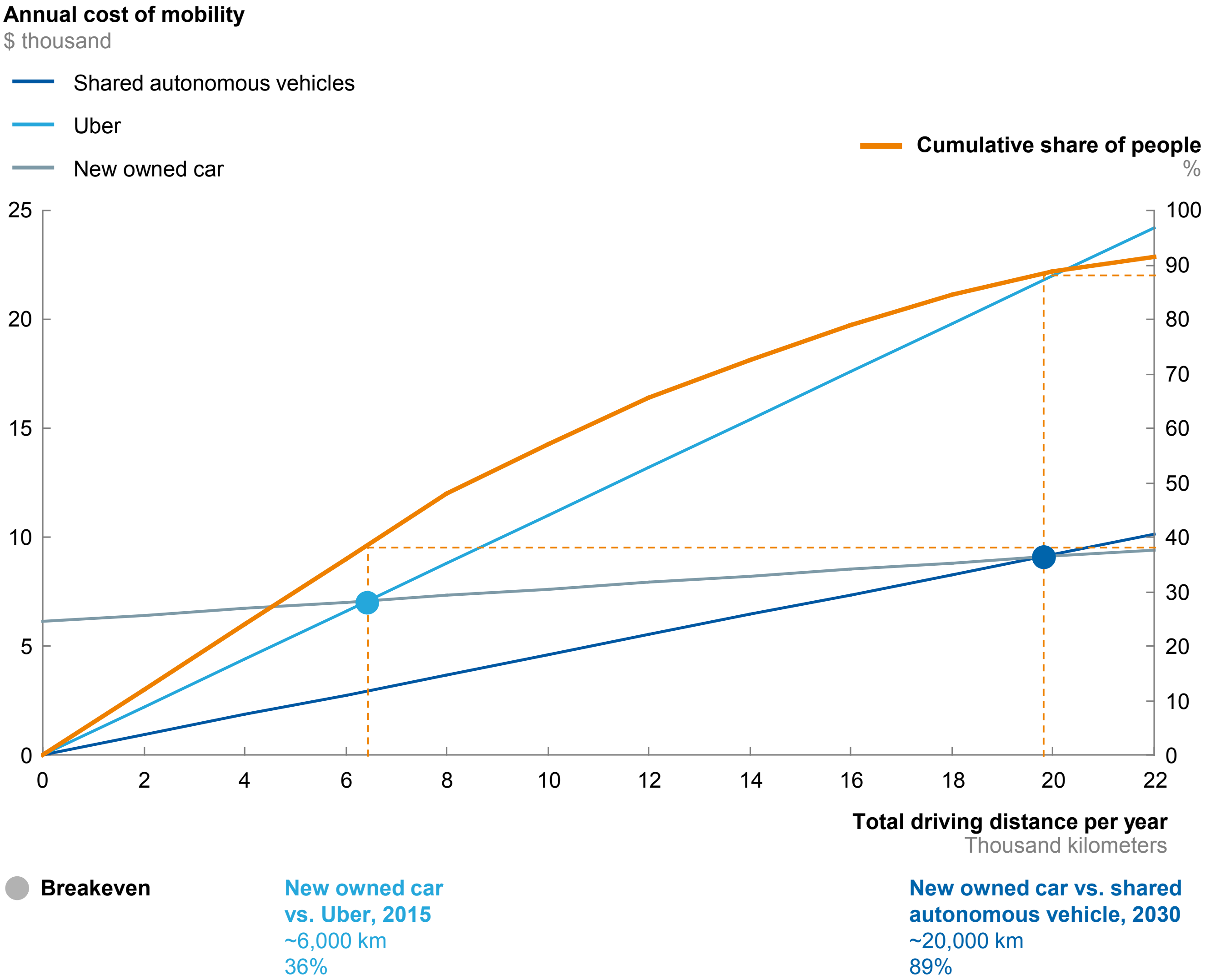
Given the importance of transportation as a major consumer of oil, and the trends leading to changed behavior, including with ride sharing and autonomous or electric vehicles, we built an automotive disruption model to understand the impact of different adoption rates of technology in this sector.

Light-duty vehicles

Technology impact on fuel economy in the light-duty automotive sector was assessed using a combination of sources. Basic fuel economy projections for internal combustion engines were held constant between the moderate adoption and accelerated adopting scenarios, and the projections were based on known policy standards within the major regions. In addition, assumptions about the relationship of economic growth and the number of vehicles and kilometers traveled within a region were held constant between the two scenarios. Variation between the two scenarios was created by varying assumptions about the penetration rates of electric vehicles in annual car sales at a regional level and the adoption rates of car sharing and carpooling at the level of urban vs. rural and developed vs. developing countries, and the level of autonomous vehicle adoption at the same sub-segment level. Car pooling and ride sharing affect the number of miles or kilometers driven per person, and thus are an important variable for oil consumption, while the level of autonomous vehicle adoption affects fuel efficiency. In addition, a time lag was introduced for developing countries, i.e., India will lag behind China, and Africa will lag behind India, which was held constant between the two scenarios. One of the findings of our scenario analysis is that, in 2030, using shared autonomous vehicles will be a more cost effective solution than owning a private car for almost 90 percent of the urban population. (Exhibit A1). In general, our assumptions were aligned with projections by McKinsey & Company's automotive practice, as described in the *McKinsey Quarterly* article "Disruptive trends that will transform the auto industry" (January 2016).

Exhibit A1

For about 90 percent of the urban population in 2030, using shared autonomous vehicles could be a more cost-effective solution than owning and driving a private car



SOURCE: McKinsey Global Institute analysis

Heavy-duty vehicles

Fuel economy improvement factors for the moderate adoption scenario were taken from the historic rates of fuel economy improvements in the sector. For the accelerated technology scenario, adoption of additional technologies which boost fuel economy were assumed to occur earlier. Technologies included were in the areas of diesel engine performance, vehicle design, telematics (real-time monitoring of the fleet), and automation.

Aviation

In the aviation sector, demand for aviation travel was modeled using underlying economic growth and expected intensity of aviation travel in the future. This underlying demand was held constant in both scenarios. Fuel economy improvements in the moderate adoption scenario were assumed to be in line with historical improvement rates (1.4 percent per year). In the technology acceleration scenario, fuel economy improvements were assumed to reach a higher level of 2 percent per year, in line with the targets set forth by industry groups, and in agreement with the potential for technology to improve fuel economy based on industry reports and expert input.

Efficiency potential in buildings

To identify the potential impact of technologies on efficiency in buildings, we expanded on prior work by the McKinsey Global Institute, and specifically on two MGI reports: *Resource Revolution: Meeting the world's energy, materials, food, and water needs* (November 2011), and *The Internet of Things: Mapping the value beyond the hype* (June 2015). Baseline data on demand in buildings was taken from the International Energy Agency. We assessed the technology impact on a sub-segment basis that included HVAC space cooling and heating, lighting, and water heating. We assumed different adoption rates for developed and developing countries based on prior research or expert input. We adjusted the results for the energy mix within a country. For example, we lowered the weighting of efficiency factors in countries using bio-feedstocks such as wood or charcoal, in their buildings. Based on adoption rates and impact of each technology, we calculated efficiency factors for every year, which were then used an input in the Global Energy Perspective model. Efficiency factors were developed for the two scenarios assuming different rates of adoption in different regions.

Efficiency potential in industry

For our moderate technology adoption case, we selected efficiency factors in industry that are aligned with historic trends. For our technology acceleration scenario, we assumed rapid adoption of Internet of Things technology in industrial settings, as per the 2015 MGI report on the Internet of Things and independent research of case studies. Adoption rates of the technology were fitted to a smooth S-curve starting from current adoption rates to full potential by 2035. We used the 2015 MGI report's definition of full potential. We weighted the impact of the Internet of Things based on the industry intensity of the sub-sector, with a 20 percent reduction potential impact assumed for energy intensive sub-sectors and a 5 percent reduction potential assumed for non-energy intense sub-sectors.

Renewable penetration rates

Projections about the growth of renewable power for our moderate technology adoption case are based on policy plans in major countries and regions and expectations from third party reports and experts.

In the technology acceleration scenario, we assume that renewable energy technology will continue to see costs decline at similar learning curve rates as the historic past, that is, at about 20 percent for every doubling of capacity installed. Based on this cost decline expectation, in most regions, renewable power generation (onshore wind and utility-scale solar PV) could become more competitive than the marginal cost of fossil fuel power (coal or natural gas) in most regions of the world by 2025-2030. Based on this, we assumed renewable power installations will occur faster than the moderate technology adoption scenario post-2025. We targeted a penetration level equal to the average capacity factor in the country or region, or double the rate of growth of the moderate case, whichever was smaller. The country/region segmentation is: Canada, China, Europe, India, Japan, Russia, South Korea, United States, and Rest of World. The resulting global penetration rates—that is, the percentage of electricity provided by renewable sources-- were 10 percent for solar PV and 26 percent for wind. We did not make any assumptions about storage availability. We also assumed no constraints to growth in the major regions, since our research and interviews with external experts revealed few definitive constraints on a 20-year time horizon.

Calculation of opportunity size from changes to energy demand

We calculated the size of the opportunity from technology adoption in the moderate case and the technology acceleration case. The opportunity size was based on the difference in primary energy demand between each of these scenarios and a reference case scenario. The reference case scenario used the same macroeconomic assumptions, but assumed no further technology adoption beyond current levels. The difference in primary energy demand between the moderate case and the reference and between the technology acceleration case and the reference was calculated for each of the major fossil fuels: oil, thermal coal, and natural gas. Demand in terajoules was then converted into a traded denomination of the fuel: barrels for oil, million British thermal units for natural gas, and metric tonnes for thermal coal. Prices used in the calculation were taken from the annual global benchmark price as found in the World Bank Commodity Price Data (Pink Sheets): $52.75/bbl Brent crude for oil, $7.26/MMBtu European natural gas, and $57.51/tonne Australian price for thermal coal.

4. INCREASED PRODUCTIVITY OF RESOURCE PRODUCERS

To assess the potential opportunity of technology to improve the productivity within the resource sector, we built bottoms-up models for each of the five sub-sectors analyzed. Our basic methodology was to assess the cost improvement potential due to technology on a per-unit basis, based on the average cost structure in the industry, and multiply by the industry volume of production in 2035 to calculate the opportunity size. To create the moderate case and technology acceleration scenarios, we varied the adoption rate assumptions. The moderate case adoption is based on extension of existing trends. The technology acceleration case assumes aggressive adoption of technologies across all operations where it would make sense to do so, for example, the technologies are not adopted where there are geological constraints. We also factored in potential limitations on capital investment, for example in coal due to declining demand. In each sub-sector, a current-state cost structure was developed using either proprietary McKinsey and Company data or available third-party estimates. We focused on a range of technologies including robotics, artificial intelligence, data analytics, and Internet of Things. We also looked at sector-specific technologies such as leaching and, where relevant, refer to them in the text. For each type of technology, the impact it would have on the cost structure was completed at a sub-cost level, such as for labor, electricity, overhead, etc. The assumed impact of a specific technology was developed using publicly available case studies or expert input based on experience in the field. We developed a range for the impact potential based on the uncertainty in the source information and calibrated using expert input. All impact values are kept in 2015 dollars.

Oil and gas

We developed a baseline cost structure for the oil and gas sector using data from the Wood MacKenzie projects database. We calculated global average costs on a per-barrel of oil equivalent basis. Projects were segmented according to resource archetypes: conventional, shallow water, deep water/ultra-deep water, heavy oil, oil sands mined, oil sands in situ, and unconventional. We only considered projects as oil if more than 50 percent of their production on a barrel of oil equivalents basis was classified as liquids. The converse was used to assign projects as natural gas plays.

The cost structure for the projects was broken down into capital expenditure and operating expenditure categories. The capital expenditure categories were drilling, processing equipment, production facilities, subsea, and other. For operating expenditure, the categories were field fixed, field variable, and other. We assessed the impact of applying a new technology by estimating the cost reduction potential by resource archetype by cost category. All technology levers then had a multiplicative effect on the individual cost category. Impact estimates came from a combination of reported case studies or expert estimates. Impact was assumed to be 100 percent for all greenfield developments. Brownfield oil projects were assumed to have only 50 percent value capture in operating expenditure cost categories and a 5 percent value capture in all capital expenditure categories except for drilling, as existing design and previously installed equipment would limit technology applicability.

Thermal coal, iron ore, and copper

We developed baseline cost structures for thermal coal, iron ore, and copper from independent data sources. For thermal coal, we used the proprietary McKinsey Basic Materials Institute seaborne thermal coal cost curve. The cost structure of mines was segmented into the following cost categories: electricity, diesel, labor, consumables, other, general administration, freight, treatment charge and refining charge, and royalties.

For iron ore, we used the McKinsey Basic Materials Institute iron ore cost curve. For copper we used proprietary cost curve data from MineSpans, a McKinsey Solution. The cost structure for copper was divided into four archetypes: high-cost country open pit, high-cost country underground, low-cost country open pit, and low-cost country underground.

As with oil and gas, the impact of individual technology levers was estimated along these cost categories. The impact of technology levers was combined in a multiplicative fashion. Where noted in the text, the impact of technology on the sector has been analyzed using single point analyses, such as the impact of automotive technology on the steel sector.

5. CALCULATION OF DEMAND OUTLOOK FOR FOCUS COMMODITIES

The demand outlook for our five focus commodities is discussed in Chapter 3.

Demand for oil, natural gas, and coal

Demand forecasts for energy commodities (oil, natural gas, and coal) were generated for the moderate case and technical acceleration case scenarios as described in the Energy Demand section above, based on the Energy Insights Global Energy Perspective.

Demand for iron ore and copper

Copper demand projections are based on projecting correlations between copper demand, economic growth conditions, population growth, and sub-sector growth in a region (e.g., infrastructure build out, automobile sales, etc.). We adjusted correlations from historic trends based on expert input. Ranges for recycling and scrap rates, and substitution rates are based on historic developments in a region (e.g., pool of copper in use) and historic precedent in other regions. Rates of decline and capacity expansions are based on historic trends in the sector and announced changes in capacity, such as closures and openings planned.

We developed initial projections for steel demand using the previously mentioned growth forecast from McKinsey's global growth model, population projections from the United Nations, and steel intensity factors based on current trends and extrapolated with calibration from expert estimates. We then developed iron ore projections based on assumptions of product mix, and recycling and scrap rates based on current trends calibrated with expert estimates at the regional level.

Oil fracturing drilling rig at dusk.

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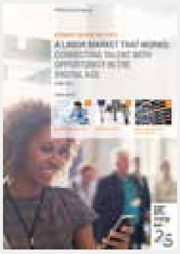

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