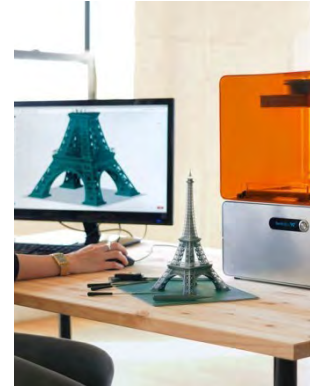
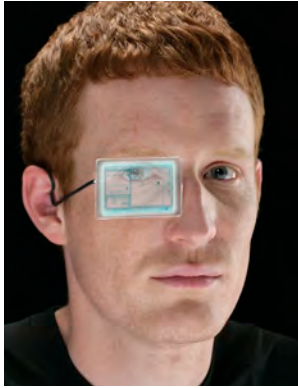


McKinsey Global Institute



May 2013

Disruptive technologies: Advances that will transform life, business, and the global economy



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The McKinsey Global Institute (MGI), the business and economics research arm of McKinsey & Company, was established in 1990 to develop a deeper understanding of the evolving global economy. Our goal is to provide leaders in the commercial, public, and social sectors with the facts and insights on which to base management and policy decisions.

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MGI is led by McKinsey & Company directors Richard Dobbs and James Manyika. Yougang Chen, Michael Chui, Susan Lund, and Jaana Remes serve as MGI principals. Project teams are led by a group of senior fellows and include consultants from McKinsey’s offices around the world. These teams draw on McKinsey’s global network of partners and industry and management experts. In addition, leading economists, including Nobel laureates, act as research advisers.

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Disruptive technologies: Advances that will transform life, business, and the global economy

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Preface

Technology is moving so quickly, and in so many directions, that it becomes challenging to even pay attention—we are victims of “next new thing” fatigue. Yet technology advancement continues to drive economic growth and, in some cases, unleash disruptive change. Economically disruptive technologies—like the semiconductor microchip, the Internet, or steam power in the Industrial Revolution—transform the way we live and work, enable new business models, and provide an opening for new players to upset the established order. Business leaders and policy makers need to identify potentially disruptive technologies, and carefully consider their potential, before these technologies begin to exert their disruptive powers in the economy and society.

In this report, the McKinsey Global Institute (MGI) assesses the potential reach and scope, as well as the potential economic impact and disruption, of major rapidly advancing technology areas. Through extensive research, we sort through the noise to identify 12 technology areas with the potential for massive impact on how people live and work, and on industries and economies. We also attempt to quantify the potential economic impact of each technology across a set of promising applications in 2025.

By definition such an exercise is incomplete—technology and innovations always surprise. The potential applications we consider reflect what McKinsey experts and respected leaders in industry and academia who aided our research believe are illustrative of emerging applications over the next decade or two and provide a good indication of the size and shape of the impact that these applications could have. The combined potential economic impact by 2025 from the applications of the 12 technologies that we have sized may be denominated in the tens of trillions of dollars per year. Some of this economic potential will end up as consumer surplus; a substantial portion of this economic potential will translate into new revenue that companies will capture and that will contribute to GDP growth. Other effects could include shifts in profit pools between companies and industries.

Our goal in pursuing this research is not to make predictions, either about the specific applications or the specific sizes of impact. Rather we hope this report will act as a guide for leaders to use as they consider the reach and scope of impact, as well as the types of impacts that these disruptive technologies could have for the growth and performance of their organizations. We fully expect and hope others will build on and enrich this research, as we plan to do. As a companion piece to this research on disruptive technologies, we have updated prior work on business trends enabled by information technologies, which will be available for download at the MGI website (www.mckinsey.com/mgi).

In any case, we believe that these technologies will have large and disruptive impact. More importantly, the results of our research show that business leaders and policy makers—and society at large—will confront change on many fronts: in the way businesses organize themselves, how jobs are defined, how we use technology to interact with the world (and with each other), and, in the case of

next-generation genomics, how we understand and manipulate living things. There will be disruptions to established norms, and there will be broad societal challenges. Nevertheless, we see considerable reason for optimism. Many technologies on the horizon offer immense opportunities. We believe that leaders can seize these opportunities, if they start preparing now.

This work was led by James Manyika, an MGI director in San Francisco, and Michael Chui, an MGI principal, working closely with McKinsey directors Jacques Bughin and Peter Bisson. We are particularly indebted to our team leaders—Alex Marrs, who managed the project, and Joi Danielson, who co-lead a portion of the research. The project team included Hyungpyo Choi, Shalabh Gupta, Tim Wegner, Angela Winkle, and Sabina Wizander. Geoffrey Lewis provided editorial support, Karla Arias assisted with research, and we thank the MGI production and communication staff: Marisa Carder, Julie Philpot, Gabriela Ramirez, and Rebeca Robboy.

We thank McKinsey experts whose insight and guidance were critical to our work, in particular directors Matt Rogers on oil and gas exploration and recovery, Stefan Heck on renewable energy, Philip Ma on genomics, and Mona Mourshed on education and training. Roger Roberts, a principal in our Business Technology Office, provided multiple insights across various areas of technology. Katy George, a director in the North American Operations Practice, provided expertise on manufacturing, as did Lou Rassey, a principal in the practice. Susan Lund, an MGI principal, provided insight on the changing nature of work and on energy. We were assisted by many experts in our Business Technology Office, including Steve Cheng and Brian Milch, as well as Bryan Hancock from the Public Sector Practice and Jimmy Sarakatsannis from the Social Sector Practice. We also thank Jonathan Ablett, Sree Ramaswamy, and Vivien Singer for their help on many topics.

We are grateful to our external advisers Hal R. Varian, chief economist at Google and emeritus professor in the School of Information, the Haas School of Business and the Department of Economics at the University of California at Berkeley; Erik Brynjolfsson, Schussel Family professor of management at the MIT Sloan School of Management, director of the MIT Center for Digital Business, and research associate at the National Bureau of Economic Research; and Martin Baily, senior fellow in the Economic Studies Program and Bernard L. Schwartz Chair in Economic Policy Development at the Brookings Institution.

This work benefited from the insight of many technology and business thought leaders, including Chamath Palihapitiya, founder and managing partner of The Social+Capital Partnership and a former Facebook executive; Eric Schmidt, executive chairman of Google; and Padmasree Warrior, chief technology and strategy officer of Cisco. We also thank McKinsey alumni Jennifer Buechel, Rob Jenks, and David Mann, as well as Vivek Wadhwa, vice president of innovation and research at Singularity University; and Ann Winblad, managing director of Hummer Winblad Venture Partners. We thank David Kirkpatrick, CEO of Techonomy; and Paddy Cosgrave, founder of F.ounders.

McKinsey colleagues from many practice areas gave generously of their time and expertise to guide our analyses for each technology. Dan Ewing, Ken Kajji, Christian Kraus, Richard Lee, Fredrik Lundberg, Daniel Pachtod, and Remi Said

were our experts in mobile Internet technology. For automation of knowledge work, we received input from Rickard Carlsson, Alex Ince-Cushman, Alex Kazaks, Nathan Marston, and Chad Wegner.

Our McKinsey experts on the Internet of Things were Mike Greene, Aditi Jain, Nakul Narayan, Jeffrey Thompson, and Peter Weed. Cloud computing insights were provided by Brad Brown, Abhijit Dubey, Lorelei Osborn, Naveen Sastry, Kara Sprague, Irina Starikova, and Paul Willmott. Peter Groves, Craig Melrose, Murali Naidu and Jonathan Tilley provided expertise on advanced robotics. For our research on next-generation genomics, we called on Myoung Cha, Nicolas Denis, Lutz Goedde, Samarth Kulkarni, Derek Neilson, Mark Patel, Roberto Paula, and Pasha Sarraf. In autonomous and near-autonomous vehicles, our experts were Nevin Carr, Matt Jochim, Gustav Lindström, Cody Newman, John Niehaus, and Benno Zerlin.

For expertise on energy storage, we called on McKinsey experts Jeremiah Connolly, Mark Faist, Christian Gschwandtner, Jae Jung, Colin Law, Michael Linders, Farah Mandich, Sven Merten, John Newman, Octavian Puzderca, Ricardo Reina, and Kyungyeol Song. In 3D printing, Bartek Blaike, Tobias Geisbüsch, and Christoph Sohns provided expertise. Helen Chen, Nathan Flesher, and Matthew Veves were our experts on advanced materials.

For expert insight on advanced oil and gas exploration and recovery, we relied on Abhijit Akerkar, Drew Erdmann, Bob Frei, Sara Hastings-Simon, Peter Lambert, Ellen Mo, Scott Nyquist, Dickon Pinner, Joe Quoyeser, Occo Roelofsen, Wombi Rose, Ed Schneider, Maria Fernanda Souto, and Antonio Volpin. In renewable energy, our experts were Ian Banks, Joris de Boer, Sonam Handa, Yunzhi Li, Jurriaan Ruys, Raman Sehgal, and Johnson Yeh.

This report is part of our ongoing work about the impact of technology on the economy. Our goal is to provide the fact base and insights about important technological developments that will help business leaders and policy makers develop appropriate strategies and responses. As with all of MGI's work, this report has not been sponsored in any way by any business, government, or other institution.

Richard Dobbs

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Seoul

James Manyika

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Connecting rate of improvement and reach today ...

\$5 million vs. \$400

Price of the fastest supercomputer in 1975¹
and an iPhone 4 with equal performance

230+ million

Knowledge workers in 2012

\$2.7 billion, 13 years

Cost and duration of the Human Genome Project,
completed in 2003

300,000+

Miles driven by Google's autonomous cars
with only one accident (human error)

3x

Increase in efficiency of
North American gas wells
between 2007 and 2011

85%

Drop in cost per watt of a solar
photovoltaic cell since 2000

¹ For CDC-7600, considered the world's fastest computer from 1969 to 1975; equivalent to \$32 million in 2013 at an average inflation rate of 4.3 percent per year since launch in 1969.

... with economic potential in 2025

2–3 billion

More people with access to the Internet in 2025

\$5–7 trillion

Potential economic impact by 2025
of automation of knowledge work

\$100, 1 hour

Cost and time to sequence a human genome
in the next decade²

1.5 million

Driver-caused deaths from car accidents in 2025,
potentially addressable by autonomous vehicles

100–200%

Potential increase in North American oil
production by 2025, driven by hydraulic
fracturing and horizontal drilling

16%

Potential share of solar and wind in
global electricity generation by 2025³

² Derek Thompson, "IBM's killer idea: The \$100 DNA-sequencing machine," *The Atlantic*, November 16, 2011.

³ Assuming continued cost declines in solar and wind technology and policy support for meeting the global environmental target of CO₂ concentration lower than 450 ppm by 2050.

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Disruptive technologies at a glance:
Word cloud of report contents¹



¹ www.wordle.net; McKinsey Global Institute analysis.

Executive summary

The parade of new technologies and scientific breakthroughs is relentless and is unfolding on many fronts. Almost any advance is billed as a breakthrough, and the list of “next big things” grows ever longer. Yet some technologies do in fact have the potential to disrupt the status quo, alter the way people live and work, rearrange value pools, and lead to entirely new products and services. Business leaders can’t wait until evolving technologies are having these effects to determine which developments are truly big things. They need to understand how the competitive advantages on which they have based strategy might erode or be enhanced a decade from now by emerging technologies—how technologies might bring them new customers or force them to defend their existing bases or inspire them to invent new strategies.

Policy makers and societies need to prepare for future technology, too. To do this well, they will need a clear understanding of how technology might shape the global economy and society over the coming decade. They will need to decide how to invest in new forms of education and infrastructure, and figure out how disruptive economic change will affect comparative advantages. Governments will need to create an environment in which citizens can continue to prosper, even as emerging technologies disrupt their lives. Lawmakers and regulators will be challenged to learn how to manage new biological capabilities and protect the rights and privacy of citizens.

Many forces can bring about large-scale changes in economies and societies—demographic shifts, labor force expansion, urbanization, or new patterns in capital formation, for example. But since the Industrial Revolution of the late 18th and early 19th centuries, technology has had a unique role in powering growth and transforming economies. Technology represents new ways of doing things, and, once mastered, creates lasting change, which businesses and cultures do not “unlearn.” Adopted technology becomes embodied in capital, whether physical or human, and it allows economies to create more value with less input. At the same time, technology often disrupts, supplanting older ways of doing things and rendering old skills and organizational approaches irrelevant. These economically disruptive technologies are the focus of our report.¹

We view technology both in terms of potential economic impact and capacity to disrupt, because we believe these effects go hand-in-hand and because both are of critical importance to leaders. As the early 20th-century economist Joseph Schumpeter observed, the most significant advances in economies are often accompanied by a process of “creative destruction,” which shifts profit pools, rearranges industry structures, and replaces incumbent businesses. This process is often driven by technological innovation in the hands of entrepreneurs. Schumpeter describes how the Illinois Central railroad’s high-speed freight

¹ Recent reports by the McKinsey Global Institute have analyzed how changes in labor forces, global financial markets, and infrastructure investment will shape economies and influence growth in coming years. See, for example, *The world at work: Jobs, pay, and skills for 3.5 billion people*, McKinsey Global Institute, June 2012.

service enabled the growth of cities yet disrupted established agricultural businesses. In the recent past, chemical-based photography—a technology that dominated for more than a century and continued to evolve—was routed by digital technology in less than 20 years. Today the print media industry is in a life-and-death struggle to remain relevant in a world of instant, online news and entertainment.

Some economists question whether technology can still deliver the kind of wide-ranging, profound impact that the introduction of the automobile or the semiconductor chip had, and point to data showing slowing productivity growth in the United States and the United Kingdom—often early adopters of new technology—as evidence. While we agree that significant challenges lie ahead, we also see considerable reason for optimism about the potential for new and emerging technologies to raise productivity and provide widespread benefits across economies. Achieving the full potential of promising technologies while addressing their challenges and risks will require effective leadership, but the potential is vast. As technology continues to transform our world, business leaders, policy makers, and citizens must look ahead and plan.

Today, we see many rapidly evolving, potentially transformative technologies on the horizon—spanning information technologies, biological sciences, material science, energy, and other fields. The McKinsey Global Institute set out to identify which of these technologies could have massive, economically disruptive impact between now and 2025. We also sought to understand how these technologies could change our world and how leaders of businesses and other institutions should respond. Our goal is not to predict the future, but rather to use a structured analysis to sort through the technologies with the potential to transform and disrupt in the next decade or two, and to assess potential impact based on what we can know today, and put these promising technologies in a useful perspective. We offer this work as a guide for leaders to anticipate the coming opportunities and changes.

IDENTIFYING THE TECHNOLOGIES THAT MATTER

The noise about the next big thing can make it difficult to identify which technologies truly matter. Here we attempt to sort through the many claims to identify the technologies that have the greatest potential to drive substantial economic impact and disruption by 2025 and to identify which potential impacts leaders should know about. Important technologies can come in any field or emerge from any scientific discipline, but they share four characteristics: high rate of technology change, broad potential scope of impact, large economic value that could be affected, and substantial potential for disruptive economic impact. Many technologies have the potential to meet these criteria eventually, but leaders need to focus on technologies with potential impact that is near enough at hand to be meaningfully anticipated and prepared for. Therefore, we focused on technologies that we believe have significant potential to drive economic impact and disruption by 2025.

- **The technology is rapidly advancing or experiencing breakthroughs.** Disruptive technologies typically demonstrate a rapid rate of change in capabilities in terms of price/performance relative to substitutes and alternative approaches, or they experience breakthroughs that drive accelerated rates of change or discontinuous capability improvements. Gene-sequencing technology, for example, is advancing at a rate even faster than computer

processing power and could soon make possible inexpensive desktop sequencing machines. Advanced materials technology is experiencing significant breakthroughs, from the first artificial production of graphene (a nanomaterial with extraordinary properties including strength and conductivity) in 2004, to IBM's creation of the first graphene-based integrated circuit in 2011.²

- **The potential scope of impact is broad.** To be economically disruptive, a technology must have broad reach—touching companies and industries and affecting (or giving rise to) a wide range of machines, products, or services. The mobile Internet, for example, could affect how five billion people go about their lives, giving them tools to become potential innovators or entrepreneurs—making the mobile Internet one of our most impactful technologies. And the Internet of Things technology could connect and embed intelligence in billions of objects and devices all around the world, affecting the health, safety, and productivity of billions of people.
- **Significant economic value could be affected.** An economically disruptive technology must have the potential to create massive economic impact. The value at stake must be large in terms of profit pools that might be disrupted, additions to GDP that might result, and capital investments that might be rendered obsolete. Advanced robotics, for example, has the potential to affect \$6.3 trillion in labor costs globally. Cloud technology has the potential to improve productivity across \$3 trillion in global enterprise IT spending, as well as enabling the creation of new online products and services for billions of consumers and millions of businesses alike.
- **Economic impact is potentially disruptive.** Technologies that matter have the potential to dramatically change the status quo. They can transform how people live and work, create new opportunities or shift surplus for businesses, and drive growth or change comparative advantage for nations. Next-generation genomics has the potential to transform how doctors diagnose and treat cancer and other diseases, potentially extending lives. Energy storage technology could change how, where, and when we use energy. Advanced oil and gas exploration and recovery could fuel economic growth and shift value across energy markets and regions.

To reach our final list of a dozen economically disruptive technologies, we started with more than 100 possible candidates drawn from academic journals, the business and technology press, analysis of published venture capital portfolios, and hundreds of interviews with relevant experts and thought leaders. We assessed each candidate according to our four criteria, eliminating some that were too narrow and others that seem unlikely to start having significant economic impact within our time period. We believe that the technologies we identify have potential to affect billions of consumers, hundreds of millions of workers, and trillions of dollars of economic activity across industries. The 12 potentially economically disruptive technologies are listed in Exhibit E1.

In Exhibit E2, we show representative metrics of how each technology fulfills our criteria for speed, range of impact, and potential scale of economic value that could be affected. The values in this chart serve to characterize the broad

2 Yu-Ming Lin et al., "Wafer-scale graphene integrated circuit," *Science*, volume 332, number 6035, June 2011.

potential of these technologies to drive economic impact and disruption and do not represent our estimates of the potential economic impact by 2025, which we describe in Exhibit E3 below. These numbers are not exhaustive; they are indicative and do not represent all possible applications or potential impacts for each technology.

Exhibit E1

Twelve potentially economically disruptive technologies










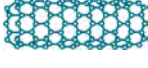











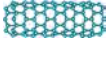


	Mobile Internet	Increasingly inexpensive and capable mobile computing devices and Internet connectivity
	Automation of knowledge work	Intelligent software systems that can perform knowledge work tasks involving unstructured commands and subtle judgments
	The Internet of Things	Networks of low-cost sensors and actuators for data collection, monitoring, decision making, and process optimization
	Cloud technology	Use of computer hardware and software resources delivered over a network or the Internet, often as a service
	Advanced robotics	Increasingly capable robots with enhanced senses, dexterity, and intelligence used to automate tasks or augment humans
	Autonomous and near-autonomous vehicles	Vehicles that can navigate and operate with reduced or no human intervention
	Next-generation genomics	Fast, low-cost gene sequencing, advanced big data analytics, and synthetic biology ("writing" DNA)
	Energy storage	Devices or systems that store energy for later use, including batteries
	3D printing	Additive manufacturing techniques to create objects by printing layers of material based on digital models
	Advanced materials	Materials designed to have superior characteristics (e.g., strength, weight, conductivity) or functionality
	Advanced oil and gas exploration and recovery	Exploration and recovery techniques that make extraction of unconventional oil and gas economical
	Renewable energy	Generation of electricity from renewable sources with reduced harmful climate impact

Exhibit E2

Speed, scope, and economic value at stake of 12 potentially economically disruptive technologies

		Illustrative rates of technology improvement and diffusion	Illustrative groups, products, and resources that could be impacted ¹	Illustrative pools of economic value that could be impacted ²
	Mobile Internet	\$5 million vs. \$400² Price of the fastest supercomputer in 1975 vs. that of an iPhone 4 today, equal in performance (MFLOPS) 6x Growth in sales of smartphones and tablets since launch of iPhone in 2007	4.3 billion People remaining to be connected to the Internet, potentially through mobile Internet 1 billion Transaction and interaction workers, nearly 40% of global workforce	\$1.7 trillion GDP related to the Internet \$25 trillion Interaction and transaction worker employment costs, 70% of global employment costs
	Automation of knowledge work	100x Increase in computing power from IBM's Deep Blue (chess champion in 1997) to Watson (Jeopardy winner in 2011) 400+ million Increase in number of users of intelligent digital assistants like Siri and Google Now in past 5 years	230+ million Knowledge workers, 9% of global workforce 1.1 billion Smartphone users, with potential to use automated digital assistance apps	\$9+ trillion Knowledge worker employment costs, 27% of global employment costs
	The Internet of Things	300% Increase in connected machine-to-machine devices over past 5 years 80–90% Price decline in MEMS (microelectromechanical systems) sensors in past 5 years	1 trillion Things that could be connected to the Internet across industries such as manufacturing, health care, and mining 100 million Global machine to machine (M2M) device connections across sectors like transportation, security, health care, and utilities	\$36 trillion Operating costs of key affected industries (manufacturing, health care, and mining)
	Cloud technology	18 months Time to double server performance per dollar 3x Monthly cost of owning a server vs. renting in the cloud	2 billion Global users of cloud-based email services like Gmail, Yahoo, and Hotmail 80% North American institutions hosting or planning to host critical applications on the cloud	\$1.7 trillion GDP related to the Internet \$3 trillion Enterprise IT spend
	Advanced robotics	75–85% Lower price for Baxter ³ than a typical industrial robot 170% Growth in sales of industrial robots, 2009–11	320 million Manufacturing workers, 12% of global workforce 250 million Annual major surgeries	\$6 trillion Manufacturing worker employment costs, 19% of global employment costs \$2–3 trillion Cost of major surgeries
	Autonomous and near-autonomous vehicles	7 Miles driven by top-performing driverless car in 2004 DARPA Grand Challenge along a 150-mile route 1,540 Miles cumulatively driven by cars competing in 2005 Grand Challenge 300,000+ Miles driven by Google's autonomous cars with only 1 accident (which was human-caused)	1 billion Cars and trucks globally 450,000 Civilian, military, and general aviation aircraft in the world	\$4 trillion Automobile industry revenue \$155 billion Revenue from sales of civilian, military, and general aviation aircraft
	Next-generation genomics	10 months Time to double sequencing speed per dollar 100x Increase in acreage of genetically modified crops, 1996–2012	26 million Annual deaths from cancer, cardiovascular disease, or type 2 diabetes 2.5 billion People employed in agriculture	\$6.5 trillion Global health-care costs \$1.1 trillion Global value of wheat, rice, maize, soy, and barley
	Energy storage	40% Price decline for a lithium-ion battery pack in an electric vehicle since 2009	1 billion Cars and trucks globally 1.2 billion People without access to electricity	\$2.5 trillion Revenue from global consumption of gasoline and diesel \$100 billion Estimated value of electricity for households currently without access
	3D printing	90% Lower price for a home 3D printer vs. 4 years ago 4x Increase in additive manufacturing revenue in past 10 years	320 million Manufacturing workers, 12% of global workforce 8 billion Annual number of toys manufactured globally	\$11 trillion Global manufacturing GDP \$85 billion Revenue from global toy sales
	Advanced materials	\$1,000 vs. \$50 Difference in price of 1 gram of nanotubes over 10 years 115x Strength-to-weight ratio of carbon nanotubes vs. steel	7.6 million tons Annual global silicon consumption 45,000 metric tons Annual global carbon fiber consumption	\$1.2 trillion Revenue from global semiconductor sales \$4 billion Revenue from global carbon fiber sales
	Advanced oil and gas exploration and recovery	3x Increase in efficiency of US gas wells, 2007–11 2x Increase in efficiency of US oil wells, 2007–11	22 billion Barrels of oil equivalent in natural gas produced globally 30 billion Barrels of crude oil produced globally	\$800 billion Revenue from global sales of natural gas \$3.4 trillion Revenue from global sales of crude oil
	Renewable energy	85% Lower price for a solar photovoltaic cell per watt since 2000 19x Growth in solar photovoltaic and wind generation capacity since 2000	21,000 TWh Annual global electricity consumption 13 billion tons Annual CO ₂ emissions from electricity generation, more than from all cars, trucks, and planes	\$3.5 trillion Value of global electricity consumption \$80 billion Value of global carbon market transactions

1 Not comprehensive; indicative groups, products, and resources only.

2 For CDC-7600, considered the world's fastest computer from 1969 to 1975; equivalent to \$32 million in 2013 at an average inflation rate of 4.3% per year since launch in 1969.

3 Baxter is a general-purpose basic manufacturing robot developed by startup Rethink Robotics.

SOURCE: McKinsey Global Institute analysis

Mobile Internet

In just a few years, Internet-enabled portable devices have gone from a luxury for a few to a way of life for more than one billion people who own smartphones and tablets. In the United States, an estimated 30 percent of Web browsing and 40 percent of social media use are done on mobile devices; by 2015, wireless Web use is expected to exceed wired use. Ubiquitous connectivity and an explosive proliferation of apps are enabling users to go about their daily routines with new ways of knowing, perceiving, and even interacting with the physical world. The technology of the mobile Internet is evolving rapidly, with intuitive interfaces and new formats, including wearable devices. The mobile Internet also has applications across businesses and the public sector, enabling more efficient delivery of many services and creating opportunities to increase workforce productivity. In developing economies, the mobile Internet could bring billions of people into the connected world.

Automation of knowledge work

Advances in artificial intelligence, machine learning, and natural user interfaces (e.g., voice recognition) are making it possible to automate many knowledge worker tasks that have long been regarded as impossible or impractical for machines to perform. For instance, some computers can answer “unstructured” questions (i.e., those posed in ordinary language, rather than precisely written as software queries), so employees or customers without specialized training can get information on their own. This opens up possibilities for sweeping change in how knowledge work is organized and performed. Sophisticated analytics tools can be used to augment the talents of highly skilled employees, and as more knowledge worker tasks can be done by machine, it is also possible that some types of jobs could become fully automated.

The Internet of Things

The Internet of Things—embedding sensors and actuators in machines and other physical objects to bring them into the connected world—is spreading rapidly. From monitoring the flow of products through a factory to measuring the moisture in a field of crops to tracking the flow of water through utility pipes, the Internet of Things allows businesses and public-sector organizations to manage assets, optimize performance, and create new business models. With remote monitoring, the Internet of Things also has great potential to improve the health of patients with chronic illnesses and attack a major cause of rising health-care costs.

Cloud technology

With cloud technology, any computer application or service can be delivered over a network or the Internet, with minimal or no local software or processing power required. In order to do this, IT resources (such as computation and storage) are made available on an as-needed basis—when extra capacity is needed it is seamlessly added, without requiring up-front investment in new hardware or programming. The cloud is enabling the explosive growth of Internet-based services, from search to streaming media to offline storage of personal data (photos, books, music), as well as the background processing capabilities that enable mobile Internet devices to do things like respond to spoken commands to ask for directions. The cloud can also improve the economics of IT for companies and governments, as well as provide greater flexibility and responsiveness. Finally, the cloud can enable entirely new business models, including all kinds of pay-as-you-go service models.

Advanced robotics

For the past several decades, industrial robots have taken on physically difficult, dangerous, or dirty jobs, such as welding and spray painting. These robots have been expensive, bulky, and inflexible—bolted to the floor and fenced off to protect workers. Now, more advanced robots are gaining enhanced senses, dexterity, and intelligence, thanks to accelerating advancements in machine vision, artificial intelligence, machine-to-machine communication, sensors, and actuators. These robots can be easier for workers to program and interact with. They can be more compact and adaptable, making it possible to deploy them safely alongside workers. These advances could make it practical to substitute robots for human labor in more manufacturing tasks, as well as in a growing number of service jobs, such as cleaning and maintenance. This technology could also enable new types of surgical robots, robotic prosthetics, and “exoskeleton” braces that can help people with limited mobility to function more normally, helping to improve and extend lives.

Next-generation genomics

Next-generation genomics marries advances in the science of sequencing and modifying genetic material with the latest big data analytics capabilities. Today, a human genome can be sequenced in a few hours and for a few thousand dollars, a task that took 13 years and \$2.7 billion to accomplish during the Human Genome Project. With rapid sequencing and advanced computing power, scientists can systematically test how genetic variations can bring about specific traits and diseases, rather than using trial and error. Relatively low-cost desktop sequencing machines could be used in routine diagnostics, potentially significantly improving treatments by matching treatments to patients. The next step is synthetic biology—the ability to precisely customize organisms by “writing” DNA. These advances in the power and availability of genetic science could have profound impact on medicine, agriculture, and even the production of high-value substances such as biofuels—as well as speed up the process of drug discovery.

Autonomous and near-autonomous vehicles

It is now possible to create cars, trucks, aircraft, and boats that are completely or partly autonomous. From drone aircraft on the battlefield to Google’s self-driving car, the technologies of machine vision, artificial intelligence, sensors, and actuators that make these machines possible is rapidly improving. Over the coming decade, low-cost, commercially available drones and submersibles could be used for a range of applications. Autonomous cars and trucks could enable a revolution in ground transportation—regulations and public acceptance permitting. Short of that, there is also substantial value in systems that assist drivers in steering, braking, and collision avoidance. The potential benefits of autonomous cars and trucks include increased safety, reduced CO₂ emissions, more leisure or work time for motorists (with hands-off driving), and increased productivity in the trucking industry.

Energy storage

Energy storage technology includes batteries and other systems that store energy for later use. Lithium-ion batteries and fuel cells are already powering electric and hybrid vehicles, along with billions of portable consumer electronics devices. Li-ion batteries in particular have seen consistent increases in performance and reductions in price, with cost per unit of storage capacity declining dramatically over the past decade. Over the next decade, advances in energy storage technology could make electric vehicles (hybrids, plug-in hybrids, and all-electrics) cost competitive with vehicles based on internal-combustion engines. On the power grid, advanced battery storage systems can help with the integration of solar and wind power, improve quality by controlling frequency variations, handle peak loads, and reduce costs by enabling utilities to postpone infrastructure expansion. In developing economies, battery/solar systems have the potential to bring reliable power to places it has never reached.

3D printing

Until now, 3D printing has largely been used by product designers and hobbyists and for a few select manufacturing applications. However, the performance of additive manufacturing machinery is improving, the range of materials is expanding, and prices (for both printers and materials) are declining rapidly—bringing 3D printing to a point where it could see rapid adoption by consumers and even for more manufacturing uses. With 3D printing, an idea can go directly from a 3D design file to a finished part or product, potentially skipping many traditional manufacturing steps. Importantly, 3D printing enables on-demand production, which has interesting implications for supply chains and for stocking spare parts—a major cost for manufacturers. 3D printing can also reduce the amount of material wasted in manufacturing and create objects that are difficult or impossible to produce with traditional techniques. Scientists have even “bioprinted” organs, using an inkjet printing technique to layer human stem cells along with supporting scaffolding.

Advanced materials

Over the past few decades, scientists have discovered ways to produce materials with incredible attributes—smart materials that are self-healing or self-cleaning; memory metals that can revert to their original shapes; piezoelectric ceramics and crystals that turn pressure into energy; and nanomaterials. Nanomaterials in particular stand out in terms of their high rate of improvement, broad potential applicability, and long-term potential to drive massive economic impact. At nanoscale (less than 100 nanometers), ordinary substances take on new properties—greater reactivity, unusual electrical properties, enormous strength per unit of weight—that can enable new types of medicine, super-slick coatings, stronger composites, and other improvements. Advanced nanomaterials such as graphene and carbon nanotubes could drive particularly significant impact. For example, graphene and carbon nanotubes could help create new types of displays and super-efficient batteries and solar cells. Finally, pharmaceutical companies are already progressing in research to use nanoparticles for targeted drug treatments for diseases such as cancer.

Advanced oil and gas exploration and recovery

The ability to extract so-called unconventional oil and gas reserves from shale rock formations is a technology revolution that has been gathering force for nearly four decades. The combination of horizontal drilling and hydraulic fracturing makes it possible to reach oil and gas deposits that were known to exist in the United States and other places but that were not economically accessible by conventional drilling methods. The potential impact of this technology has received enormous attention. With continued improvements, this technology could significantly increase the availability of fossil fuels for decades and produce an immediate boon for energy-intensive industries such as petrochemicals manufacturing. Eventually, improving technology for oil and gas exploration and recovery could even unlock new types of reserves, including coalbed methane, tight sandstones, and methane clathrates (also known as methane hydrates), potentially ushering in another energy “revolution.”

Renewable energy

Renewable energy sources such as solar, wind, hydro-electric, and ocean wave hold the promise of an endless source of power without stripping resources, contributing to climate change, or worrying about competition for fossil fuels. Solar cell technology is progressing particularly rapidly. In the past two decades, the cost of power produced by solar cells has dropped from nearly \$8 per watt of capacity to one-tenth of that amount. Meanwhile, wind power constitutes a rapidly growing proportion of renewable electricity generation. Renewable energy sources such as solar and wind are increasingly being adopted at scale in advanced economies like the United States and the European Union. Even more importantly, China, India, and other emerging economies have aggressive plans for solar and wind adoption that could enable further rapid economic growth while mitigating growing concerns about pollution.

The 12 technologies in our final list do not represent all potentially economically disruptive technologies in 2025. Many of the other advancing technologies that we reviewed are also worth following and thinking about. In our view they do not have the same potential for economic impact and disruption by 2025, but we cannot rule out sudden breakthroughs or other factors, such as new public policies, that might change that (see Box 1, “Other technologies on the radar”).

Box 1. Other technologies on the radar

Some of the technologies that we reviewed, but which did not make our final list, are nonetheless interesting and worthy of consideration. Here we note two groups of these technologies.

Five technologies that nearly made our final list:

- **Next-generation nuclear (fission)** has potential to disrupt the global energy mix but seems unlikely to create significant impact by 2025 given the time frames of current experiments and pilots.
- **Fusion power** also has massive potential, but it is even more speculative than next-generation nuclear fission in terms of both technological maturity and time frame.
- **Carbon sequestration** could have great impact on reducing carbon dioxide (CO₂) concentration in the atmosphere, but despite sustained R&D investment it may not become cost-effective and deployed at scale by 2025.
- **Advanced water purification** could benefit millions of people facing water shortages, but approaches with substantially better economics than currently known approaches may not be operating at scale by 2025.
- **Quantum computing** represents a potentially transformative alternative to digital computers, but the breadth of its applicability and impact remain unclear and the time frame for commercialization is uncertain.

A sampling of other interesting and often hyped candidates that were not close in the final running:

- **Private space flight** is likely to be limited to space tourism and private satellite launches through 2025, though after that, applications such as asteroid mining could drive greater economic impact.
- **OLED / LED lighting** has potential for extensive reach in terms of people affected but seems unlikely to disrupt pools of economic value beyond narrow industries by 2025.
- **Wireless charging** is promising for some applications but overall offers limited impact at high cost. Simple versions exist, but it is not clear that the technology serves an important need versus substitutes such as improved energy storage technology.
- **Flexible displays** have long been in development and could offer exciting new possibilities for the designs of mobile devices and TVs, but on their own seem unlikely to have broad-based disruptive impact by 2025.
- **3D and volumetric displays** have received a lot of attention, but it is not clear that these technologies will drive broad economic impact by 2025.

ESTIMATED POTENTIAL ECONOMIC IMPACT IN 2025 ACROSS SIZED APPLICATIONS

Exhibit E3 shows our estimates of the potential economic impact that select applications of each technology could create in 2025 (see Box 2, “Approach to estimating potential economic impact in 2025”). While these estimates are incomplete by definition, the analysis suggests significant potential impact from even a few possible applications. It is important to note, however, that this economic potential should not be equated with market sizes for these technologies. The economic potential will be captured as consumer surplus as well as in new revenue and GDP growth as companies commercialize these technologies. For company leaders, it is worth noting the great extent to which Internet-based technologies have tended to shift value to consumers; in our work we see that as much as two-thirds of the value created by new Internet offerings has been captured as consumer surplus.³

Moreover, our sizing is not comprehensive: we have estimated the potential economic impact in 2025 of applications that we can anticipate today and which appear capable of affecting large amounts of value. But it is impossible to predict all the ways in which technologies will be applied; the value created in 2025 could be far larger than what we estimate here. Based on our analysis, however, we are convinced that collectively the potential for our sized technologies and applications is huge: taken together and netting out potential overlaps, we find that they have the potential to drive direct economic impact on the order of \$14 trillion to \$33 trillion per year in 2025.

3 *Internet matters: The Net's sweeping impact on growth, jobs, and prosperity*, McKinsey Global Institute, May 2011.

Exhibit E3

Estimated potential economic impact of technologies from sized applications in 2025, including consumer surplus

\$ trillion, annual

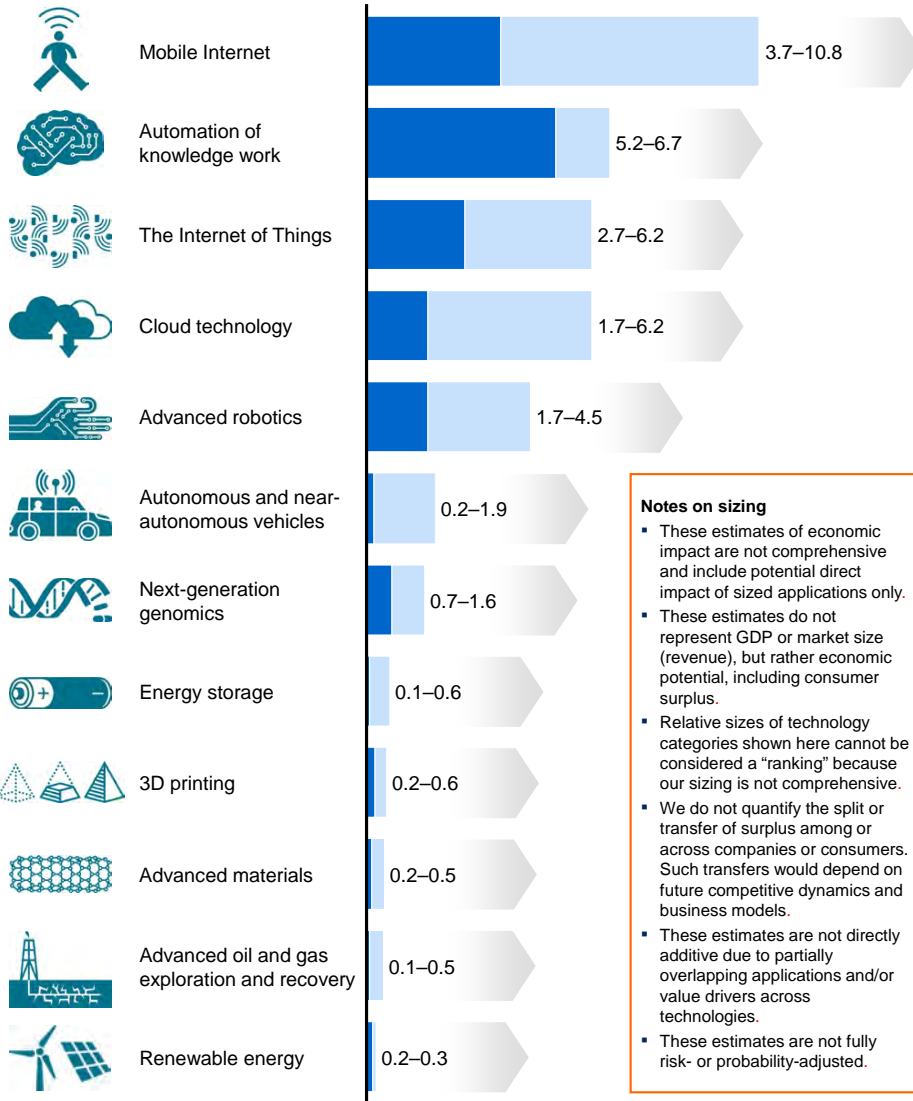
Range of sized potential economic impacts

Low

High

X-Y

Impact from other potential applications (not sized)



Notes on sizing

- These estimates of economic impact are not comprehensive and include potential direct impact of sized applications only.
- These estimates do not represent GDP or market size (revenue), but rather economic potential, including consumer surplus.
- Relative sizes of technology categories shown here cannot be considered a "ranking" because our sizing is not comprehensive.
- We do not quantify the split or transfer of surplus among or across companies or consumers. Such transfers would depend on future competitive dynamics and business models.
- These estimates are not directly additive due to partially overlapping applications and/or value drivers across technologies.
- These estimates are not fully risk- or probability-adjusted.

SOURCE: McKinsey Global Institute analysis

Box 2. Approach to estimating potential economic impact in 2025

We focus on estimating the potential economic impact of 12 technologies across a set of promising applications, based on feasible scenarios for technology advancement, reach, and resulting productivity or value gains that could be achieved by 2025. We focus on estimating the potential (rather than realized) value in 2025 by assuming that addressable barriers to technology adoption and value creation (such as the need for supporting regulations) can be overcome and that reasonable, necessary investments can be made.

Our estimates represent annual value, including consumer surplus, that could be realized in 2025 across sized applications. These estimates are not potential revenue, market size, or GDP impact. We do not attempt to size all of the many possible indirect and follow-on effects. We also do not size possible surplus shifts among companies and industries, or between companies and consumers. Finally, our estimates are not adjusted for risk or probability.

To estimate the potential direct economic impact of technologies by 2025, we first identify applications and drivers of value for each technology. We then define a scope of potential impact for each application (for example, the operating cost base of an industry where the introduction of a technology might alter costs) which we project forward to 2025 to create a hypothetical base case in which the technology under examination is effectively “frozen” or held constant with no technology progress, diffusion, or additional use. We next consider potential rates of technology diffusion and adoption across the estimated scope of impact for the application, taking into account price/performance improvement. Finally, we estimate potential productivity or value gains from each application that could be achieved across our defined scope of impact by 2025 to determine the potential direct economic impact of the use of the technology for this application. In some cases, we use prior McKinsey research to estimate a portion of the additional surplus that could be created by use of technologies such as the Internet. In the case of advanced oil and gas exploration and recovery and renewable energy, we focus on estimating the value of additional output that could be cost-effectively produced using improved technology.

In many cases there could be a lag between the introduction of new technology and its economic impact, owing in part to the need to reconfigure processes to fully capture benefits. We account for this lag by factoring in structural constraints such as the need for supporting infrastructure, up-front investments (for example, the cost of advanced robots), and prevailing industry investment cycles. We do not take into account less tangible barriers such as cultural resistance or political opposition, as these barriers could potentially be overcome by 2025.

We have focused on quantifying the total value from use of each technology because we believe this is a better measure than GDP or other growth accounting metrics for evaluating the potential of a technology to drive transformative impact on people and the economy. GDP, for example, does not include consumer surplus, which is an important portion of the value created from new technology.

SOME OBSERVATIONS

While we evaluated each technology separately and sized their potential economic impacts independently, we did observe some interesting patterns in the results. These observations reflect common traits among economically disruptive technologies. Here we examine a set of overarching implications for stakeholders to consider as they plan for the coming decade of economically disruptive technology.

Information technology is pervasive. Most of the technologies on our list are directly enabled, or enhanced, by information technology. Continuing progress in artificial intelligence and machine learning are essential to the development of advanced robots, autonomous vehicles, and in knowledge work automation tools. The next generation of gene sequencing depends highly on improvements in computational power and big data analytics, as does the process of exploring and tapping new sources of oil and natural gas. 3D printing uses computer generated models and benefits from an online design sharing ecosystem. The mobile Internet, the Internet of Things, and cloud technology are themselves information and communications technologies. Information technologies tend to advance very rapidly, often following exponential trajectories of improvement in cost/performance. Also, information technologies are often characterized by strong network effects, meaning that the value to any user increases as the number of users multiplies. Just as IT creates network effects for users of social media and the mobile Internet, IT-enabled platforms and ecosystems could bring additional value to users of 3D printing or to researchers experimenting with next-generation genomics technology. In a separate report, also released in May 2013, we take a look at how advances in IT are shaping important business trends in the next few years (see Box 3, “Ten IT-enabled business trends for the decade ahead”).

Box 3. Ten IT-enabled business trends for the decade ahead

We have revisited and updated previous perspectives on IT-enabled business trends that appeared in the *McKinsey Quarterly* in 2007 and 2010. These trends are powerful ways in which businesses, organizations, and governments can use information technologies to implement strategy, manage people and assets, alter organizational structures, and build new business models.

These IT-enabled business trends are already driving pervasive impact across thousands of companies and across sectors. These trends include some of the technologies in this report, such as automation of knowledge work. Some technologies in this report, such as cloud computing, underpin IT-enabled business trends.

The report can be downloaded at www.mckinsey.com/mgi.

- **Combinations of technologies could multiply impact.** We see that certain emerging technologies could be used in combination, reinforcing each other and potentially driving far greater impact. For example, the combination of next-generation genomics with advances in nanotechnology has the potential to bring about new forms of targeted cancer drugs. It is possible that the first commercially available nano-electromechanical machines (NEMS), molecule-sized machines, could be used to create very advanced sensors for wearable mobile Internet devices or Internet of Things applications. And automated knowledge work capabilities could help drive dramatic advances across many areas, including next-generation genomics. Another example of symbiotic development exists between advances in energy storage and renewable energy sources; the ability to store electricity created by solar or wind helps to integrate renewables into the power grid. The advances in energy storage that make this possible could benefit, in turn, from advances in nanomaterials for batteries. Similarly, the mobile Internet might never live up to its enormous potential without important advances in cloud computing to enable applications—including tools for automating knowledge work—on mobile devices.
- **Consumers could win big, particularly in the long run.** Many of the technologies on our list have the potential to deliver the lion's share of their value to consumers, even while providing producers with sufficient profits to encourage technology adoption and production. Technologies like next-generation genomics and advanced robotics could deliver major health benefits, not all of which may be usable by health-care payers and providers, many of whom face growing pressure to help improve patient outcomes while also reducing health-care costs. Many technologies will also play out in fiercely competitive consumer markets—particularly on the Internet, where earlier McKinsey research has shown consumers capture the majority of the economic surplus created.⁴ Mobile Internet, cloud technology, and the Internet of Things are prime examples. Also, as technologies are commercialized and come into widespread use, competition tends to shift value to consumers.
- **The nature of work will change, and millions of people will require new skills.** It is not surprising that new technologies make certain forms of human labor unnecessary or economically uncompetitive and create demand for new skills. This has been a repeated phenomenon since the Industrial Revolution: the mechanical loom marginalized home weaving while creating jobs for mill workers. However, the extent to which today's emerging technologies could affect the nature of work is striking. Automated knowledge work tools will almost certainly extend the powers of many types of workers and help drive top-line improvements with innovations and better decision making, but they could also automate some jobs entirely. Advanced robotics could make more manual tasks subject to automation, including in services where automation has had less impact until now. Business leaders and policy makers will need to find ways to realize the benefits of these technologies while creating new, innovative ways of working and providing new skills to the workforce.

4 *Internet matters: The Net's sweeping impact on growth, jobs, and prosperity*, McKinsey Global Institute, May 2011.

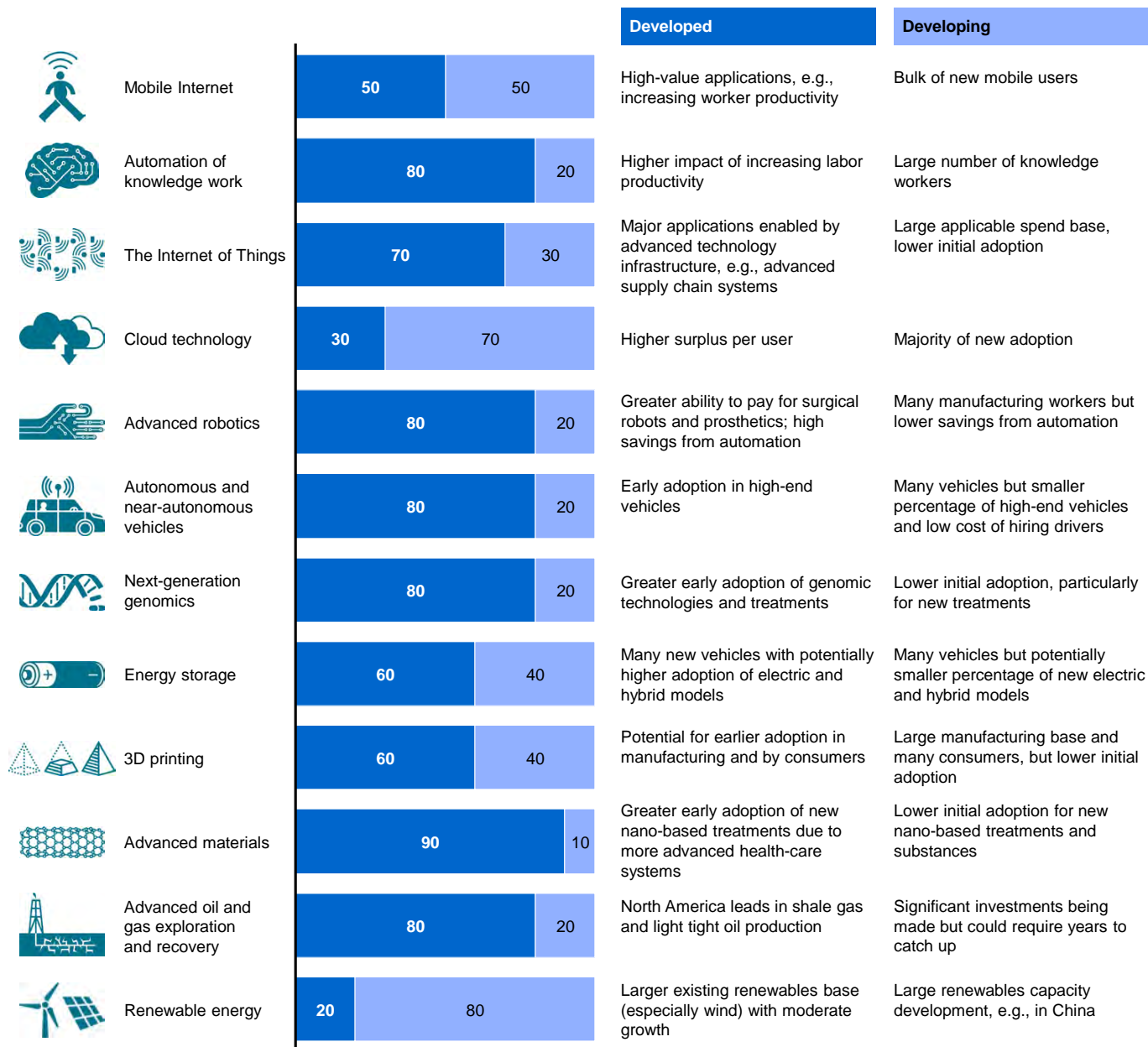
- **The future for innovators and entrepreneurs looks bright.** A new wave of unprecedented innovation and entrepreneurship could be in the offing as a result of falling costs and rapid dissemination of technologies. Many of the technologies discussed in this report will be readily available and may require little or no capital investment. 3D printing, for example, could help “democratize” the design, production, and distribution of products and services. Cloud-based services and mobile Internet devices could help level the playing field, putting IT capabilities and other resources within reach of small enterprises, including in developing nations. Finally, the opportunities and innovation unleashed by a new wave of entrepreneurship could provide new sources of employment.
- **Technology impact differs between advanced and developing economies.** There are many examples: in advanced economies and in the fastest-growing developing economies, the chief value of energy storage could be to make electric vehicles competitive with cars that rely solely on internal-combustion engines. But in the poorest developing economies, advanced batteries can provide millions of people with access to electricity, enabling them to connect to the digital world and join the global economy (Exhibit E4). Advanced robots could be a boon to manufacturing, but could reduce global demand for the low-cost labor that developing economies offer the world and which drives their development. Mobile Internet devices could deliver remarkable new capabilities to many people in advanced economies, but could connect two billion to three billion more people to the digital economy in the developing world. Also, with less legacy infrastructure and fewer investments in old technology, developing economies could leapfrog to more efficient and capable technologies (e.g., adopting the mobile Internet before telephone or cable-TV wiring has been installed, or possibly even adopting solar power plus energy storage solutions before being connected to the power grid).
- **Benefits of technologies may not be evenly distributed.** While each of the technologies on our list has potential to create significant value, in some cases this value may not be evenly distributed, and could even contribute to widening income inequality. As MIT economist Erik Brynjolfsson has observed, it is possible that advancing technology, such as automation of knowledge work or advanced robotics, could create disproportionate opportunities for some highly skilled workers and owners of capital while replacing the labor of some less skilled workers with machines. This places an even greater importance on training and education to refresh and upgrade worker skills and could increase the urgency of addressing questions on how best to deal with rising income inequality.
- **The link between hype and potential is not clear.** Emerging technologies often receive a great deal of notice. News media know that the public is fascinated with gadgets and eager for information about how the future might unfold. The history of technology is littered with breathless stories of breakthroughs that never quite materialized. The hype machine can be equally misleading in what it chooses to ignore. As Exhibit E5 shows, with the exception of the mobile Internet, there is no clear relationship between the amount of talk a technology generates and its potential to create value. The lesson for leaders is to make sure that they and their advisers have the knowledge to make their own assessments based on a structured analysis involving multiple scenarios of technology advancement and potential impact.

Exhibit E4

Estimated distribution of potential economic impact between developed and developing economies for sized applications

% of potential economic impact for sized applications

Impact on
■ Developed economies
■ Developing economies



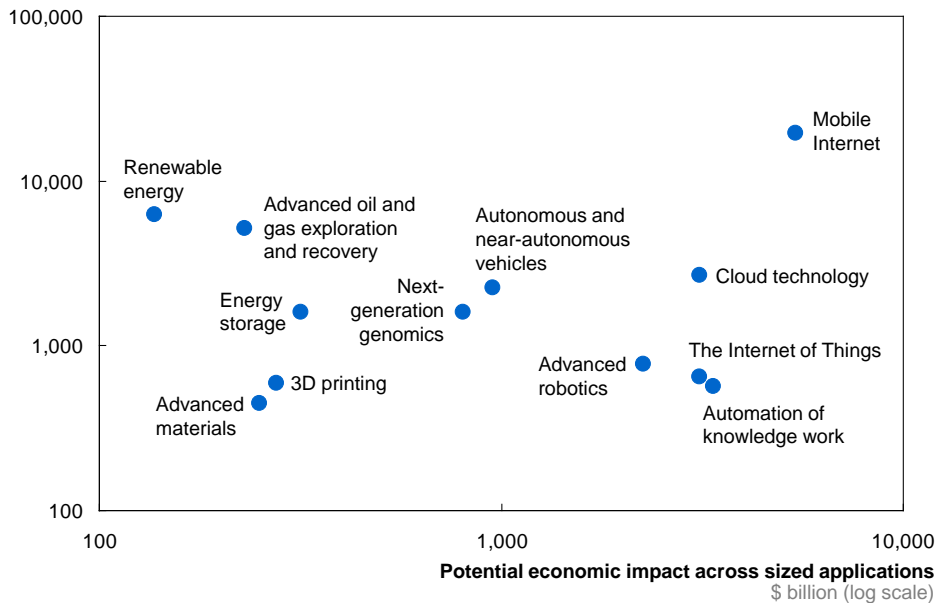
Notes on sizing

- These economic impact estimates are not comprehensive and include potential direct impact of sized applications only.
- These estimates do not represent GDP or market size (revenue), but rather economic potential, including consumer surplus.
- Relative sizes of technology categories shown here cannot be considered a “ranking” because our sizing is not comprehensive.
- We do not quantify the split or transfer of surplus among or across companies or consumers, as this would depend on emerging competitive dynamics and business models.
- These estimates are not directly additive due to partially overlapping applications and/or value drivers across technologies.
- These estimates are not fully risk- or probability-adjusted.

SOURCE: McKinsey Global Institute analysis

Exhibit E5**The relationship between hype about a technology and its potential economic impact is not clear****Media attention**

Number of relevant articles in major general interest and business publications over 1 year (log scale)



NOTE: Estimates of potential economic impact are for only some applications and are not a comprehensive estimate of total potential impact. Estimates include consumer surplus and cannot be related to potential company revenue, market size, or GDP impact. We do not size possible surplus shifts among companies and industries, or between companies and consumers. These estimates are not risk- or probability-adjusted.

SOURCE: Factiva; McKinsey Global Institute analysis

- Scientific discovery and innovation will surprise us.** We examined many technologies to evaluate their potential, but in doing so we were impressed by the reality that it is impossible to predict how new technologies will emerge and play out. Many of the technologies on our list likely will, at some point, be revolutionized by advancements in science. The technologies that define the 20th and 21st centuries, including modern medicine and electronics, were enabled by scientific breakthroughs like germ theory and Maxwell's laws of electromagnetism. Emerging technologies like genomics and nanotechnology are likewise being driven by unpredictable scientific breakthroughs, from the completion of the Human Genome Project in 2003 to the first artificial production of graphene in 2004. Harnessing the full potential of advanced nanomaterials like graphene will require major improvements or breakthroughs in cost-effective production techniques. Moreover, when breakthroughs in technologies like advanced materials or energy storage occur, they could drive impact across a host of applications and sectors, likely including some major direct impacts, but potentially also including a wide array of indirect and follow-on impacts.
- There are some troubling challenges.** The technologies on our list have great potential to improve the lives of billions of people. Cloud computing and the mobile Internet, for example, could raise productivity and quality in education, health care, and public services. At the same time, some of these technologies could bring unwanted side effects. The benefits of the mobile Internet and cloud computing are accompanied by rising risks of security and privacy breaches. Objects and machines under the control of computers across the Web (the Internet of Things) can also be hacked, exposing

factories, refineries, supply chains, power plants, and transportation networks to new risks. Next-generation genomics has the potential to grant new powers over biology, but these powers could be abused to disastrous effect. Low-cost desktop gene-sequencing machines will not only put the power of genomics in doctor offices, but also potentially in the hands of terrorists. Even well-intentioned experiments in garages using inexpensive sequencing and DNA synthesis equipment could result in the production and release of dangerous organisms. And nanomaterials offer great promise, but more research will be required to fully ascertain their potential impact on health. It will be up to business leaders, policy makers, and societies to weigh these risks and navigate a path that maximizes the value of these technologies while avoiding their dangers.

IMPLICATIONS

As we conducted our research and created estimates of the potential economic impact of disruptive technologies, we focused on identifying how each of these technologies could affect individuals, societies, organizations, economies, and governments in transformative and disruptive ways. Exhibit E6 lays out some major ways in which each technology on our list could drive transformative and disruptive impact by 2025.

In considering the disruptive potential of these technologies, we see that each could drive profound changes across many dimensions—in the lives of citizens, in business, and across the global economy. As noted, the future seems bright for entrepreneurs and innovators. 3D printing, the mobile Internet, cloud technology, and even next-generation genomics could provide the opportunities and the tools to allow small enterprises to compete on a meaningful scale and advance into new markets rapidly.

Many technologies, including advanced robotics, next-generation genomics, and renewable energy, have real potential to drive tangible improvements in quality of life, health, and the environment. For example, advanced robotic surgical systems and prosthetics could improve and extend many lives, while renewable energy sources could help clean up the environment and lessen the deleterious health effects of air pollution, a major and growing issue, particularly in developing economies. Many of these technologies could change how and what consumers buy, or alter overall consumption of certain resources such as energy and materials. Others could fundamentally change the nature of work for many employees around the world, both in manufacturing and knowledge work.

Almost every technology on our list could change the game for businesses, creating entirely new products and services, as well as shifting pools of value between producers or from producers to consumers. Some, like automation of knowledge work and the mobile Internet, could also change how companies and other organizations structure themselves, bringing new meaning to the anytime/anywhere work style. With automation of knowledge work tasks, organizations that can augment the powers of skilled workers stand to do well.

Exhibit E6

How disruptive technologies could affect society, businesses, and economies

■ Primary ■ Secondary ■ Other potential impact

	Implications for individuals and societies			Creates opportunities for entrepreneurs	Implications for established businesses and other organizations				Implications for economies and governments			
	Changes quality of life, health, and environment	Changes patterns of consumption	Changes nature of work		Creates new products and services	Shifts surplus between producers or industries	Shifts surplus from producers to consumers	Changes organizational structures	Drives economic growth or productivity	Changes comparative advantage for nations	Affects employment	Poses new regulatory and legal challenges
Mobile Internet	Other potential impact	Primary	Secondary	Primary	Primary	Other potential impact	Secondary	Secondary	Primary	Other potential impact	Other potential impact	Other potential impact
Automation of knowledge work	Other potential impact	Other potential impact	Primary	Secondary	Secondary	Other potential impact	Other potential impact	Primary	Primary	Secondary	Secondary	Secondary
The Internet of Things	Primary	Secondary	Other potential impact	Secondary	Primary	Secondary	Other potential impact	Other potential impact	Primary	Other potential impact	Other potential impact	Secondary
Cloud technology	Other potential impact	Primary	Other potential impact	Primary	Primary	Other potential impact	Secondary	Other potential impact	Primary	Other potential impact	Other potential impact	Secondary
Advanced robotics	Primary	Other potential impact	Primary	Secondary	Primary	Other potential impact	Other potential impact	Secondary	Primary	Secondary	Secondary	Other potential impact
Autonomous and near-autonomous vehicles	Primary	Other potential impact	Secondary	Secondary	Primary	Secondary	Other potential impact	Other potential impact	Secondary	Other potential impact	Secondary	Primary
Next-generation genomics	Primary	Secondary	Other potential impact	Primary	Primary	Secondary	Other potential impact	Other potential impact	Secondary	Other potential impact	Other potential impact	Primary
Energy storage	Primary	Secondary	Other potential impact	Secondary	Secondary	Primary	Other potential impact	Other potential impact	Secondary	Other potential impact	Other potential impact	Other potential impact
3D printing	Other potential impact	Primary	Secondary	Primary	Primary	Other potential impact	Secondary	Other potential impact	Primary	Secondary	Secondary	Other potential impact
Advanced materials	Primary	Other potential impact	Other potential impact	Secondary	Primary	Secondary	Other potential impact	Other potential impact	Secondary	Secondary	Other potential impact	Secondary
Advanced oil and gas exploration and recovery	Other potential impact	Secondary	Other potential impact	Other potential impact	Other potential impact	Primary	Other potential impact	Other potential impact	Primary	Primary	Other potential impact	Secondary
Renewable energy	Primary	Other potential impact	Other potential impact	Secondary	Secondary	Primary	Other potential impact	Other potential impact	Other potential impact	Secondary	Other potential impact	Secondary

SOURCE: McKinsey Global Institute analysis

Each of these technologies has significant potential to drive economic growth and even change the sources of comparative advantages among nations. Energy technologies such as unconventional oil and gas and energy storage could power overall economic growth, while technologies such as advanced robotics and 3D printing could foster increased productivity and growth in the manufacturing sector. These types of impacts could help nations develop and exploit their unique resources and capabilities in new ways, potentially shifting the global center of gravity across sectors and regions. Many of these technologies pose new regulatory and legal challenges. Some, such as autonomous vehicles, will require sensible regulatory regimes to help foster their growth and realize their benefits. Next-generation genomics and the Internet of Things will need appropriate controls to help avoid accidents or misuse.

As these disruptive technologies continue to evolve and play out, it will be up to business leaders, entrepreneurs, policy makers, and citizens to maximize their opportunities while dealing with the challenges. Business leaders need to be on the winning side of these changes. They can do that by being the early adopters or innovators or by turning a disruptive threat into an opportunity. The first step is for leaders to invest in their own technology knowledge. Technology is no longer down the hall or simply a budget line; it is the enabler of virtually any strategy, whether by providing the big data analytics that reveal ways to reach new customer groups, or the Internet of Things connections that enable a whole new profit center in after-sale support. Top leaders need to know what technologies can do and how to bend it to their strategic goals. Leaders cannot wait until technologies are fully baked to think about how they will work for—or against—them. And sometimes companies will need to disrupt their own business models before a rival or a new competitor does it for them.

One clear message: the nature of work is changing. Technologies such as advanced robots and knowledge work automation tools move companies further to a future of leaner, more productive operations, but also far more technologically advanced operations. The need for high-level technical skills will only grow, even on the assembly line. Companies will need to find ways to get the workforce they need, by engaging with policy makers and their communities to shape secondary and tertiary education and by investing in talent development and training; the half-life of skills is shrinking, and companies may need to get back into the training business to keep their corporate skills fresh.

The scope of impact of the technologies in this report makes clear that policy makers could benefit from an informed and comprehensive view of how they can help their economies benefit from new technologies. Policy makers can find ways to turn the disruptions into positive change; they can encourage development of the technologies that are most relevant to their economies. In many cases, such as in next-generation genomics or autonomous vehicles, the proper regulatory frameworks will need to be in place before those technologies can blossom fully. In other cases governments may need to be the standards setters or the funders of the research that helps move ideas from science labs into the economy. In still others, they will need to draw the lines between progress and personal rights.

The challenge for policy makers—and for citizens—is enormous. It is a good time for policy makers to review how they address technology issues and develop a systematic approach; technology stops for no one, and governments cannot afford to be passive or reactive. The time may be right, for example, to rethink how governments measure the economic impact of technology—to look beyond GDP and employment and look for metrics that truly capture the value added (or put at risk) when new technologies take hold.

Introduction: Understanding the impact of technologies

The power of new technologies is everywhere. They change how businesses make money and how we live and work, sometimes with amazing speed. Social media was practically unknown a decade ago, yet almost one billion people now have Facebook accounts; in fact, entirely new ways of socializing and interacting with friends, family, and colleagues have become the norm.⁵ Around the world, hundreds of millions of people have been lifted out of poverty as developing nations have adopted the technologies that drove growth in advanced economies in earlier times. Today, technologies such as the mobile Internet are helping to accelerate economic development, allowing millions of people in remote areas of developing regions to leapfrog into the 21st-century global economy.

Technology's power is particularly transformative in business. Technology can create immense value, but it often does so through a highly disruptive process. In the past, technological change has reordered industry after industry. Profit pools have shifted between owners of capital, labor, and consumers. Incumbent businesses have lost out, and startups have become dominant players. Whole product lines have been relegated to niches or forgotten altogether.

Yet despite the increasingly notable presence of technology in our world, the ability to fully measure its impact remains limited. We notice the effects of new technologies as they rapidly change our work routines, the way we spend our leisure time, or the products and services we use (often, increasingly, for free). We experience the benefits of new technologies in profound ways when they save or extend our lives or those of our loved ones. But existing economic statistics such as GDP struggle to fully account for this value, which is often realized as consumer surplus and can take decades to show up in the numbers. Better approaches are needed to measure the full economic impact of technologies, both to evaluate their potential and to set an appropriate course.

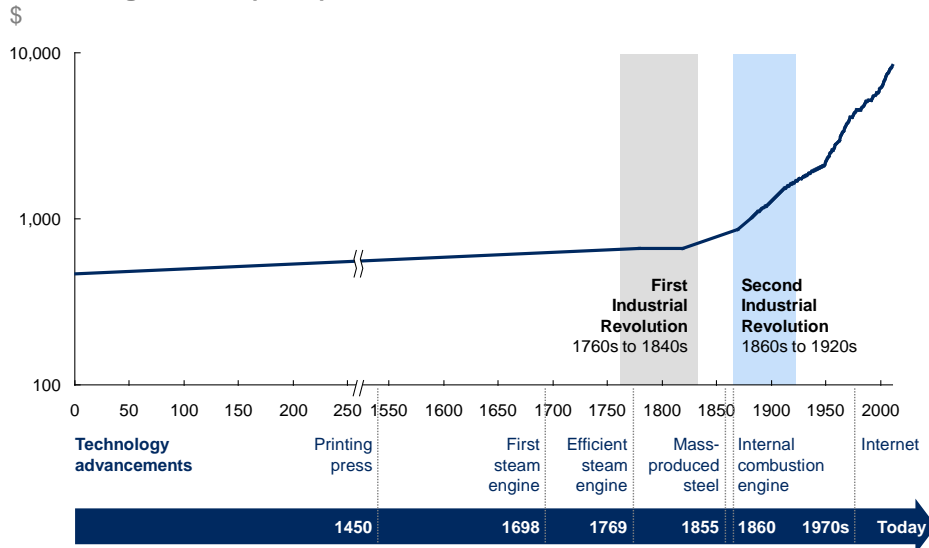
HOW TECHNOLOGY DRIVES GROWTH

Since the start of the Industrial Revolution more than 250 years ago, the global economy has been on a steep growth trajectory propelled by a series of advances in technology (see Exhibit 1). From steam engines that replaced water mills to electricity, telephones, automobiles, airplanes, transistors, computers, and the Internet, each new wave of technology has brought about surges in productivity and economic growth, enabling efficient new methods for performing existing tasks and giving rise to entirely new types of businesses. Certain technologies, particularly general-purpose ones such as steam power or the Internet that can be applied across economies, have massive and disruptive effects. In this report we focus on the potential impact of such economically disruptive technologies.

5 eMarketer, February 2012.

Exhibit 1

Since the Industrial Revolution, the world has experienced an unprecedented rise in economic growth that has been fueled by innovation
Estimated global GDP per capita



SOURCE: Angus Maddison, "Statistics on world population, GDP and per capita GDP, 1–2008 AD," the Maddison Project database; McKinsey Global Institute analysis

Technological progress is not the only force that drives transformative growth in economies; for example, US growth during the 1970s was driven by the entry of millions of women and baby boomers into the labor force. However, technological advances have been an especially valuable source of growth because they tend to be "non-rival" in nature, meaning they can be used over and over, benefiting different users and driving increasing returns. And unlike other sources of growth, such as increases in the labor force, the effects of technology do not go away.⁶

General-purpose technologies are particularly powerful. They are not only non-rival and long lasting, but their pervasiveness also makes them especially disruptive. The Internet is an excellent example. It introduced new ways of communicating and using information that enabled major innovations, imposing new rules from outside on all sorts of industries, rearranging value chains and enabling new forms of competition. In industry after industry, Internet-enabled innovations brought transparency to pricing, disrupted commercial relationships, created new customer expectations, and made old business models obsolete. Napster and iTunes all but eliminated record stores, online booking systems have made travel agents largely redundant, and Amazon has forever changed both bookselling and the book publishing industry as a whole.

General-purpose technologies also tend to shift value to consumers, at least in the long run. This is because new technologies eventually give all players an opportunity to raise productivity, driving increased competition that leads to lower prices. General-purpose technologies can also enable—or spawn—more technologies. For example, steam power enabled the locomotive and railroads, and the printing press accelerated learning and scientific discovery. General-

⁶ Economists call technology-driven growth "intensive" (meaning a change in the rate inputs are converted to outputs), as opposed to extensive growth, which involves increasing inputs into the system.

purpose technologies can take many forms—including materials, media, and new sources of energy—but they all share the ability to bring about transformative change (see Box 4, “Three general-purpose technologies that changed the world”).

Box 4. Three general-purpose technologies that changed the world

The development of steel-manufacturing technology enabled the spread of a new material that accelerated growth and innovation in the Industrial Revolution. Steel is a stronger, lighter, and more ductile material than iron, but it was not easily produced until Henry Bessemer developed a technological advance that blew air through molten iron to remove the impurities. The Bessemer process enabled rapid, inexpensive mass production of steel, which could be done with mostly unskilled labor.¹ Steel was quickly adopted for tools and machinery and in construction, ship-building, trains, and later in automobiles. Steel became an engine of growth, helping double global GDP per capita between 1850 and 1900. Since then, steelmaking has been used repeatedly as an engine of growth for developing economies.

The printing press, one of the first great information technologies, illustrates how a general-purpose technology can have unpredictable effects. First used as a way to make the bible accessible, the printing press almost immediately became the agent of seismic social disruption in Europe as the leaders of the Reformation adopted the technology to print the tracts and pamphlets that spread the movement at unprecedented speed. Next, printing presses helped spark the scientific revolution—and the Enlightenment—by disseminating research and discoveries across the continent. Indirect effects included accelerated city growth; between 1500 and 1600, cities with printing presses grew 60 percent faster than other cities.² Some historians attribute Europe’s rapid growth and global influence and the eclipse of Islamic nations after the 15th century to printing’s rapid adoption in Europe and its slow adoption in Islamic economies.³

The story of the electric dynamo (the first type of electric motor) demonstrates that unleashing the full disruptive potential of new technology can be a long and difficult process. The electric dynamo represented a major improvement over existing steam- and water-powered engines because manufacturing stages or workstations no longer had to be tied to central power shafts in each factory. This allowed for improved factory organization and increased efficiency. However, as Stanford economist Paul David has noted, it took two decades (between 1900 and 1920) for this technology to reach 50 percent of factories in the United States and several more decades for the full impact to be seen in productivity numbers.⁴ This was because firms were heavily invested in the legacy technology of the day (steam) and adopting the dynamo required redesigning equipment and reconfiguring facilities. David argues that similar factors could explain the observed lag between adoption of IT systems and measurable productivity increases.

1 Kathryn Kish Sklar, *Florence Kelley and the nation's work: The rise of women's political culture, 1830–1900*, Yale University Press, 1995.

2 J. E. Dittmar, “Information technology and economic change: The impact of the printing press,” *The Quarterly Journal of Economics*, volume 126, number 3, 2011.

3 Metin Cosgel, *The political economy of law and economic development in Islamic history*, University of Connecticut Department of Economics working paper number 2012–44, December 2012, and Jared Rubin, “The printing press, reformation, and legitimization,” *Stanford*, Stanford University.

4 Paul David, “The dynamo and the computer: An historical perspective on the modern productivity paradox,” *American Economic Review*, volume 80, number 2, May 1990.

Some economists today raise concerns that technology-driven growth could be slowing down. Economists Robert Gordon of Northwestern University and Tyler Cowen of George Mason University both cite slowing growth in productivity in advanced economies in recent years, arguing that technological advances such as the Internet may not have the same power to drive growth as prior generations of technology, such as those that occurred during the first and second Industrial Revolutions.⁷

Neither technology skeptics nor optimists can predict the future. Technologies and innovations are diffused and adopted at unpredictable rates. Wholly unanticipated applications may arise and become dominant, while the most obvious potential uses may not pan out. Moreover, when technologies are commercialized and widely used, the ways in which their impacts are measured can provide a distorted picture. Most metrics focus on industry impact—the amount of GDP generated by the production and consumption of a new technology in sectors where there is clear and direct impact (for example, how many microchips are made and then sold in computers). This misses the economic surplus that accrues to users, which can be the largest pool of value from disruptive technologies (such as the Internet). It also ignores effects on third parties, like children afflicted with asthma as a result of poor air quality or fishermen whose livelihoods are affected by water pollution.

The debate over how to measure technology impact is ongoing. In the 1980s economist Robert Solow caused a stir when he noted that despite the large investments that had been made in information technologies, there was no evidence of higher productivity in the service industries (e.g., banking) that had made the largest investments. GDP and other growth accounting metrics of IT impact do not fully account for improved quality of outputs through use of technology. Nor do they measure the surplus that users capture through improvements in quality and other benefits that new technologies provide. In fact, GDP doesn't directly measure any aspect of sustainability—whether in terms of environment, debt levels, or income distribution.

Another problem with judging the economic impact of technologies is timing. Because technologies often create value in unpredictable ways, early assessments frequently turn out to be misleading. For example, many social media technologies have been dismissed as trivial based on how they are used by consumers. However, when applied to complex business organizations to improve communications, collaboration, and access to knowledge, the same tools that are used to share links to cute cat videos have enormous potential to improve the productivity of knowledge workers.⁸ Realizing the full value of new technology can also be a long, difficult process. The electric dynamo was a major innovation that ushered in a revolution in manufacturing during the early 20th century but nevertheless took decades to reach widespread adoption and drive major productivity impact.

Finally, the rate of adoption for a technology can vary a great deal from one economy to another. While it is true that productivity and GDP growth have been modest in the United States—which is on the leading edge of technology adoption—rapid technology adoption (albeit of older technologies) is driving

7 Economists describe this as a state of diminishing returns.

8 *The social economy: Unlocking value and productivity through social technologies*, McKinsey Global Institute, July 2012.

growth in developing economies. For example, mobile phone carrier Roshan has become Afghanistan's largest employer by introducing the kind of mobile technology that is now several generations behind in advanced economies.⁹

Some economists have used alternative metrics to estimate the true impact of technologies. For example, Robert Fogel, a Nobel laureate at the University of Chicago, calculates social savings from technologies by estimating what it would cost society to accomplish a task in the same way that it did before an innovation was adopted (e.g., comparing the cost of transportation using railroads to the cost in a hypothetical scenario in which railroads were never adopted).¹⁰ Today, policy makers are increasingly aware of the limits of GDP. Institutions like the Organisation for Economic Co-operation and Development, the European Commission, and the United Nations have all examined or adopted alternatives ranging from the Human Development Index to Bhutan's Gross National Happiness measure.

We are not technology cheerleaders—or pessimists. We believe, however, that there is reason for optimism. As we examine potentially economically disruptive technologies on the horizon, we see significant potential for these technologies to raise productivity, disrupt existing business models, and create new profit pools. We also see that this growth will be accompanied by risks and challenges—as has always been the case for technology-led growth. As Erik Brynjolfsson and Andrew McAfee have argued, some advances that have the potential to drive productivity growth, such as advanced robotics and automated knowledge work, could also cause worrisome employment effects.¹¹

As new technologies come into use, society will need to continually balance their benefits and risks. Consumers can be relied upon to embrace technologies that make their lives more convenient and provide new sources of entertainment. Businesses and public-sector institutions will not forgo the productivity gains and other benefits that new technologies will make possible. We also believe that over the long term and on an economy-wide basis, productivity growth and job creation can continue to grow in tandem, as they generally have historically, if business leaders and policy makers can provide the necessary levels of innovation and education.¹²

However one measures its impact, the role of technology is growing in our economy and in society. The pace and direction of technological progress increasingly determines who gets hired, how our children are educated, how we find information and entertainment, and how we interact with the physical world. This puts the onus on society to find the most meaningful measures of the value derived from new technologies so that we can truly understand and control what is happening to our economies and our lives. In addition to GDP measures that

9 "Shining a light," *The Economist*, March 8, 2007.

10 Tim Leunig, "Social Savings," *Journal of Economic Surveys*, volume 24, issue 5, December 2010. Other attempts to supplement GDP measures include Amartya Sen's Human Development Index (HDI), which we believe has limited applicability for estimating the potential economic impact of a particular technology. We have not used HDI or social savings in our estimates.

11 Erik Brynjolfsson and Andrew McAfee, *Race against the machine: How the digital revolution is accelerating innovation, driving productivity, and irreversibly transforming employment and the economy*, Digital Frontier Press, 2011.

12 *Growth and renewal in the United States: Retooling America's growth engine*, McKinsey Global Institute, February 2011.

focus on economic activity, we need metrics that account for true value—such as the consumer surplus that arises when a student using a tablet computer suddenly connects the dots and can solve a math equation on her own, or the value that an elderly person might place on the ability to move without assistance.

Many efforts have been made to supplement GDP as a measure of value, but every alternative has its challenges, and GDP continues to dominate global discourse and decision making. This report attempts to examine and estimate the potential economic impact of disruptive technologies using a consistent methodology that includes consumer surplus. But producing broad estimates of the potential economic impact of specific technologies is easy compared to the challenges of measuring the actual, full value that technologies create in the global economy. This challenge is likely to remain—and grow—over the coming decade. As the saying goes, what gets measured is what gets done. As leaders think about realizing and capturing the full value of economically disruptive technologies, this idea might serve as a call to action.

1. Mobile Internet



The use of mobile Internet technology is already widespread, with more than 1.1 billion people currently using smartphones and tablets. The rapid and enthusiastic adoption of these devices has demonstrated that mobile Internet technology is far more than just another way to go online and browse. Equipped with Internet-enabled mobile computing devices and apps for almost any task, people increasingly go about their daily routines using new ways to understand, perceive, and interact with the world. In a remarkably short time, mobile Internet capability has become a feature in the lives of millions of people, who have developed a stronger attachment to their smartphones and tablets than to any previous computer technology.¹³ However, the full potential of the mobile Internet is yet to be realized; over the coming decade, this technology could fuel significant transformation and disruption, not least from its potential to bring two billion to three billion more people into the connected world, mostly from developing economies.

Mobile computing devices and applications are evolving every day. New devices now incorporate features such as ultra-high resolution screens with precise touch sensing, graphic-processing power rivaling that of gaming consoles, and new kinds of sensors. The mobile Internet is also being offered in entirely new formats, such as wearable devices. New 4G wireless networks offer increasingly fast data speeds, allowing users to seamlessly transition from home broadband and office Wi-Fi to mobile voice and data services.

New mobile software and apps offer a wide range of capabilities, effectively placing the capabilities of an array of gadgets (including PCs) in a mobile package that provides voice calling, Internet access, navigation, gaming, health monitoring, payment processing, and cloud access. We estimate that for the applications we have sized, the mobile Internet could generate annual economic impact of \$3.7 trillion to \$10.8 trillion globally by 2025. This value would come from three main sources: improved delivery of services, productivity increases in select work categories, and the value from Internet use for the new Internet users who are likely to be added in 2025, assuming that they will use wireless access either all or part of the time.

The prospect of up to three billion more consumers joining the digital economy could represent an unprecedented growth opportunity. Entrepreneurs in developing economies might be able to compete globally in online commerce, and global players will have a new channel to reach the fastest-growing markets. Consumers in both advanced and developing economies stand to benefit substantially from mobile Internet usage, as they have from the Internet itself—

13 A recent survey indicated that more people would prefer to leave home without their wallet than without their smartphone (“Consumer priorities: Choice of taking wallet or smartphone to work in 2012,” Statista, www.statista.com/statistics/241149/consumer-choice-of-taking-wallet-or-smartphone-to-work-in-2012/); the McKinsey iConsumer survey indicated that in the United States, 61 percent of smartphones are used only by their owner, versus 40 percent for laptops.

consumers have captured roughly two-thirds of the economic surplus generated by the Internet.¹⁴ The mobile Internet also has great potential to improve delivery and raise productivity in health care, education, and other public and social services.

DEFINITION

We define the mobile Internet as a combination of mobile computing devices, high-speed wireless connectivity, and applications. Today, smartphones and tablets are the devices used to access the mobile Internet, but new forms are constantly emerging. In coming years, mobile Internet devices could well be smaller, far more powerful, more intuitive, wearable, and packed with many types of sensors. With every new cycle of updates and models, tablets and smartphones are gaining capabilities. The processing power of the average smartphone has increased by about 25 percent per year over the past five years, and the latest processors can adeptly juggle multiple resource-intensive applications and produce vivid graphics. Smartphones and tablets are packed with sensors, including accelerometers and location sensors, and more recent models now include sensors that monitor temperature, humidity, and air pressure, as well as infrared sensors and sensors that detect screen proximity, making phones easy to use in any light and extending battery life.¹⁵

Meanwhile, mobile Internet technologies are becoming more richly and intuitively interactive (see Box 5, “Vision: Living in a connected world”). Apple’s Siri and Google Now both offer accurate voice recognition. Gesture recognition, already in wide use in gaming systems, is being adapted to mobile Internet devices; for example, the Samsung Galaxy S4 phone allows users to browse by waving their hands in front of the screen.¹⁶ Wearable devices such as Google Glass and smart watches will soon be available as well.

In addition to advances in devices, progress is being made in high-speed mobile connectivity. Today, mobile devices connect to the Internet via cellular networks (3G and 4G/LTE networks) or Wi-Fi networks used in offices, factories, homes, and public spaces. Over the coming decade, network advances could include 5G cellular networks (the as yet unspecified next-generation standard), satellite services, and possibly long-range Wi-Fi. These technologies will need to fight for increasingly scarce wireless frequencies, but new approaches to dynamically sharing spectrum, such as software-defined radios, could help ease the crunch. At the same time, mobile operators are creating application programming interfaces (APIs) that allow developers to control quality of service and bandwidth, potentially enabling new tiered pricing models.¹⁷

A crucial element in the success of mobile Internet use is the software applications (apps) that deliver innovative capabilities and services on devices. These apps help make mobile Internet use very different from using either

14 *Internet matters: The Net’s sweeping impact on growth, jobs, and prosperity*, McKinsey Global Institute, May 2011.

15 Stephanie Lanier, “Hidden features and sensors in the Samsung Galaxy S4,” *AndroidGuys.com*, April 10, 2013.

16 Brian X. Chen, “The Samsung Galaxy S4 review roundup,” Bits blog, *The New York Times*, April 24, 2013.

17 Venkat Atluri, Umit Cakmak, Richard Lee, and Shekhar Varanasi, *Making smartphones brilliant: Ten trends*, McKinsey & Company Telecom, Media, and High Tech Extranet, June 2012.

conventional phones or computers, providing location-based services (directions and location-based shopping tips, for example); personalized feeds of information and entertainment content; and constant online contact with friends, colleagues, and customers. Many of these apps seamlessly tap powerful resources on the cloud to fetch information or carry out tasks; when an iPhone owner asks a question of Siri, Apple's voice-activated search interface/digital assistant (see Chapter 2, "Automation of knowledge work"), for example, the heavy processing takes place on the cloud (see Chapter 4, "Cloud technology").

Apps are crucial to the potential impact of mobile Internet use, multiplying its capabilities and potentially disrupting established business models (including older online business models in industries such as retail, banking, and media). By 2025, many apps could still require some footprint on each device, but they could also offload much of their processing and storage to the cloud and might be accessed entirely over the Web using technologies such as HTML5, which can deliver applications via a Web browser without the need for downloading. Cloud enablement makes sense as devices become smaller and more seamlessly connected.

Box 5. Vision: Living in a connected world

What will the world be like when everyone is connected almost all the time? Imagine your morning routine. You strap on your smart watch, put on your smart glasses, and head to work. As you glance at the shoes arrayed in a department store window, information about them pops up in your line of vision. Descriptions of the shoes, along with prices, sizes, colors, and availability appear. You're about to make a selection when an audio alarm sounds in your earpiece. The next express bus will be at the corner in two minutes. You get to the bus stop just in time. The doors open and a display installed where the fare box used to be greets you by name and tells you how much credit you will have on your virtual transit card (stored on your smartphone) after this trip.

Or imagine you are a farmer in a developing economy. Until recently, you have been limited to subsistence farming, producing only enough to feed your family. But since acquiring a smartphone, your fortunes have improved. You have participated in online instruction regarding irrigation and other farming techniques, which have raised your crop yield, and you now sell most of what you grow. Using your new Internet connection, you have linked up with other farmers to form a cooperative to buy seed, fertilizer, and equipment and to pool your crops at harvest time to get better prices. While your crops are growing, you use your phone to photograph them and use a smart app to automatically grade them. These data are entered into the co-op's database, which then gives you an estimated price. Every day you get automatic reports on world prices for your crops. When the harvest is sold, your phone alerts you when payment hits your bank account. Without leaving your village, you have joined the global economy.

POTENTIAL FOR ACCELERATION

The largest opportunity for growth of mobile Internet use and impact will be in developing economies, where access to the Internet has important implications for economic development, potentially helping hundreds of millions of people to leapfrog into the 21st-century global economy. At this time, half of the world's adult population uses no banking services. UNICEF estimates that more than 100 million children do not attend school, and few of the farmers on the world's 500 million small-scale farms have broader access to markets.¹⁸ Mobile access to the Internet could address many of the basic needs of the developing world and enable its citizens to become participants in the global digital economy, including as entrepreneurs. In the developed world, growth will continue to be driven by new devices and applications, as well as by growing intensity of use as consumers and businesses come to rely on mobile Internet access in more aspects of their daily routines and operations.

Mobile Internet technology consists largely of smartphones and tablets. Sales growth of these devices has been extremely rapid and will likely continue at a brisk pace and perhaps even accelerate, particularly in developing economies.¹⁹ The number of smartphones in use grew 50 percent in 2012, and smartphones now account for 30 percent of mobile devices in use globally.²⁰ Sales of smartphones are projected to reach 1.3 billion units per year in 2013, while tablet sales are expected to reach 200 million units.²¹ Sales of smartphones and tablets exceeded personal computer sales in 2010, and in 2013 the number of smartphones and tablets in use is expected to exceed the installed base of personal computers.²² By 2025, nearly 80 percent of all Internet connections could be through mobile devices, and a majority of new Internet users could be using mobile devices as their primary or sole means of connecting to the Internet.

As consumers spend more time online, the number and quality of Internet-based services are increasing, further driving demand. App downloads grew 150 percent in 2012, and an array of new mobile services has emerged. So-called near-field payments (which use unpowered radio frequency chips to easily exchange data between devices) grew 400 percent in 2012 and are expected to increase 20-fold by 2016.²³ These are the systems that allow consumers to wave a phone near a point of sale terminal to make a payment, for example. Media and entertainment consumption on mobile devices has grown and is rapidly shifting viewers from cable and broadcast channels. Time spent playing video games, emailing, and text messaging on mobile phones grew 200 percent in the past four years. In the United States, an estimated 30 percent of all Web browsing and 40 percent of social media usage are now done on mobile devices. Time spent online on mobile phones is increasing at 25 percent per year, and data traffic on mobile devices has reached 15 percent of total Internet traffic.²⁴ The rapid shift of activities and content consumption to mobile Internet devices could represent

18 *Agriculture at a crossroads*, International Assessment of Agricultural Knowledge, Science and Technology, Center for Resource Economics, 2009.

19 Yankee Group Global Mobile Forecast.

20 Ibid.

21 Ibid.

22 Mary Meeker, *Internet trends*, Kleiner Perkins Caufield & Byers, March 2013.

23 Yankee Group Global Mobile Forecast.

24 2012 McKinsey US iConsumer Survey; StatCounter Global Stats.

only the beginning of a long-term trend. It is possible that by 2025, a far higher percentage of media consumption could be dominated by this technology.²⁵

The level of demand for mobile Internet access in developing economies will depend largely on how well device makers and mobile Internet services tailor their offerings to the needs of people who are just entering the global consumer class. While Internet use has been growing by 25 percent a year in developing economies (compared with 5 percent in advanced economies), 64 percent of the population in developing economies are not yet connected.²⁶ By 2016 developing economy markets are expected to be the largest source of smartphone market growth. India's share of global smartphone sales is expected to grow from 2 percent in 2012 to 9 percent in 2016, and Brazil's share is expected to rise from 2 percent to 5 percent.²⁷ Continued reductions in the prices of smartphones and data plans should help sustain rapid adoption rates. Anticipated decomponent costs are expected to continue to decline, which could reduce producer costs for midrange smartphones by about 30 percent by 2016.

The evolution of smartphone hardware and the emergence of other mobile devices should also help fuel sales and inspire new uses. Wearable devices such as the Google Glass not only make it possible to deliver all sorts of content in novel ways (for example, projecting images from the Web that appear to float in space in front of the wearer), but also make it possible to develop “augmented reality” applications that let the wearer step into virtual spaces just as virtual reality goggles do. This technology has obvious applications for entertainment and gaming, but these devices could also be used to help people in new ways. For example, a wearable mobile device could be programmed to help Alzheimer's patients recognize people and remind them of what various objects around the home are. Instant translation apps on wearable devices could be used to read signs and menus, making travel to foreign lands far easier. Finally, as mobile Internet devices become more integrated into day-to-day life—and gain new capabilities—they have the potential to become intelligent personal assistants, capable of managing our schedules, answering questions, and even alerting us to important information (see Chapter 2, “Automation of knowledge work”).

POTENTIAL ECONOMIC IMPACT

In the uses we analyzed, mobile Internet usage could generate global economic impact of \$3.7 trillion to \$10.8 trillion per year by 2025 (Exhibit 2). Half of this potential value could come from using mobile devices to spread Internet access in developing regions. More than 3.5 billion citizens in developing economies are expected to have access to the Internet in 2025, more than two billion of them via mobile Internet services. People who have had poor access to education, health care, and government services and have never participated in the formal economy could become participants in the global economy through the Internet.

25 2012 McKinsey US iConsumer Survey.

26 *Online and upcoming: The Internet's impact on aspiring countries*, McKinsey Global Institute, January 2012.

27 *Worldwide quarterly mobile phone forecast*, IDC, March 2012.

Exhibit 2

Sized applications of mobile Internet could have direct economic impact of \$3.7 trillion to \$10.8 trillion per year in 2025



Sized applications	Potential economic impact of sized applications in 2025 \$ trillion, annually	Estimated scope in 2025	Estimated potential reach in 2025	Potential productivity or value gains in 2025
Health care	0.9–2.1	▪ \$15.5 trillion cost of treating chronic diseases	▪ 70–80% mobile penetration among patients accounting for 95% of health-care spending	▪ 10–20% cost reduction in chronic disease treatment through remote health monitoring
		▪ \$11 trillion global spending on education	▪ K–12 adoption of online/hybrid learning – Developed world: 80–90% ¹ – Developing: 65–80% ▪ 90–100% adoption in post-secondary, corporate, and government education	▪ 5–15% rise in secondary graduation rates ▪ 10–30% productivity gain in post-secondary, corporate, and government education
Education	0.3–1.0	▪ \$0.9–1.2 trillion government spending on customer-facing services	▪ Adoption by 90–100% of governments for online or mobile services	▪ 60–75% cost savings on administrative tasks driven by labor efficiency
Service delivery	0.2–0.5	▪ \$7.2 trillion cost of retail	▪ 30–50% of retail consumption ▪ Mobile devices used in 50% of purchases	▪ 6–15% productivity gain of online hybrid retail versus traditional
Retail	0.1–0.4	▪ \$3 trillion in global transaction revenue	▪ Implementation of advanced electronic payments systems in – 80–100% of advanced economies – 65–80% of developing economies ¹	▪ 50% productivity gain in managing transactions across all stakeholders
Payments	0.2–0.3			
Other worker productivity ²	0.9–1.3	▪ \$19 trillion in interaction worker salaries	▪ 80–90% of workers in advanced economies ▪ 65–80% of workers in developing economies	▪ 4–5% increase in efficiency through social technology via mobile
		▪ \$15 trillion in transaction worker salaries	▪ 80–90% of workers in advanced economies ▪ 65–80% of workers in developing economies ▪ Mobile devices needed for 10% of work tasks	▪ 10–30% productivity gain from time saved accessing information
Additional consumer surplus	1.0–4.8	▪ 3.6–4.9 billion mobile users	▪ 100% of users	▪ \$500–1,500 per user in developed world ▪ \$300–1,000 per user in developing world
Other potential applications (not sized)				
Sum of sized potential economic impacts	3.7–10.8			

¹ Estimates of adoption are based on Internet penetration rates in advanced and developing economies.

² Estimates of potential economic impact for worker productivity applications exclude labor productivity impact sized as part of service delivery applications.

NOTE: Estimates of potential economic impact are for some applications only and are not comprehensive estimates of total potential impact. Estimates include consumer surplus and cannot be related to potential company revenue, market size, or GDP impact. We do not size possible surplus shifts among companies and industries, or between companies and consumers. These estimates are not risk- or probability-adjusted. Numbers may not sum due to rounding.

SOURCE: McKinsey Global Institute analysis

To estimate the potential economic impact of mobile Internet technology, we looked at how mobile applications could improve service delivery, raise productivity, and create value for consumers in time savings and convenience surplus.²⁸ We have attempted to exclude the value of Internet use via fixed connections while including the value of the additional Internet use and value that users of fixed Internet connections derive from also using the mobile Internet. For potential mobile Internet users in 2025 who previously lacked Internet access (that is, new users in developing economies), we have treated all Internet use as incremental.

Among the types of services that stand to benefit from mobile Internet technology, health care is one of the most promising. In just one application—management of chronic disease—this technology potentially could cut more than \$2 trillion a year in the projected cost of care by 2025. Today, treating chronic diseases accounts for about 60 percent of global health-care spending, and it could be more than \$15 trillion globally by 2025.²⁹ Patients with conditions such as heart disease and diabetes could be monitored through ingestible or attached sensors, which can transmit readings and alert the patient, nurses, and physicians when vital signs indicate an impending problem, thus avoiding crises and the costs of emergency room visits or hospitalization.

For example, the US Veterans Health Administration has provided remote monitoring devices to more than 70,000 patients with chronic diseases, combined with access to video chats with physicians. These patients used 20 to 50 fewer service resources than those in the control group.³⁰ Taking into account hurdles such as patient resistance, the cost of chronic disease treatment could be reduced by 10 to 20 percent through better disease management via the use of mobile Internet access, a relatively conservative estimate. Such a reduction could drive a potential economic impact of \$900 billion to \$2.1 trillion per year by 2025.

In education, mobile computing has the potential to raise productivity and improve learning both inside and outside classrooms. In K–12 education, early experiments show promise for hybrid online/offline teaching models using tablets to increase lesson quality, improve student performance, and increase graduation rates. Based on studies of the effectiveness of hybrid teaching models that incorporate mobile devices in instruction, drills, and testing (alongside traditional classroom teaching), an improvement in graduation rates of 5 to 15 percent could be possible. This assumes a gradual adoption rate, with most of the benefit coming closer to 2025, when more students will have benefited from online learning via tablets for most of their K–12 years. In higher education, as well as government and corporate training, such hybrid models could improve productivity by 10 to 30 percent. Over the next decade, most types of education and training could adopt Internet-based hybrid education, affecting billions of

28 We used recent case examples as a conservative means of estimating potential productivity gains from mobile Internet technology. Our estimates do not include uses that have yet to be adopted, although the history of this technology indicates that such inventions are likely.

29 Based on spending on chronic diseases in France, Canada, the United Kingdom, and the United States.

30 Based on a case study by the US Veterans Health Administration regarding chronic heart failure, diabetes, and chronic obstructive pulmonary disease, including more than 70,000 patients. See Andrew Broderick and David Lindeman, “Scaling telehealth programs: Lessons from early adopters,” *Case Studies in Telehealth Adoption*, The Commonwealth Fund, January 2013.

individuals. The share delivered via mobile devices could have economic impact of \$300 billion to \$1 trillion annually.

In the public sector, many citizen services (such as information requests, license applications, and tax payments), could become online services through mobile apps. Based on McKinsey experience, it is possible to raise productivity by 60 to 70 percent by moving functions such as tax refund services and vehicle registration renewals to online channels. Assuming high adoption rates motivated by the need to control government spending, the potential economic impact of delivering government services using mobile Internet technology could reach \$200 billion to \$500 billion per year by 2025.

In the retail sector, mobile Internet usage has great potential to extend the reach of online and hybrid online shopping (for instance, visiting showrooms and then purchasing online). Based on differences in prices and margins between traditional retail and online stores, the productivity gain of delivering retail goods through a digital channel could be 6 to 15 percent, based on reduced labor, inventory, and real estate costs. By 2025, 30 to 50 percent of retail transactions (40 to 70 percent in advanced economies and 20 to 30 percent in developing economies) might take place online, with a potential economic impact of \$100 billion to \$400 billion per year.

For government and private-sector organizations, mobile payments represent a very large opportunity made possible by mobile Internet technology. Today, 90 percent of the more than three trillion transactions made every year globally are cash transactions, and McKinsey analyses show that an electronic transaction can save 50 to 70 percent of processing costs over a paper transaction. In an advanced economy, moving to an increased share of electronic transactions could have a productivity benefit equivalent to 0.35 percent of GDP. The total potential economic impact of moving transactions to an electronic format is estimated to be \$200 billion to \$300 billion per year by 2025.

Mobile applications could have considerable impact on improving internal operations, from frontline workers to sales reps to highly paid knowledge workers. Frontline workers, for example, could use mobile Internet devices to manage equipment and physical assets more effectively, monitor supply chains, maintain the condition of vital equipment, and provide post-sale services (see Chapter 3, “The Internet of Things”). Boeing and BMW have developed virtual reality glasses for assemblers and mechanics that display online manuals and instructions explaining, for example, exactly how parts should fit together.³¹ A University of Chicago study recently found that giving iPads to medical residents reduced the time it took to schedule procedures and improved the residents’ ability to explain complicated diagnoses to patients using visual aids.³²

For transaction workers such as sales reps, mobile devices are already showing potential to increase productivity by making pricing, options, configurations, financing terms, and other information instantly available. In business-to-business sales, this has increased close rates by 35 to 65 percent in some cases.

31 Clay Dillow, “BMW augmented reality glasses help average Joes make repairs,” PopSci.com, September 3, 2009.

32 Mary Modahl, *Tablets set to change medical practice*, QuantiaMD report, June 15, 2011.

One of the biggest opportunities for operational improvements involves using mobile Internet technology to increase the productivity of knowledge workers, including so-called interaction workers, a category that includes professionals, administrative support staff, and others whose jobs require person-to-person interaction and independent judgment. Such workers stand to benefit most from the use of social technologies that enable communications and collaboration, which could raise interaction worker productivity by 20 to 25 percent, particularly by reducing the time it takes to handle email, search for information, and collaborate with colleagues.³³ Assuming that interaction workers spend about 25 percent of the workweek away from their desks, mobile Internet access could improve their productivity by 4 to 5 percent. For transaction workers, we estimate a time savings of one to two hours per day; however, only 10 percent of worker time online, depending on mobile connection. The estimated potential economic impact of worker productivity gains achieved via the use of mobile Internet applications in internal operations could be \$1.0 trillion to \$1.7 trillion annually by 2025.

Consumer surplus will make up a large portion of the potential impact of mobile Internet access. We base our estimate of value on survey research by the Interactive Advertising Bureau (IAB) Europe and McKinsey & Company that established how consumers in developed and developing economies value Internet services.³⁴ The applications we considered for an analysis of the surplus that would accrue through mobile Internet use are email, social networks, entertainment (music, videos, and games), and Web services such as search and mapping. To gauge the value of Internet use in 2025, we estimate that usage will grow by between 6 and 9 percent annually. Applying this estimate of consumer surplus to new users (two billion to three billion), as well as the incremental value for existing users (and subtracting estimated fixed Internet use), the impact could be between \$1.0 trillion and \$4.8 trillion annually by 2025.

BARRIERS AND ENABLERS

Reaching the full potential of mobile Internet use will require device makers to pack more computing power, sharper displays, multiple sensors, and powerful antennas into ever-smaller mobile devices. Adding to the complexity of the task, these features, processors, and data-intensive uses all raise power consumption—yet battery size cannot increase due to the size constraints of mobile devices. Since 2000, battery capacity has only doubled, while processing speed has increased roughly 12-fold.³⁵ Progress is possible: there could be rapid advances in lithium batteries, while advanced nanomaterials such as graphene could be used in electrode coatings that improve battery performance (see Chapter 8, “Energy storage,” and Chapter 10, “Advanced materials”). Progress in battery technology will be needed in order to bring mobile Internet access to places in the developing world that lack a reliable supply of electricity. If these performance improvements are not achieved, the full economic potential of mobile Internet access might not be realized.

33 *The social economy: Unlocking value and productivity through social technologies*, McKinsey Global Institute, July 2012.

34 *Internet matters: The Net's sweeping impact on growth, jobs, and prosperity*, McKinsey Global Institute, May 2011

35 Venkat Atluri, et al., *Making smartphones brilliant*, McKinsey & Company Telecom, Media, and High Tech Extranet, June 2012.

As mobile Internet devices and connections continue to proliferate and the amount of data per user grows, availability of sufficient radio spectrum is becoming a growing concern. Over the past several years, as users have started streaming more “rich media” (including TV shows), downloading apps, and using more complex websites, data traffic on mobile networks has grown by 80 percent to 100 percent annually. The growing scarcity of unused wireless spectrum has prompted some telecom carriers to spend billions of dollars buying spectrum rights in public airwave auctions or from other companies.³⁶ This shortage is creating an urgent need for better use of frequencies, such as dynamically allocating spectrum among users. Creating the infrastructure to increase global high-speed Internet coverage will require significant capital expenditure. The expected investment in infrastructure necessary to facilitate mobile Internet usage could be as high as \$300 billion annually in 2025, including cost for installation (the majority of which would be in Asia). The economic potential of mobile Internet usage may not be fully realized if sufficient wireless spectrum capacity cannot be made available.

IMPLICATIONS

The economic impact of mobile Internet usage is potentially massive, and its effects could be highly disruptive across a wide range of sectors. Consumers, business leaders, and policy makers all have a stake in seeing mobile Internet usage spread and take on greater capabilities. And all of these stakeholders will also have to grapple with challenges that could limit the realization of this full potential.

Makers of mobile Internet devices, software providers, and other technology suppliers are likely to compete intensely to develop new and better products. They will need to adopt new components, explore new product forms (such as “wearable” devices), and keep up with constantly evolving consumer preferences.

Wireless carriers could face increasing challenges in profiting from the growth of mobile Internet use. Intensifying competition among wireless carriers is already squeezing margins on mobile data plans. As more people get mobile Internet access and new data-intensive uses—such as streaming video programming—become more widely used, networks could slow down. Wireless carriers will need to address these network capacity constraints, balancing capital investment with long-term profitability. They will also face difficult decisions regarding whether to upgrade existing infrastructure or leapfrog to more advanced platforms through expansion or acquisition.

For incumbent Internet businesses, growing mobile Internet use poses multiple challenges. To remain competitive, they must adapt their services to mobile networks, often requiring significant investment. Today, the biggest challenge for many online businesses is capturing revenue as Internet traffic goes mobile. At the same time, low barriers to launching a mobile-based online business make it easier for upstarts to challenge established online players. Mobile Internet use is attracting entrepreneurs and capital, and the next innovators could come from literally anywhere: more than 143,000 Internet-related businesses are started in developing economies every year.³⁷

36 One recent example of a wireless spectrum purchase is Verizon’s purchase of spectrum for \$3.9 billion from Time Warner Cable, Comcast, Cox Communications, and Bright House Networks.

37 *Online and upcoming: The Internet’s impact on aspiring countries*, McKinsey Global Institute, January 2012.

For many businesses, the prospect of up to three billion more consumers coming into the digital economy could represent an unprecedented growth opportunity, but one that will require fresh thinking and new approaches. Products and services must not only fit within more limited budgets, but must also cater to very different tastes and priorities. Business leaders will have to learn how to please these new consumers and effectively meet their needs.

Business leaders will also need to identify employee functions that could be performed more efficiently or more effectively on a mobile platform. They will need to consider how performance could be enhanced by enabling increased mobility, augmenting worker knowledge and capabilities or facilitating collaboration and social interaction.

Consumers in both advanced and developing economies stand to benefit substantially from mobile Internet usage, as they have from the Internet itself. Consumers have captured roughly two-thirds of the economic surplus generated by the Internet, and this pattern could hold true for mobile Internet use as well. The proliferation of mobile devices has also raised important societal concerns, however. This includes the effect of excessive screen time on child development and potential loss of productivity as a result of a distracted workforce. Entrepreneurs and companies that can develop products and services that address and alleviate these issues could create significant value.

Policy makers around the world must learn how to use mobile Internet access to improve services, increase productivity, and drive economic development. Governments can also play a crucial role in accelerating the adoption of mobile Internet access by funding basic research and helping to overcome major barriers, for example by allocating scarce spectrum.

In developing economies, governments have much to gain from mobile Internet usage as a driver of development and employment. As it has done in other places, the shift of business to the Internet can be disruptive to employment. However, for every job that is lost due to the Internet in small and medium-size enterprises survey data indicates that in some developing countries 3.2 new jobs could be created.³⁸ Furthermore, mobile Internet technologies could provide access to education and have a direct impact on critical issues such as malnutrition and malaria by helping to spread knowledge and distribute supplies where they are needed most.

Even if the ultimate economic value of mobile Internet technology falls far short of its potential, mobile Internet use will almost certainly have lasting and profound effects. In just the past few years, smartphones and tablets have had enormous impact on business sectors ranging from personal computers to TV networks. They have opened up new paths to economic inclusion and growth in developing economies. But perhaps the most enduring effects will come from our now ubiquitous connectivity, which in many societies has changed human behavior profoundly. Mobile Internet access does not endow users with superhuman powers, but it has shown the potential to make our lives more convenient, effortless, and enjoyable.

³⁸ *Online and upcoming: The Internet's impact on aspiring countries*, McKinsey Global Institute, January 2012.

2. Automation of knowledge work



A confluence of advances in computational speed, machine learning, and natural user interfaces has brought computing to an important milestone: computers are now becoming capable of doing jobs that it was assumed only humans could perform.³⁹ Computers, for example, can now act on “unstructured” commands—answering a question posed in plain language—and even make subtle judgments. They can sift through massive amounts of information to discern patterns and relationships. They can “learn” rules and concepts based on examples or simply by crunching data. And, with advanced interfaces and artificial intelligence software, they can understand and interpret human speech, actions, and even intentions from ambiguous commands. In short, computers can increasingly do many of the tasks that are currently performed by knowledge workers (see Box 6, “Vision: The power of omniscience”).

The commercialization of computers with this level of intelligence over the coming decade could have massive implications for how knowledge work is conducted. Such tools could both extend the powers of human workers and allow them to offload tedious detail work. But these advanced tools could also ultimately lead to some jobs being automated entirely.

Automation has already swept through manufacturing and transaction work (tasks that consist of executing simple exchanges, such as taking deposits or checking customers out of a grocery store). When it comes to knowledge work, the impact of automated tools could be less direct. Knowledge work jobs generally consist of a range of tasks, so automating one activity may not make an entire position unnecessary (the way welding robots make welders redundant, for example). In addition, knowledge work has become more complex, in large part due to information technology, creating demand for workers with new skills who can perform new kinds of tasks.

Nonetheless, there is potential for emerging tools to have a dramatic economic impact by 2025. In the applications we sized, we estimate that knowledge work automaton tools and systems could take on tasks that would be equal to the output of 110 million to 140 million full-time equivalents (FTEs). It is possible that this incremental productivity—which does not include any estimate of the value of higher quality output due to better knowledge tools—could have as much as \$5.2 trillion to \$6.7 trillion in economic impact annually by 2025.⁴⁰

As with advanced robotics (see Chapter 5), automation of knowledge work could bring great societal benefits—such as improved quality of health care and faster drug discovery—but may also spark complex societal challenges, particularly in employment and the education and retraining of workers. This technology could

³⁹ Erik Brynjolfsson and Andrew McAfee, *Race against the machine: How the digital revolution is accelerating innovation, driving productivity, and irreversibly transforming employment and the economy*, Digital Frontier Press, 2011.

⁴⁰ Cost of employment numbers include salaries and benefits.

change the nature of work for many people, requiring innovation to fully realize its potential while managing its risks.

Box 6. Vision: The power of omniscience

It's 2025 and you arrive at your desk for another day at work. As you take your seat, the day's appointments are displayed in front of you and your digital assistant begins to speak, giving you a quick rundown of the 43 new posts on the departmental communications site. Three are important for today's meetings; the rest will be summarized by the system and sent in the daily report. The assistant notes that all the reports and multimedia presentations have been uploaded for your meetings.

Now it's time for the tough part of the day: your doctor appointment. You received a request for an appointment yesterday when your biosensor alerted your digital physician to a change in your blood pressure. Your vital signs are scanned remotely, and the system cross-checks this information with journal cases, your family's history of hypertension, your diet and exercise routines, and the vital signs of other men your age. Good news: "You don't need drugs, but you do need to stop eating fast food and skipping the gym," your computerized doctor says. Relieved, you stop at the gym on the way home and ask your mobile device to order a salad to be delivered when you get home.

DEFINITION

We define knowledge work automation as the use of computers to perform tasks that rely on complex analyses, subtle judgments, and creative problem solving. Knowledge work automation is made possible by advances in three areas: computing technology (including processor speeds and memory capacity), machine learning, and natural user interfaces such as speech recognition technology.

These capabilities not only extend computing into new realms (for example, the ability to "learn" and make basic judgments), but also create new relationships between knowledge workers and machines. It is increasingly possible to interact with a machine the way one would with a coworker. So, instead of assigning a team member to pull all the information on the performance of a certain product in a specific market or waiting for such a request to be turned into a job for the IT department, a manager or executive could simply ask a computer to provide the information. This has the potential to provide more timely access to information and raise the quality and pace of decision making and, consequently, performance.

Advances in software, especially machine learning techniques such as deep learning and neural networks, are key enablers of knowledge work automation.⁴¹ These techniques give computers the ability to draw conclusions from patterns they discern within massive data sets (anything from all legal cases of the past 20 years to data concerning the way in which molecular compounds react with one another). Importantly, computers with machine learning capabilities no longer rely only on fixed algorithms and rules provided by programmers. They can also modify and adjust their own algorithms based on analyses of the data, enabling them to “see” relationships or links that a human might overlook. Moreover, these machines can “learn” more and get smarter as they go along; the more they process big data, the more refined their algorithms become.

Finally, advances in user interfaces, such as speech and gesture recognition technology, give computers the ability to respond directly to human commands and requests. So, for example, managers will no longer have to learn computer syntax or send a request to the IT department to get a question answered by a computer. Apple’s Siri and Google Now use such natural user interfaces to recognize spoken words, interpret their meanings, and act on those meanings. This requires significant processing power and sophisticated software to filter words from background noise, to parse sentences, and to then make “smart” guesses about the intent of the query—for example, by offering up the names of sushi restaurants when the speaker asks for Japanese food.

POTENTIAL FOR ACCELERATION

Using these emerging tools, it will be possible to automate an expanding variety of knowledge worker tasks. As noted, the force of automation has already swept through manufacturing and transaction work, with profound impact. To put this in perspective, in 40 years of automating transaction work, in some US transaction occupations, more than half of the jobs were eliminated. ATMs took on the work of bank tellers, self-serve airline reservation systems replaced travel agents, and typists all but disappeared (Exhibit 3).

Today, total global employment costs are \$33 trillion a year and, on current trend, could reach \$41 trillion by 2025. We analyzed a subset of knowledge worker occupations with employment costs that could reach \$14 trillion by 2025. These workers—professionals, managers, engineers, scientists, teachers, analysts, and administrative support staff—represent some of the most expensive forms of labor and perform the most valuable work in many organizations. Few of these workers have benefited from tools that can augment core aspects of their work involving decision making and judgment.

41 Many current machine learning approaches mimic aspects of the human brain. Neural networks simulate brain structures via interconnected layers of “artificial neurons,” which adaptively strengthen or weaken their interconnections based on experience. Deep learning technology makes use of algorithms that form a learning hierarchy in which higher-level concepts are defined using layers of lower-level concepts (often using neural networks). Some machine-learning algorithms don’t require labeling or preclassification of their training examples and can instead identify their own categories and concepts (e.g., by cluster analysis).

Rapid advances in underlying technologies are reducing costs and boosting performance, making knowledge automation more attractive. Computing power continues to grow exponentially (approximately doubling every two years on a price/performance basis), and today a \$400 iPhone 4 offers roughly equal performance (in millions of floating point operations per second, or MFLOPS) to the CDC 7600 supercomputer, which was the fastest supercomputer in 1975 and cost \$5 million at the time.⁴² These advances in computational power have been accompanied by significant strides in data storage systems, big data (the ability to process and analyze huge amounts of data, such as real-time location feeds from millions of cellphones), and cloud computing (which makes the computational power needed for knowledge work automation accessible to even individuals and small businesses via Internet-enabled devices).

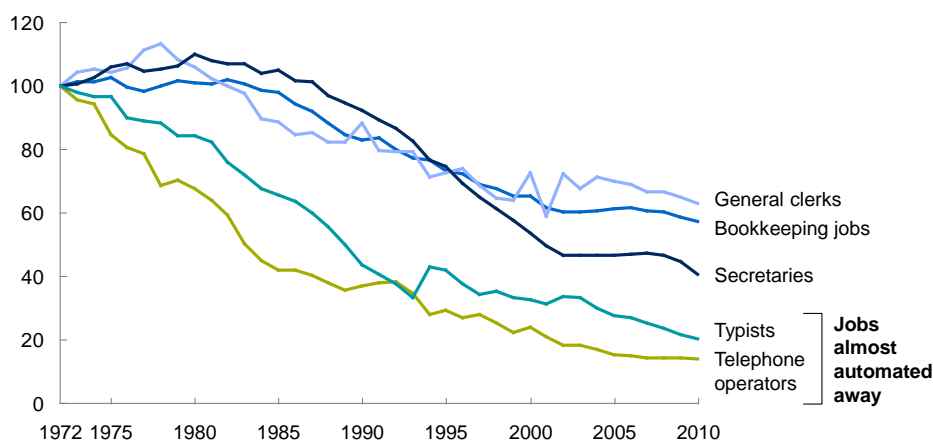
Exhibit 3

The number of transaction workers in the United States across some major job types declined more than 50 percent between 1970 and 2010

Decline in transactional jobs between 1970 and 2010¹

% workforce share decline for select highly automatable jobs

Index: 100 = 1972



¹ Job types that can be scripted, routinized, automated (e.g., cashiers, receptionists, stock traders). Data are for the US private economy. Occupation data normalized in 1983 and 2003 to account for classification differences.

SOURCE: US Bureau of Labor Statistics 1972–2010; McKinsey Global Institute analysis

POTENTIAL ECONOMIC IMPACT

Overall, we estimate the potential economic impact of knowledge automation tools in the types of work we assessed could reach \$5.2 trillion to \$6.7 trillion per year by 2025 due to greater output per knowledge worker (Exhibit 4). Of this total, the lion's share (\$4.3 trillion to \$5.6 trillion) could be generated in advanced economies where wage rates are higher. In advanced economies, we estimate annual knowledge worker wages at about \$60,000, compared with about \$25,000 in developing economies, and project that increased automation could drive additional productivity equivalent to the output of 75 million to 90 million full-time workers in advanced economies and 35 million to 50 million full-time workers in developing countries.

⁴² Gordon Bell, "A Seymour Cray perspective," Microsoft Research, November 1997.

Exhibit 4
Sized applications of automation of knowledge work could have direct economic impact of \$5.2 trillion to \$6.7 trillion per year in 2025



Sized knowledge worker occupations		Potential economic impact of sized occupations in 2025 \$ trillion, annually	Estimated scope in 2025	Estimated potential reach in 2025	Potential productivity or value gains in 2025
Common business functions	Clerical	1.1–1.3	<ul style="list-style-type: none"> \$4.4 trillion in knowledge worker costs 125 million knowledge workers 	50–65 million full-time equivalents (FTEs) of work potentially automatable	\$35,000 value per FTE of additional productivity
	Customer service and sales	0.6–0.9			
Social sector services	Education	0.8–1.0	<ul style="list-style-type: none"> \$2.8 trillion in knowledge worker costs 55 million knowledge workers 	20–30 million FTEs of work potentially automatable	\$50,000 value per FTE of additional productivity
	Health care	0.3–0.4			
Technical professions	Science and engineering	0.6–0.7	<ul style="list-style-type: none"> \$2.2 trillion in knowledge worker costs 35 million knowledge workers 	15 million FTEs of work potentially automatable	\$60,000 value per FTE of additional productivity
	IT	0.4–0.5			
	Managers	0.8–1.1	<ul style="list-style-type: none"> \$2.9 trillion in knowledge worker costs 50 million knowledge workers 	15–20 million FTEs of work potentially automatable	\$60,000 value per FTE of additional productivity
Professional services	Finance	0.4–0.5	<ul style="list-style-type: none"> \$1.5 trillion in knowledge worker costs 25 million knowledge workers 	10 million FTEs of work potentially automatable	\$65,000 value per FTE of additional productivity
	Legal	0.2–0.3			
Other potential applications (not sized)					
Sum of sized potential economic impacts		5.2–6.7			

NOTE: Estimates of potential economic impact are for some applications only and are not comprehensive estimates of total potential impact. Estimates include consumer surplus and cannot be related to potential company revenue, market size, or GDP impact. We do not size possible surplus shifts among companies and industries, or between companies and consumers. These estimates are not risk- or probability-adjusted. Numbers may not sum due to rounding.

SOURCE: McKinsey Global Institute analysis

To gauge the impact of automation across knowledge work, we looked at the number of employees and employment costs for 20 knowledge worker occupations across 11 countries (seven developed and four developing), which employ 75 percent of all workers in these occupations and whose employers pay about 80 percent of global employment costs. From this, we estimated the potential productivity improvement per unit of labor by comparing the estimated costs of relevant technology against the total cost of employment for potentially affected occupations. We found the largest potential impact in common business functions such as clerical and administrative work (\$1.7 trillion to \$2.2 trillion), followed by jobs in the social services sector such as education and health care (\$1.1 trillion to \$1.4 trillion), and then technical professions and management (about \$1 trillion each).

Common business functions

Many common business functions (for example, call center sales, administrative support, and customer service) involve answering questions or carrying out tasks for other workers or customers. Advances in natural user interfaces (including software that can understand and act on questions using ordinary speech, rather than in the strict format and syntax of computer languages) could make many of these tasks automatable. It is possible that by 2025, productivity gains

of 40 to 50 percent could be achieved for the 125 million knowledge workers in this category, which would lead to economic impact of \$1.7 trillion to \$2.2 trillion per year.

A company called SmartAction, for example, provides call automation solutions that use machine learning combined with advanced speech recognition to improve upon conventional interactive voice response (IVR) systems. SmartAction says that an auto club using its system has cut the time per call for its 24/7 roadside assistance service by half, realizing cost savings of 60 to 80 percent over an outsourced call center using human agents. These types of intelligent systems are able to automate many calls while minimizing customer frustration with touch-tone or primitive voice-response systems (which offer prompts such as, “If this is correct, say yes”). This can lead to higher call completion and lower abandoned call rates.⁴³

Currently available intelligent personal assistants such as Apple’s Siri and Google Now illustrate some of the possible uses of these technologies in administrative support roles. The Google Now service already anticipates user needs, making recommendations or delivering information based on browser history, calendar entries, and current location. For example if traffic is bad, Google Now may suggest that the user leave early, having combined routing and traffic information with data about the time and location of the user’s next appointment.

Social sector services

Knowledge work automation could have important effects in education and health care, two large service sectors that are under pressure to improve productivity and quality. Knowledge work automation can augment teacher abilities and enhance or replace lectures with “adaptive” learning programs—dynamic instruction systems that alter the pace of teaching to match the student’s progress and suggest additional drills based on student responses. Another area of potential impact is automated grading. A company called Measurement Incorporated won a \$100,000 prize from the Hewlett Foundation in 2012 for developing technology that enables a computer to grade student-written responses, including essays, as well as a skilled human grader can.⁴⁴

The economic impact of such tools in education would come from improving instructional quality and enabling teachers to provide more one-on-one attention and coaching. New self-teaching tools could also enable fundamental changes in scheduling: courses could be tied to subject mastery, rather than semesters or quarters, allowing students to progress at their own pace.

In health care, oncologists at Memorial Sloan-Kettering Cancer Center in New York are using IBM’s Watson supercomputer to provide chronic care and cancer treatment diagnostics by accessing knowledge from 600,000 medical evidence reports, two million pages of text from 42 medical journals, and 1.5 million patient records and clinical trials in the field of oncology. It can then compare each patient’s individual symptoms, vital signs, family history, medications, genetic makeup, diet, and exercise routine to diagnose and recommend a treatment

43 *Roadside assistance customers benefit from smart support during peak and after hours*, SmartAction case study of Canadian Automobile Association Saskatchewan, June 2012.

44 Measurement Incorporated, “MI’s automated essay scoring system takes first prize in national competition,” press release, October 4, 2012.

plan with the highest probability of success.⁴⁵ This could be the first of many applications of knowledge work automation in medical diagnostics, given the costs of misdiagnoses.

It is possible that productivity gains of 40 to 50 percent could be achieved by 2025 in the social sector categories we sized, which employ 55 million people worldwide. We estimate that this could lead to economic impact of \$1.1 trillion to \$1.4 trillion per year.

Technical professions

The ability to use deep learning techniques to discover new relationships in huge amounts of data and to determine which relationships are the most important amounts to an enormous shortcut in many kinds of technical work—from software design to drug discovery. For example, by applying deep learning to drug development data, researchers can quickly narrow the field of possible formulations from thousands to dozens, drastically speeding up the discovery process and saving thousands of hours of labor. A team of researchers in a contest sponsored by Merck recently proved that a deep-learning computer could examine an unfamiliar data set of chemical structures and develop its own rules to narrow down the thousands of unique molecules to those with the greatest potential to be effective.⁴⁶ Software engineers are using machine learning to speed up software development through automated testing and algorithm performance optimization, as well as project management tasks such as managing code libraries, tracking version control, and dividing tasks between developers.⁴⁷

By 2025, there is potential for productivity gains of about 45 to 55 percent in this category, which employs about 35 million knowledge workers worldwide. This could lead to economic impact of \$1.0 trillion to \$1.2 trillion per year. In our analysis, we examined the impact of knowledge work automation only on the cost of employment in technical fields, excluding the potential value of new scientific discoveries or improved research. Therefore, the full impact of innovation in this category could be substantially larger than our estimates.

Management

Machine learning excels at the complex analytics that managers use to monitor activities under their responsibility, understand the root causes of issues as they arise, and accurately forecast future trends on the horizon. For example, managers currently use machine-learning technology to monitor, control, and diagnose faults in manufacturing plants.

By 2025, it is possible that productivity gains of 30 to 40 percent could be achieved for the 50 million knowledge workers in this category, which would lead to economic impact of \$0.8 trillion to \$1.1 trillion per year.

45 Jonathan Cohn, “The robot will see you now,” *The Atlantic*, February 20, 2013.

46 John Markoff, “Scientists see promise in deep-learning programs,” *The New York Times*, November 23, 2012.

47 Jitesh Dundas, “Machine learning helps software development,” *Software Magazine*, June 2012.

Professional services

Fields such as law and financial services are already beginning to see the benefits of knowledge worker automation. Law firms, for example, are using computers that can scan thousands of legal briefs and precedents to assist in pretrial research—work that would once have taken hundreds or thousands of hours of paralegal labor. Symantec's Clearwell system uses language analysis to identify general concepts in documents and present the results graphically. In one case, this software was able to analyze and sort more than 570,000 documents in two days.⁴⁸

Artificial intelligence (AI) has played a role in financial transactions for some time. AI algorithms are able to parse myriad news stories, financial announcements, and press releases, make decisions regarding their trading relevance, and then act in slivers of a second—faster and with greater information recall than any human trader.⁴⁹ Banks can also use machine learning to detect fraud, finding charges or claims outside a person's normal buying behavior. Even services like Future Advisor use AI to offer personalized financial advice inexpensively and at scale.

Based on our estimates, it is possible that by 2025, productivity gains of 45 to 55 percent could be achieved for the 25 million knowledge workers in this category, which would lead to economic impact of \$0.6 trillion to \$0.8 trillion per year.

BARRIERS AND ENABLERS

Realizing the full potential impact of knowledge work automation will involve overcoming some technological, regulatory, and organizational hurdles. Artificial intelligence, while showing remarkable advances, will still have to develop significantly before the scale of benefits that we estimate here can be realized. While we believe that very rapid advances in these areas could be possible over the coming decade, many of the most important future applications, such as diagnosis support for physicians, are still in experimental stages.

Cultural and organizational hurdles also exist. Risk-averse firms may delay adoption until the benefits of these technologies have been clearly proven. And, in some cases, there could be resistance. Many attorneys were initially hesitant to use computerized research systems because they did not trust the machines to catch every document. Some business leaders might have concerns about legal liability regarding situations in which these technologies make mistakes (for example, with a patient diagnosis).

Once the decision is made to adopt these technologies, business leaders will need to prepare for how they will be introduced, what tasks will be either augmented or fully automated, and how to alter roles and organizational processes to adjust for these changes. Figuring out how best to design roles and restructure organizations to fully realize the value of this technology could take time.

48 John Markoff, "Armies of expensive lawyers replaced by cheaper software," *The New York Times*, March 4, 2011.

49 For one interesting example of the use of AI in stock trading, see Christopher Mims, "AI that picks stocks better than the pros," *MIT Technology Review*, June 10, 2010.

Finally, in some cases there may be regulatory hurdles to overcome. To protect citizens, many knowledge work professions (including legal, medical, and auditing professions) are governed by strict regulatory requirements regarding who may perform certain types of work and the processes they use. Automated knowledge work applications in many highly regulated industries may need to undergo significant testing to verify their effectiveness before they will be allowed to perform skilled knowledge worker tasks; in many cases, humans may have to retain final review and approval over the work of these systems.

IMPLICATIONS

The automation of knowledge work has the potential to become pervasive, transforming the economics of many industries, but also posing challenges and opportunities for technology providers, virtually all business leaders, individuals, and policy makers.

Technology providers (both software and hardware) will play a critical role in this nascent field by designing powerful, easy-to-use knowledge work applications and supporting adoption within organizations. There could be many opportunities across a range of possible capabilities and approaches. Some technology providers might focus on high-end, advanced systems such as the Watson supercomputer, perhaps configured as enterprise solutions or programmed for specific verticals such as medicine. Others might focus on next-generation assistants similar to Apple's Siri for both businesses and consumers. And many might focus on special-purpose tools for analytics, search functions, or a host of other potential applications. These knowledge work automation tools could be delivered in many ways, including via enterprise solutions, apps, or Web services. They could be delivered via the cloud (see Chapter 4) and on mobile Internet devices (see Chapter 1). They could also integrate with Internet of Things devices, both to analyze additional data and to directly control processes and environments (see Chapter 3).

Many companies will need support in change management, technical installation, process redesign, and employee training as they upgrade their technology platforms. Technology providers, IT consultants, and systems integrators are likely to find new opportunities to help businesses make these transitions successfully, perhaps using knowledge work automation technology themselves to better manage projects and conduct advanced analyses.

The first task for business leaders is to understand how knowledge work is (and will be) carried out in their organizations, including where the most time and money are spent, which functions contribute the most value, and which contribute the least, and where productivity is lowest. Answering such questions will help set priorities regarding areas in which the adoption of tools to automate knowledge work might be both feasible and able to create consistently higher performance. Given the potential power of these tools, the biggest benefits may come from applying knowledge work automation to boost the productivity of employees in high-value-added functions, rather than focusing on simple tasks that might be turned over entirely to machines.

To capture the benefits of knowledge work automation, companies and social service institutions will need to manage fundamental organizational change. Many knowledge worker jobs could be redefined, and if so, workers will need retraining, both to work with new technologies and to learn new tasks and skills as their jobs evolve. Some categories of knowledge jobs could become obsolete, as happened when word processing programs on desktop computers reduced the need for typists. In addition, much of the automation of knowledge work technology may require the intelligence of organizations to be codified, perhaps in many cases by the very workers who are adopting or even being replaced by this technology. This could create challenges for employers looking to obtain robust employee support for adoption and will require careful communication and change management.

Knowledge work automation has the potential to provide enormous societal benefits, including helping to discover new medicines. These technologies could also directly address serious gaps in the supply of workers who have the skills needed to drive 21st-century economies.⁵⁰ However, the potential impact of this technology on employment could be a subject of intense debate. As we have seen in previous waves of manufacturing and transaction work automation, these changes often happen faster than social institutions can adjust. And while previous productivity gains have generally resulted in the emergence of new high-value-added jobs, it is not always the displaced workers who benefit most from these opportunities.

Automation of knowledge work could drive the creation of many new types of jobs if businesses and governments can innovate effectively and adjust education and training to focus on new skills. As with advanced robotics, these technologies could also create jobs for experts who can create and maintain the technology itself. However, increased productivity without innovation and retraining could ultimately exert downward pressure on wages and increase income disparities.

The effects of these technologies on developing economies could be mixed. Some countries could lose opportunities to provide outsourced services if companies in advanced economies choose automation instead. But access to knowledge work automation technologies could also help level the playing field, enabling companies in developing countries to compete even more effectively in global markets.

In addition to dealing with the employment and macro-economic effects of these technologies, policy makers and business leaders will be confronted with legal and ethical considerations. How will regulators and courts deal with harmful decisions made by computers (for example, if a computer were to give inappropriate medical treatment advice)? Who would be liable in such situations? Organizations might require that a human always make or approve final decisions, but what would happen when decisions and analyses become so complex as to exceed most people's ability to fully understand or audit them? We have already seen complex but poorly understood computer algorithms drive stock market turbulence. Similar risks could very well arise in other applications.

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

Finally, as computers transform knowledge work in the coming decade, debates about the role of thinking machines in society will undoubtedly intensify. Within this century, it could very well be possible to create machines with processing powers that far exceed those of the human brain. What capabilities will such machines have? How will they be harnessed? Will machines become “smarter” than humans? The answers to these questions will no longer be left to science fiction writers, academics, and philosophers.

3. The Internet of Things



Increasingly, the connected world includes physical objects. Machinery, shipments, infrastructure, and devices are being equipped with networked sensors and actuators that enable them to monitor their environment, report their status, receive instructions, and even take action based on the information they receive. Even people can be equipped with sensor-enabled devices—to track their health status, for example. This is what is meant by the term “the Internet of Things,” and it is growing rapidly. More than nine billion devices around the world are currently connected to the Internet, including computers and smartphones. That number is expected to increase dramatically within the next decade, with estimates ranging from quintupling to 50 billion devices to reaching one trillion.⁵¹

By bringing machines and assets such as shipping containers or hospital beds into the connected world, the Internet of Things enables new ways of monitoring and managing all the “moving parts” that make up a business. At any moment, management can see the status and flow of goods or materials through plants, distribution centers, and even onto store shelves. By monitoring machinery in real time, companies can better control the flow of goods through factories and avoid disruptions by taking immediate action or engaging in preventive maintenance when problems arise. Machines with embedded actuators in addition to sensors can be programmed to take action on their own. The widespread adoption of the Internet of Things will take time, but that timeline is shrinking thanks to improvements in underlying technologies such as miniature sensors and wireless networks.

The Internet of Things has the potential to create economic impact of \$2.7 trillion to \$6.2 trillion annually by 2025. Some of the most promising uses are in health care, infrastructure, and public-sector services—helping society tackle some of its greatest challenges. Remote monitoring, for example, has the potential to make a huge difference in the lives of people with chronic diseases while simultaneously attacking a significant source of rising health-care costs. The ability to monitor and control power grids and water systems could have major impacts on energy conservation, greenhouse gas emissions, and water loss. By using sensors to gather information to streamline operations, public-sector functions such as garbage collection can become much more productive. Sensor data could also be used to improve policing.

Realizing the full potential of the Internet of Things will not be easy. To capture the potential value of these applications, organizations will need to have the systems and capabilities to make sense of the flood of data that remote sensors can provide. For example, with more widespread use of radio-frequency identification (RFID) tags, some companies could track hundreds of thousands, or perhaps even millions, of items in real time, requiring considerable analytical capabilities and talent.

⁵¹ Joseph Bradley, Joel Barbier, and Doug Handler, *Embracing the Internet of everything to capture your share of \$14.4 trillion*, Cisco Systems, February 12, 2013.

Merging the physical and digital world also has implications for privacy, security, and even how companies are organized. As with any data connection, the connections that allow remote machines to take action without a human operator are subject to hacking by criminals or terrorists. The data collected via health monitoring could be abused. Even the in-home controllers for some smart grid applications (for example, controllers that can selectively turn air-conditioning or appliances on and off to save energy or take advantage of lower rates) raise questions about privacy and autonomy. These issues will need to be addressed before society and businesses will be able to enjoy the full benefits of the Internet of Things.

DEFINITION

The Internet of Things refers to the use of sensors, actuators, and data communications technology built into physical objects—from roadways to pacemakers—that enable those objects to be tracked, coordinated, or controlled across a data network or the Internet. There are three steps in Internet of Things applications: capturing data from the object (for example, simple location data or more complex information), aggregating that information across a data network, and acting on that information—taking immediate action or collecting data over time to design process improvements. The Internet of Things can be used to create value in several ways. In addition to improving productivity in current operations, the Internet of Things can enable new types of products and services and new strategies: remote sensors, for example, make possible pay-as-you-go pricing models such as Zipcar.

Internet of Things technology ranges from simple identification tags to complex sensors and actuators. RFID tags can be attached to almost any object. Sophisticated multisensor devices and actuators that communicate data regarding location, performance, environment, and condition are becoming more common. With newer technologies such as micro electromechanical systems (MEMS), it is becoming possible to place very sophisticated sensors in virtually any object (and even in people). And, because they are manufactured using a semiconductor-like fabrication process, MEMS are rapidly falling in price.

With increasingly sophisticated Internet of Things technologies becoming available, companies can not only track the flow of products or keep track of physical assets, but they can also manage the performance of individual machines and systems—an assembly line full of robots and other machines, for example. Sensors can also be embedded in infrastructure; for example, magnetic sensors in roads can count vehicles passing by, enabling real-time adjustments in traffic signal timing. Equally important as these sensors and actuators are the data communications links that transmit this data and the programming—including big data analytics—that make sense of it all.

Increasingly, Internet of Things applications include closed-loop setups in which actions can be triggered automatically based on data picked up by sensors. For example, in process industries, sensor-based systems can automatically react to incoming signals and adjust process flow accordingly. They can change a traffic light to green when a sensor in the pavement signals that cars are backed up at the intersection, or alert a doctor when the heart rate of a patient with a remote monitor spikes.

Basic uses of the Internet of Things are already well under way. One of the biggest applications so far employs RFID to track the flow of raw materials, parts, and goods through production and distribution. These tags emit a radio signal that can be used to pinpoint their location. So, for example, as a tagged product moves through a factory, computers can track where it is at any given moment. Using that information, the company can spot bottlenecks, managing the timing of the release of more parts into the system, or schedule trucks to pick up finished goods. RFID tags on containers and boxes are used to track products as they make their way through warehouses and transportation hubs to store shelves and (in cases where tags are used on packaging) even all the way to the consumer. Tracking these flows gives companies the opportunity to tighten supply chains and avoid stock-outs or building too much inventory. RFID tags are also used in E-ZPass toll-collection systems, speeding traffic flow on toll roads and bridges.

In another example, FedEx now offers a program that allows customers to track the progress of packages almost continuously by placing a small device (about the size of a mobile phone) into packages. These devices contain both a global positioning system and sensors to monitor temperature, humidity, barometric pressure, and light exposure, which are critical to cargo such as biological samples and sensitive electronic equipment. These devices are programmed to relay location and atmospheric condition information periodically so customers can know the exact whereabouts and condition of their packages and learn immediately if they veer off course or have been exposed to risky conditions. This type of continuous data availability obviously has implications for companies that operate long and complex supply chains.

POTENTIAL FOR ACCELERATION

The Internet of Things is still in early stages of adoption, but it already has a wide variety of uses, and the portfolio of applications is expanding daily. As Internet of Things technology proliferates, it has the potential to address many major needs, including improved resource productivity and infrastructure management. Smart grids for electricity, water, and transportation networks are examples. Electric and water utilities have been among the early adopter industries. Sensors are essential to smart grid systems, which give utility operators a way to gauge usage and network performance in real time. This means that rather than waiting to receive calls from customers whose lights have gone out, the electric company can spot a failure as it happens and, under some circumstances, even restore power by rerouting service around the failed transmission or generating equipment. Minnesota Power, a US utility company, has installed a smart grid system and upgraded feeder lines that allow the company to offer “100 percent uptime” to commercial customers.⁵² Internet-connected sensors are also being used to take seismic readings under the earth’s crust and monitor the flow of water through supply pipes. In the energy industry, sensors are used to map unexplored fossil fuel fields to pinpoint deposit locations.

⁵² SGIG accelerates grid modernization in Minnesota, Smartgrid.gov, US Department of Energy.

Internet of Things technology can also have a direct impact on human lives and health. The so-called Quantified Self concept—which involves using sensors to track exercise performance or monitor health—is an increasingly popular trend powered by Internet of Things technologies. For example, several companies are now selling wearable sensors that allow consumers to track the number of miles they run, their heart rate, and other data generated during exercise, which can then be used to manage health. Doctors now perform “capsule endoscopy” using a pill-shaped micro-camera with wireless data communication capabilities that travels through a patient’s digestive system and transmits images to a computer.

Several technological advances are improving the effectiveness of Internet of Things applications while also reducing costs. The price of RFID tags and sensors is falling, and new developments such as MEMS are enabling new uses. Sales of sensors have grown by 70 percent annually since 2010, and advances in technology are making more capable sensors more affordable. More sensors of various types are being integrated into more physical devices, and improved power management is allowing devices to run unattended for longer periods of time. Miniaturization and high-volume manufacturing techniques make it possible to install sensors in even the smallest devices; for example, a smartphone may have a single chip that includes a positioning sensor, a thermometer, and a motion detector. Finally, the spread of high-speed wireless data networks is extending the coverage area of the mobile Internet, helping pave the way to greater Internet of Things uses.

POTENTIAL ECONOMIC IMPACT BY 2025

We estimate the potential economic impact of the Internet of Things to be \$2.7 trillion to \$6.2 trillion per year by 2025 through use in a half-dozen major applications that we have sized (Exhibit 5). The largest impacts among sized applications would be in health care and manufacturing. Across the health-care applications we analyzed, Internet of Things technology could have an economic impact of \$1.1 trillion to \$2.5 trillion per year by 2025.

The greatest benefits in health care could come from improved efficiency in treating patients with chronic conditions. Using sensors that read the vital signs of patients at home, nurses and doctors can be alerted to emerging problems, such as a dangerous drop in the glucose levels of a diabetic patient. Advising patients about how to address problems at home or treating them in outpatient settings lowers the frequency of costly emergency room visits and unnecessary hospitalizations. Treatment costs for chronic diseases constitute approximately 60 percent of total health-care spending, and the annual cost of these diseases in 2025 could be as high as \$15.5 trillion globally.⁵³ We estimate that remote monitoring could reduce this cost by 10 to 20 percent where applied, although realized value might be reduced by factors such as adoption rates and patient acceptance (or resistance).⁵⁴

53 McKinsey estimate based on current data from Canada, France, the United States, and the United Kingdom.

54 Based on a case study by the US Veterans Health Administration regarding chronic heart failure, diabetes, and chronic obstructive pulmonary disease, including more than 70,000 patients. See Andrew Broderick and David Lindeman, “Scaling telehealth programs,” *Case Studies in Telehealth Adoption*, January 2013.

Exhibit 5

Sized applications of the Internet of Things could have direct economic impact of \$2.7 trillion to \$6.2 trillion per year in 2025



Sized applications	Potential economic impact of sized applications in 2025 \$ trillion, annually	Estimated scope in 2025	Estimated potential reach in 2025	Potential productivity or value gains in 2025
Health care	1.1–2.5	<ul style="list-style-type: none"> \$15.5 trillion cost of treating chronic diseases \$400 billion cost of counterfeit drugs, 40% addressable with sensors 50 million nurses for inpatient monitoring <ul style="list-style-type: none"> Developed world: \$30 per hour Developing: \$15 per hour 	<ul style="list-style-type: none"> 70–80% mobile penetration in patients who account for bulk of health-care spending Counterfeit drug tracking <ul style="list-style-type: none"> Developed world: 50–80% Developing world: 20–50% Inpatient monitoring <ul style="list-style-type: none"> Developed world: 75–100% Developing: 0–50% 	<ul style="list-style-type: none"> 10–20% cost reduction in chronic disease treatment through remote health monitoring 80–100% reduction in drug counterfeiting 0.5–1.0 hour time saved per day by nurses
Manufacturing	0.9–2.3			
Electricity	0.2–0.5	<ul style="list-style-type: none"> \$47 trillion in global manufacturing operating costs 	<ul style="list-style-type: none"> 80–100% of all manufacturing 	<ul style="list-style-type: none"> 2.5–5.0% saving in operating costs, including maintenance and input efficiencies
Urban infrastructure	0.1–0.3	<ul style="list-style-type: none"> 27,000–31,000 TWh global electricity consumption \$200 billion spending on transmission lines 300 billion consumer minutes outage 	<ul style="list-style-type: none"> 25–50% of consumers could adopt energy management 25–50% of grid monitored through sensors 50–100% of consumer meters automated 	<ul style="list-style-type: none"> 2–4% reduction in demand peaks in the grid Reduction of total load on grid Operating/maintenance savings; shorter outage time through automated meters
Security	0.1–0.2			
Resource extraction	0.1–0.2	<ul style="list-style-type: none"> 200–300 hours commuting time per urban worker per year \$200 billion spent on urban water \$375 billion cost of waste handling 	<ul style="list-style-type: none"> 40–70% of working urban population living in cities with smart infrastructure 50–70% of large urban regions adopting smart water infrastructure and waste handling 	<ul style="list-style-type: none"> 10–20% reduction in average travel time through traffic and congestion control 10–20% reduction in water consumption and leaks with smart meters and demand control 10–20% reduction in cost of waste handling
Agriculture	~0.1			
Retail	0.02–0.10	<ul style="list-style-type: none"> \$6 trillion cost of crime 	<ul style="list-style-type: none"> Adoption of advanced surveillance by countries accounting for 50–70% of global GDP 	<ul style="list-style-type: none"> 4–5% crime reduction through improved surveillance
Vehicles	~0.05	<ul style="list-style-type: none"> \$3.7 trillion in global mining operating costs 	<ul style="list-style-type: none"> 80–100% of all resource extraction 	<ul style="list-style-type: none"> 5–10% saving in operating costs from productivity gains
Other potential applications (not sized)		<ul style="list-style-type: none"> \$630 billion in automotive insurance premiums¹ 	<ul style="list-style-type: none"> 10–30% of all insured cars equipped with sensors 	<ul style="list-style-type: none"> 25% reduction in cost of vehicle damage from collision avoidance and increased security¹
Sum of sized potential economic impacts	2.7–6.2	<ul style="list-style-type: none"> \$200 billion lost due to stockouts \$1.2–1.3 trillion in agricultural production (wheat, maize, rice, soybeans, barley) 	<ul style="list-style-type: none"> 30–80% of retail adopting smart logistics 20–40% adoption of advanced irrigation systems and precision farming 	<ul style="list-style-type: none"> 1.5–2.0% increased sales 10–20% increase in yields from precision application of fertilizer and irrigation

¹ Automotive premiums used as proxy for cost of collisions.

NOTE: Estimates of potential economic impact are for some applications only and are not comprehensive estimates of total potential impact. Estimates include consumer surplus and cannot be related to potential company revenue, market size, or GDP impact. We do not size possible surplus shifts among companies and industries, or between companies and consumers. These estimates are not risk- or probability-adjusted. Numbers may not sum due to rounding.

SOURCE: McKinsey Global Institute analysis

Additional value from use of Internet of Things systems in health care would include in-hospital health monitoring. Based on cases where physicians and nurses have had access to real-time patient data, potential gains of 30 minutes to one hour of time per day per nurse could be possible. Counterfeit drugs are another health-care problem with a possible Internet of Things solution. Currently, more than \$75 billion worth of counterfeit drugs are sold per year, and that amount is growing by around 20 percent annually.⁵⁵ Using sensors on bottles and packages could reduce the sale of counterfeit drugs by enabling consumers to ensure that their medications are legitimate. We estimate that this technique could apply to 30 to 50 percent of drugs sold and could be successful 80 to 100 percent of the time.

In manufacturing, Internet of Things technology can improve operational efficiency in a variety of ways. Sensors can be used to track machinery and provide real-time updates on equipment status, decreasing downtime. Sensors can also be placed on trucks and pallets to improve supply chain tracking and management. They can be used to monitor the flow of inventory around factory floors or between different workstations, reducing work-in-progress inventory levels, decreasing wait times, and creating transparency to better optimize flows. In precision manufacturing, sensors and actuators can even be used to change the position of objects as they move down assembly lines, ensuring that they arrive at machine tools in an optimum position, avoiding the small deviations in the position of work in process that can jam or even damage machine tools.

We estimate that productivity gains equivalent to 2.5 to 5 percent are possible from Internet of Things applications that we sized in discrete and process manufacturing industries. The total operating cost of global manufacturing is currently about \$25 trillion per year and could reach more than \$47 trillion by 2025. Given the low cost of sensors and the large demand for process optimization in manufacturing, very high adoption rates are possible; in fact, perhaps 80 to 100 percent of all manufacturing could be using Internet of Things applications by 2025. This would lead to potential economic impact of \$900 billion to \$2.3 trillion per year by 2025.

Smart electrical grid systems are an important Internet of Things application, with a potential annual value that we estimate could be \$200 billion to \$500 billion by 2025. The bulk of this impact would come from demand-management applications that could reduce costly peak usage, which often requires utilities to buy electricity at the highest rates or invest in extra peak capacity (see Chapter 8, “Energy storage”). Many commercial customers already avoid scheduling energy-intensive processes and production during periods of peak energy demand, when energy costs are at their highest, and some have formal agreements with utilities to reduce usage whenever demand reaches a certain level. Operators of data centers, which constitute one of the fastest-growing consumers of electricity, are starting to adopt power-management techniques based on real-time grid information. With smart grids, consumers can let the utility company automatically power down high-use systems and appliances during periods of peak demand or they can make their own choices based on real-time rate information that the utility supplies. Demand management could reduce peak demand by 2 to 4 percent and cut overall demand by 1 to 2 percent. This would allow utilities to avoid building potentially billions of dollars’ worth of additional capacity and infrastructure.

⁵⁵ Center for Medicine in the Public Interest.

Smart grids also help cut utility operating costs by providing real-time information about the state of the grid. Potential benefits of this include reducing total outage times and decreasing electricity waste by better regulating voltage and balancing load between lines. Grid sensors can monitor and diagnose network problems to prevent outages and reduce maintenance costs. At the user end, smart meters equipped with two-way communication capabilities could reduce outage minutes and enable faster outage detection. Smart meters also enable automatic meter reading, eliminating the need for personnel to gather that information.

The Internet of Things is an important enabler of better management of urban infrastructure, systems, and services, including traffic, waste and water systems, and public safety. Sensors that monitor traffic patterns can generate the data to optimize flow by adjusting traffic light timing, imposing congestion charges, and changing bus routes, for example. Sensors can automatically trigger an alert to divert traffic around accidents to minimize costly delays. London, Singapore, and Houston have all realized significant reductions in commuting times using this technology. Based on these examples, cities could cut motor vehicle commuting time by 10 to 20 percent on average, saving hundreds of millions of hours a year.

Cities can also use Internet of Things technology to streamline garbage collection and improve water management. In the United States, the cities of Cleveland and Cincinnati in Ohio have both supplied households with garbage and recycling bins equipped with RFID tags, which allow city crews to see whether residents are putting out garbage and recycling on the designated days. As a result of these data, Cleveland was able to eliminate 10 pickup routes and cut operating cost by 13 percent through improved labor productivity. Both cities also instituted “pay as you throw” programs, which require residents to pay extra for putting out more garbage than fits in city-issued bins. In Cincinnati, residential waste volume fell 17 percent and recycling volume grew by 49 percent through the use of these programs. Using conservative assumptions, such measures could reduce waste handling costs by 10 to 20 percent by 2025.

The cities of Doha, São Paulo, and Beijing all use sensors on pipes, pumps, and other water infrastructure to monitor conditions and manage water loss, identifying and repairing leaks or changing pressure as necessary. On average, these cities have reduced leaks by 40 to 50 percent. Smart meters at the user end allow real-time monitoring of demand and leak detection by residents and property managers, reducing costs. Dubuque and Indianapolis in the United States, as well as Malta, New Delhi, and Barrie (Ontario), have seen, on average, a 5 to 10 percent reduction in water usage via the use of smart water meters.

The total potential economic impact from traffic applications, smart waste handling, and smart water systems in urban areas could total \$100 billion to \$300 billion per year by 2025. This assumes that 80 to 100 percent of cities in advanced economies and 25 to 50 percent of cities in the developing world could have access to this technology by that time.

The Internet of Things can also improve law enforcement efforts. It will soon be possible to place inexpensive sensors on light poles, sidewalks, and other objects on public property to capture sound and images that can be analyzed in real time—for example, to determine the source of a gunshot by analyzing the sound from multiple sensors. This could potentially take policing to a new level of effectiveness, creating an opportunity to reduce both the human and economic

costs of crime. The economic cost of crime is estimated to be 5 to 10 percent of GDP around the world. If 4 to 5 percent of this could be eliminated, the potential economic impact could be \$100 billion to \$200 billion per year in 2025.

In the oil, metal, and mineral extraction industries, Internet of Things technology could help find and map mineral deposits and increase recoverability. Operating costs reductions of 5 to 10 percent have been realized through the use of sensors and big data in basic material extraction. The total operating cost for the oil, metal, and mineral extraction industries in 2025 is estimated to be \$1.4 trillion. The adoption of Internet of Things technologies could be very high in this industry, perhaps 80 to 100 percent. At that level of adoption, potential economic impact of \$100 billion to \$200 billion per year might be possible by 2025.

In agriculture, the Internet of Things has the potential to create significant value. For example, leaf sensors can measure stress in plants based on moisture levels. Soil sensors can gather information about how water moves through a field and track changes in soil moisture, carbon, nitrogen, and soil temperature. Such data would help farmers optimize irrigation schedules, avoiding crop damage. Soil and plant data can be used to guide “drip fertigation,” which applies liquid fertilizer through drip irrigation systems to ensure crops receive the correct amount of nutrients and water at all times. For example, in the United States, drip fertigation was used by Stamp Farms in Decatur, Michigan, to increase yields by 10 to 40 percent in corn. We estimate that using sensor data for “precision farming” could raise yields 10 to 20 percent globally. Assuming that 25 to 50 percent of farms adopt this approach, we estimate that in these applications, the Internet of Things could have the potential to create \$100 billion per year in economic impact in 2025.

The Internet of Things could help address the out-of-stock challenge in retail sales. It is estimated that retailers lose the equivalent of 4 percent of sales every year due to items desired by the consumer that are not in stock. By 2025, this could represent \$200 billion a year in lost value. We estimate that 35 to 50 percent of this value can be recaptured by using sensors and tags to tighten supply chains and predict where stock-outs are likely to occur. This could drive potential economic impact of \$20 billion to \$100 billion per year by 2025.

Adding sensors to automobiles to prevent crashes could create economic value of as much as \$50 billion per year by 2025. This estimate is based on the reduced property damage that would occur if automatic braking systems were widely used and prevented a large portion of low-speed collisions (we do not consider high-speed collisions, which often involve injury or death, in this analysis). We estimate that 25 percent of the damage caused by low-speed accidents could be avoided using Internet of Things technology, potentially resulting in \$50 billion globally in reduced property damages.

BARRIERS AND ENABLERS

The Internet of Things offers great promise, but all the pieces are not yet in place to guarantee that rising interest will turn into widespread investment and adoption. There are technical, financial, and regulatory issues that must be resolved. For example, early adopters will need to prove that sensor-driven business models create superior value.

On the technology side, the cost of sensors and actuators must fall to levels that will spark widespread use. Also, technology providers need to agree on standards that will enable interoperability between sensors, computers, and actuators. Until such standards exist, investing in Internet of Things applications will require extra effort to build and maintain integrated systems. It will also carry the additional risk of betting on the wrong technology, which could slow adoption. Progress is also needed in creating software that can aggregate and analyze data and convey complex findings in ways that make them useful for human decision makers or for use by automated systems (for example, calculating medication dosages based on real-time patient data).

The Internet of Things also faces hurdles due to privacy and security concerns, which will require action by both businesses and policy makers. As Internet of Things applications become more sophisticated and more operations fall under the supervision of sensor-based systems, data security and network reliability will be important concerns. As sensors are introduced into the lives of consumers via traffic control systems, health-care applications, smart grids, and retail space uses, concerns are likely to grow over how the data that are collected will be used. Will the information from medical monitors be used to deny individuals health insurance coverage? Could hackers steal sensor data regarding how your car moves in order to track your personal movements? Both businesses and regulators will have to address questions such as this to foster widespread adoption of these technologies.

For both consumers and businesses, sensor-based systems also create liability issues that policy makers need to address. For example, it is not fully clear who will be legally responsible for injuries or damages that are caused by errors in closed-loop systems in which an algorithm dictates the actions of a machine.

IMPLICATIONS

The Internet of Things is such a sweeping concept that it is a challenge to even imagine all the possible ways in which it will affect businesses, economies, and society. For the first time, computers are now able to receive data from almost any kind of physical object, enabling us to monitor the well-being and performance of machines, objects, land, and even people. Using the data from these sources, computer systems will be able to control machines, manage traffic, or tell a diabetic it is time to eat. Businesses will be challenged to make the most effective use of this technology given the level of innovation and technical expertise that will be required. This is new territory for almost everyone, even those with a high degree of technical expertise. Policy makers will likely have a long list of issues to resolve to allow the benefits of Internet of Things applications while protecting the rights and privacy of citizens.

For technology suppliers and the companies that adopt that technology, the Internet of Things promises rewards that will not always be easy to obtain. Hardware manufacturers that supply sensors, actuators, and communications devices will be pressed to continue to refine their products and reduce costs. For example, despite many years on the market, RFID tags are still too expensive for many businesses to use as extensively as was predicted a decade ago. Moreover, because systems could include hundreds of thousands of devices, sensors and other hardware will need to be reliable, maintenance-free, and interoperable. New partnerships will be needed between companies with capabilities in sensors and manufacturers of the machines, products, and objects into which they will

go. Some of the best-positioned companies may be suppliers of big data and analytical software that can help extract meaning from the enormous flows of data that the Internet of Things will produce.

Companies that hope to reap the benefits of operational improvements and use the Internet of Things to deliver new kinds of customer service and higher-quality products will face an array of technological and organizational challenges. Over the past two decades, the need to understand and use IT tools has spread across organizations. The Internet has forced sales and marketing departments to become masters of websites and Web analytics, for example. The Internet of Things takes this trend to a new extreme in which every department within an organization, from production to logistics to customer service and sales, could potentially receive real-time data about how the company's products are being built, distributed, sold, and used. Few organizations are ready to deal with this sheer amount of data and have personnel who are able to do so. Gaining access to the talent to manage Internet of Things applications and educating executives and managers across functions will need to be a top priority.

For policy makers, the Internet of Things also brings great opportunities and challenges. As operators of infrastructure and public services (often including health care), governments could be major adopters of Internet of Things applications. These technologies can reduce costs and improve quality of service, sometimes in lifesaving ways. City residents could see traffic flowing more smoothly, garbage picked up more efficiently, crime reduced, and water systems operating more efficient. The potential is enormous—but as in business, it will not be realized without substantial investments in capabilities.

In terms of public policy, government leaders will need to establish clear understandings of the privacy risks that accompany the Internet of Things. The ability to put sensors virtually anywhere—to observe the traffic on a residential street or to monitor a home's electricity use—will undoubtedly raise serious concerns about how all that information will be used. Realizing the benefits of the Internet of Things in policing, for example, may require an unprecedented level of surveillance that the public may reject.

Policy makers faced with these issues will need to think comprehensively and globally. One-off regulations and rules that are in conflict from one jurisdiction to another will not suffice. Policy makers will need to build consensus regarding what protections to put in place and work across borders and levels of government to make sure these protections can and will be universally enforced.

Unfortunately, computer systems and networks could be the targets of criminals, terrorists, or even just hackers trying to prove a point. With sensors and networks controlling critical systems such as the electric grid, the consequences of such attacks could be staggering. It will take a great deal of thought and planning, as well as collaboration with the private sector, to both create proper safeguards and keep them up to date as technological advances continue.

4. Cloud technology



Cloud technology has become a huge buzzword in recent years, and with good reason. The cloud already creates tremendous value for consumers and businesses by making the digital world simpler, faster, more powerful, and more efficient. In addition to delivering valuable Internet-based services and applications, the cloud can provide a more productive and flexible way for companies to manage their IT. Cloud technology has the potential to disrupt entire business models, giving rise to new approaches that are asset-light, highly mobile, and flexible.

Cloud technology allows the delivery of potentially all computer applications and services through networks or the Internet. With cloud resources, the bulk of computational work can be done remotely and delivered online, potentially reducing the need for storage and processing power on local computers and devices.⁵⁶ The most commonly used Internet services are already delivered through the cloud, including online searching, social networks, and streaming media. The cloud also enables pay-as-you-go models for consuming IT, as exemplified by the phrases “software as a service” and “infrastructure as a service.” By 2025 most IT and Web applications and services could be cloud-delivered or -enabled, and most businesses could be using cloud facilities and services for their computing resources.

The cloud enables some of the most highly impactful technologies we analyze in this report: mobile Internet, automation of knowledge work, and the Internet of Things. Since apps often rely on cloud resources, the cloud is expected to be a major driver of smartphone use. The total economic impact of cloud technology could be \$1.7 trillion to \$6.2 trillion annually in 2025. Most of this impact (\$1.2 trillion to \$5.5 trillion) could be in the form of additional surplus generated from cloud delivery of services and applications to Internet users, while the rest could result from the use of cloud technology to improve enterprise IT productivity.

As the cloud setup becomes a dominant computing paradigm, it could have wide-ranging implications for businesses, consumers, and policy makers. Consumers will likely continue to benefit as new cloud-enabled apps and services emerge and reduce the need to install and maintain local applications. Providers of “public” cloud services (services offered to multiple businesses) could see new competition from both large technology companies and their current enterprise customers, who could decide to develop their own cloud capabilities. Enterprises that take advantage of public or private cloud models could potentially see productivity gains and enjoy increased flexibility. Small enterprises and entrepreneurs could be able to use the agility provided by cloud technology to level the playing field with larger rivals. Finally, as cloud technology enables Internet-based delivery of more and more applications and services,

⁵⁶ This concept is also sometimes referred to as having a “thin client.”

policy makers will be under pressure to update laws relating to data ownership and privacy as they relate to the cloud.

DEFINITION

The concept of the cloud originated as a symbol for networks on diagrams of IT systems. Back then—in the days before personal computers, which first made processing and storage on the desktop the norm—users had “dumb” terminals that relied on a minicomputer or mainframe somewhere on the network (the cloud) for all resources. The modern cloud brings computer architecture full circle, enabling network access (from a computer or mobile Internet device) to a shared pool of computing resources such as servers, storage, and applications that can be used as needed.⁵⁷ Behind the scenes, this requires a complex system of servers and storage systems that can allocate computing resources to serve multiple customers simultaneously and keep track of what each user needs. This is the technology that makes it possible for a consumer to begin streaming a movie on a PC, pause it, then resume it from a tablet. When thousands of users suddenly demand the same content, streaming services seamlessly tap more processing power, then release the excess capacity when demand falls below the peak.

In enterprise IT, cloud technology provides on-demand self-service, anytime and anywhere availability, pooling of computing resources for multiple users or organizations, and usage-based pricing. One of the chief advantages of the cloud model is elasticity—users can expand or shrink capacity as needed. Cloud technology can be implemented as a third-party service or by companies that pool their computing resources on their own private clouds. By centralizing computers, storage, and applications on the cloud, companies raise IT productivity by increasing utilization (which is currently limited by the fact that many computers are used at peak capacity for only 30 to 40 days a year) and reducing the number of employees needed to maintain systems and develop software. With public clouds, companies can move to an “asset-light” model by turning a large capital investment (IT infrastructure) into an operating cost. Cloud setups are also more reliable (since they are capable of shifting processing from one machine to another if one becomes overloaded or fails), eliminating productivity-draining outages.

POTENTIAL FOR ACCELERATION

The biggest driver of incremental cloud technology demand in the coming decade could be the rapid proliferation of services and applications for Internet “clients”—the computers and mobile devices that are used to access online services and resources. The world population of Internet users is estimated at 2.5 billion today, and could swell to more than five billion by 2025 thanks to the rapid proliferation of smartphones. Not only will there be more Internet users in the near future, but these users will also be relying more on off-device processing, storage, and applications. Consumers are using mobile Internet devices for increasingly

⁵⁷ The full definition according to the US National Institute of Standards and Technology: “Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction.” See Peter Mell and Timothy Grace, *The NIST definition of cloud computing*, National Institute of Standards and Technology, NIST Special Publication 800-145, September 2011.

demanding applications, including HD video streaming. All of that computational work will likely be carried out on cloud systems.

Demand for enterprise cloud services will continue to grow as well. IT departments face ever-growing demands to do more and improve productivity at the same time. Cloud computing not only cuts costs, but also helps companies implement new applications and add services and computational capacity more quickly than they can using in-house staff.

Another source of cloud usage growth could be small and medium-sized enterprises (SMEs), which may have even more to gain from cloud services than do large corporations. Small companies often find it difficult to build and manage extensive IT infrastructure and plan for future needs. Like larger enterprises, they also often struggle with a poor rate of return on IT systems due to rapid obsolescence of technology. Cloud computing lets SMEs avoid tying up capital in IT and frees them from IT infrastructure management and demand planning, giving them the ability to compete more effectively with big companies. The utility of the cloud extends to software and applications (so-called software as services). For example, Microsoft Office 365 and Google Apps offer suites of applications available over the Internet (instead of via traditional software packages that must be purchased and installed).

Meanwhile, the cost of implementing cloud setups has fallen, while performance has improved. For example, renting a server in the cloud is now about one-third as expensive as buying and maintaining similar equipment. According to the Cisco Global Cloud Index, global cloud traffic could increase by a factor of six in the next five years; by 2019, more than two-thirds of the global traffic through data centers could be cloud-based—double what it is today.⁵⁸

POTENTIAL IMPACT BY 2025

While enterprise IT use will continue to grow, the largest source of economic impact through 2025 will likely come from enabling the delivery of services and applications to Internet users. We estimate the total potential economic impact for cloud technology across sized applications could be \$1.7 trillion to \$6.2 trillion in 2025 (Exhibit 6). Of this total, \$1.2 trillion to \$5.5 trillion could be in the form of surplus from use of cloud-enabled Internet services, while \$500 billion to \$700 billion could come through productivity improvements for enterprise IT.

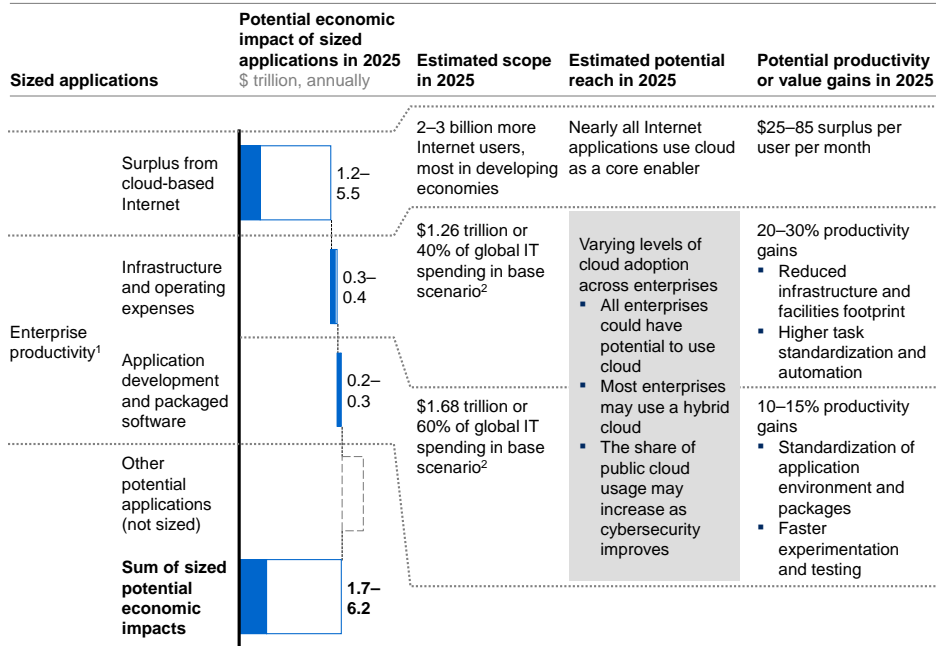
In estimating the potential incremental consumer surplus from cloud computing, we assume the Internet will continue to grow at projected rates through 2025 and that users will continue to use email and social networks, entertainment services (music, video, and games), and Web services such as search and mapping. We used research on Internet surplus by McKinsey and IAB Europe to estimate the current surplus.⁵⁹ We have used a surplus per user growth rate based on estimates of the growth rate of time spent by a typical user on the Internet. At the low end of our range, we assume time spent could grow at current rates and nearly double by 2025; at the high end, we assume nearly all media consumption

58 *Cisco Global Cloud Index: Forecast and Methodology, 2011–2016*, Cisco Systems, October 2012.

59 *Consumers driving the digital uptake: The economic value of online advertising-based services for consumers*, McKinsey & Co. and IAB Europe, September 2010; *Internet matters: The Net's sweeping impact on growth, jobs, and prosperity*, McKinsey Global Institute, May 2011.

could eventually be provided through cloud-enabled Internet services.⁶⁰ We apply this estimate of surplus on an estimated two billion to three billion additional Internet users, as well as 2.5 billion existing users who will gain incremental utility. Developing economies could be home to more than 3.5 billion Internet users by 2025, many of whom may have only mobile devices (see Chapter 1, “Mobile Internet”).⁶¹ We assume, however, that the surplus available from the use of mobile Internet will be lower than that from other forms of Internet access.

Exhibit 6 Sized applications of cloud technology could have economic impact of \$1.7 trillion to \$6.2 trillion per year in 2025



1 We have not sized the impact of increased flexibility and convenience to enterprises.

2 Estimates for enterprise cloud based on a global IT budget that does not include telecommunications.

NOTE: Estimates of potential economic impact are for some applications only and are not comprehensive estimates of total potential impact. Estimates include consumer surplus and cannot be related to potential company revenue, market size, or GDP impact. We do not size possible surplus shifts among companies and industries, or between companies and consumers. These estimates are not risk- or probability-adjusted. Numbers may not sum due to rounding.

SOURCE: McKinsey Global Institute analysis

To size the potential for productivity improvements due to cloud technology, we built a hypothetical “base” scenario of global IT spending and then estimated potential productivity improvements using this base across two main categories: infrastructure (both capital and operating expenses) and software development and packaged software costs. To construct this base scenario, we assumed a growth rate for each of these categories informed by historical rates and other factors, such as standardization of software, without assuming discontinuities in cloud adoption.

60 Lisa E. Phillips, “Trends in Consumers’ Time Spent with Media,” *eMarketer.com*, December 28, 2010

61 Several economists have tried to size the surplus generated by the Internet. See Hal Varian, “The value of the Internet now and in the future,” *The Economist*, March 10, 2013; Shane Greenstein, “Measuring consumer surplus online,” *The Economist*, March 2013; *Consumers driving the digital uptake: The economic value of online advertising-based services for consumers*, McKinsey & Company and IAB Europe, September 2010.

We then applied an estimate for productivity improvement in this base scenario to obtain a range for potential impact from cloud adoption by enterprise IT. For example, we have applied a potential productivity improvement of 20 to 30 percent in infrastructure support activities based on the efficiencies that arise when data centers are consolidated. For software development and packages, our estimate is 10 to 15 percent productivity improvements created by time savings and quality improvements. Together, this leads us to productivity improvements of \$500 billion to \$700 billion by 2025. However, given the IT needs across all sectors in the global economy, as well as the impact of greater flexibility and agility for which we have not estimated economic value, the actual impact could be even greater.

BARRIERS AND ENABLERS

Network capacity is a critical enabler for cloud computing, especially wireless networks for consumers using the mobile Internet. Cloud technology is deployed through massive data centers that require high-capacity bandwidth. Some mobile networks are already straining to keep up with ever-increasing demand. The lag between rising demand and network capacity expansion could grow even wider as consumers try to stream more HD content and businesses begin to monitor millions of devices over wireless Internet services. Some companies are already starting to trial the next generation of broadband networks to anticipate and meet this demand—for example, Google Fiber in Kansas City, which is nearly 100 times as fast as current commercially available high-speed broadband.⁶²

Reservations by some consumers and enterprises regarding trusting the cloud represent a potentially significant hurdle. The cloud requires a level of trust that some managers and consumers are reluctant to grant. Many consumers still prefer to store their data on PC hard disks instead of trusting the cloud as a permanent and secure repository for their photos, personal records, and other irreplaceable material. Enterprises, too, continue to have concerns about placing sensitive data on a third-party cloud, especially as questions of ownership and liability for data residing in a particular online location have yet to be settled by policy makers. Despite improvements in cloud technology, high-profile failures continue, affecting public perception of cloud reliability. For example, Amazon Web Services suffered an outage on Christmas Eve in 2012, taking down popular services such as Netflix for almost a day.⁶³

Structural issues and cultural resistance in IT departments are also barriers. Cloud deployment represents a significant shift in IT management practices, from in-house work to lower-cost, outsourced solutions, raising concerns about loss of control. Moving to cloud technology also requires new IT budget discipline and skill sets. Another factor is the complexity of migrating enterprise IT systems with multiple platforms, network protocols, and programming environments to the cloud.

62 Greg Kumparak, "Google announces Provo, Utah as the third Google Fiber city and acquires the local fiber provider," *TechCrunch.com*, April 17, 2013.

63 Stephen Musil, "Amazon apologizes for Netflix's Christmas Eve streaming outage," *CNet.com*, December 31, 2012.

IMPLICATIONS

As a core enabler of the Internet, cloud computing could have a huge impact on consumers' lives. The surplus generated by the Internet could be valued in trillions of dollars by 2025. The imperative for lighter and faster mobile devices as the primary means of using online services, combined with consumption of rich media such as movies and music, could make cloud computing a popular (and nearly default) technology for delivering applications and software as services. The rise of the Internet of Things, exponential growth in data, and increasingly automated knowledge work could all rely on cloud technology to provide the computational resources needed to harness their benefits.

Though we expect growing adoption of cloud technology as a computing paradigm for enterprises, stakeholders across the provider value chain could be differently affected. True, demand for cloud solutions could increase; however, providers of integrated cloud services may face greater competition as large technology players join early leaders in offering services. Many of these companies build their own data centers and cloud applications from the bottom up, buying components directly from manufacturers and then customizing completely, and could view public cloud services as a natural extension of their experience in building data centers and running private clouds. At the same time, manufacturers of components (such as motherboards, chipsets, and router switches) could recognize the potential for selling directly to enterprise customers keen to customize to their requirements. These manufacturers could begin to invest in building customer-facing sales organizations, potentially competing against server manufacturers for business from cloud providers.

More software and media companies can be expected to transition from selling products to offering cloud-based services, which has implications for their business models. A seller of packaged software or solutions may achieve lower margins by switching to a software-as-a-service model, but the cloud-based model could attract new customers by making products more affordable and accessible. For example, renting a movie on a subscription-based cloud service costs much less than renting a physical DVD from a video store, potentially representing a drop in revenue per movie watched at home. However, the cloud model of delivery allows a service such as Netflix to serve millions of viewers across multiple countries, generating far greater revenue.

The proliferation and sophistication of cloud services could be a boon to entrepreneurs and small enterprises. Cloud platforms make it much easier and cheaper for small businesses to pay for IT resources on a per-use basis, allowing them to scale their IT capacity up or down and build critical operational capabilities. The cloud could become a major force in making entrepreneurship more feasible in the coming decade.

The growing role of the Internet as an enabler of economic growth makes the cloud a phenomenon that policy makers need to address. To make the benefits of cloud technology available to citizens, governments and policy makers should consider programs to build greater network capacity and create incentives for providing high-speed Internet service. In developing economies, policy makers can encourage the build-out of wireless broadband, which will be the main way in which their citizens will access the Internet.

Policy makers should take a thoughtful approach to regulations related to data ownership, security, privacy, and liability to remove uncertainty about cloud use. The law in most countries does not address these issues. In addition, data protection laws in many countries restrict the storage and transfer of several types of data outside their borders, which constrains the ability to take advantage of some of the benefits of cloud technology.

5. Advanced robotics



During the past few decades, industrial robots have taken on a variety of manufacturing tasks, usually those that are difficult, dangerous, or impractical for humans—welding, spray-painting, or handling heavy materials, for example. Robotics is now seeing major advances that could make it practical to substitute machines for human labor in increasing numbers of manufacturing applications, in many service applications, and, importantly, in extremely valuable uses such as robotic surgery and human augmentation. Advances in artificial intelligence, machine vision, sensors, motors, and hydraulics—even in materials that mimic a sense of touch—are making this possible. Robots are not only becoming capable of taking on more delicate and intricate tasks, such as picking and packing or manipulating small electronics parts, but they are also more adaptable and capable of operating in chaotic conditions and working alongside humans. At the same time, the cost of robots is declining.

Advanced robotics promises a world with limited need for physical labor in which robot workers and robotic human augmentation could lead to massive increases in productivity and even extend human lives (see Box 7, “Vision: Machines end physical toil and improve lives”). Many goods and services could become cheaper and more abundant due to these advances. The physically handicapped and the elderly could lead healthier and less-restricted lives using robotic prosthetics and “exoskeletons” that strap on like braces and assist in locomotion. We estimate that the application of advanced robotics across health care, manufacturing, and services could generate a potential economic impact of \$1.7 trillion to \$4.5 trillion per year by 2025, including more than \$800 billion to \$2.6 trillion in value from health-care uses. This impact would result from saving and extending lives and transforming the way in which many products are built and many services are delivered.

Advanced robotics also holds a great deal of promise for businesses and economies. Early adopters could gain important quality, cost, and speed advantages over competitors, while some companies could find that advanced robotics lowers the barriers for new competitors. Businesses in developing economies could be among the biggest buyers of robotics given the current rate of automation; however, these economies could be negatively impacted by falling demand for low-wage manual labor, upon which they rely for economic development. The ability of robots to take on a far wider range of jobs economically could encourage global companies to move some production back to advanced economies. In advanced economies, some workers might find new job opportunities in developing, maintaining, or working with robots. At the same time, many jobs in advanced economies involving manual labor might be automated away, placing even more importance on educating and retraining workers for higher-skill jobs.

Box 7. Vision: Machines end physical toil and improve lives

Imagine a world in which advanced robots expertly and inexpensively perform and augment most physical tasks. Imagine you are a manager in a manufacturing plant in 2035. At your plant, injuries are virtually unheard-of. In fact, there are few people on the floor: a small group of highly skilled specialists oversee thousands of robots, interacting naturally with the robot workforce to produce goods with unprecedented speed and precision, 24 hours a day, 365 days a year.

When a new product or design improvement is introduced, factory workers train robots to follow new routines, using simple touch-screen interfaces, demonstration, and even verbal commands. Most of your day is spent optimizing processes and flows and even assisting with product designs based on what you see on the factory floor and the data that your robots generate.

During lunch, you swing by a local fast-food restaurant. You watch as your meal is prepared and cooked exactly the way you like it by a robot. Back at your desk, you see service robots making deliveries and cleaning the floors and windows. Outside, robots pick up trash and replace broken street lights.

In a world of advanced robotics, surgeons are assisted by miniature robotic surgery systems, greatly reducing both the time necessary for procedures and their invasiveness. Recovery is more rapid as well. People suffering from paralysis due to spinal injuries are able to walk again with the help of robotic exoskeletons directly connected to the nervous system.

DEFINITION

Traditional robots excel at tasks that require superhuman speed, strength, stamina, or precision in a controlled environment (robot welding or semiconductor fabrication, for example). They are bolted in place behind railings to prevent injuries to humans. They do exactly what they are programmed to do—and nothing more. But now, a new generation of more sophisticated robots is becoming commercially available. These advanced robots have greater mobility, dexterity, flexibility, and adaptability, as well as the ability to learn from and interact with humans, greatly expanding their range of potential applications. They have high-definition machine vision and advanced image recognition software that allows them to position objects precisely for delicate operations and to discern a part in a pile. They are powered by sophisticated motors and actuators, allowing them to move faster and more precisely, and some are made from lighter, softer materials. The US Defense Advanced Research Projects Agency (DARPA) is even working on robots that can fully automate the sewing of garments, using a process that tracks the movement of individual threads and precisely moves fabric to perform exact stitching.⁶⁴

64 Katie Drummond, "Clothes will sew themselves in DARPA's sweat-free sweatshops," *Wired*, June 8, 2012.

Advances in artificial intelligence, combined with improved sensors, are making it possible for robots to make complex judgments and learn how to execute tasks on their own, enabling them to manage well in uncertain or fluid situations. By 2025 advanced robots could be capable of producing goods with higher quality and reliability by catching and correcting their own mistakes and those of other robots or humans. These robots can sense and quickly react to obstacles, other robots, or human coworkers, giving them greater “awareness” and making it possible for them to work more safely side-by-side with humans. Many advanced robots can also communicate with one another and work together on shared tasks. Some advanced robots are designed to be simple, small, and inexpensive, while having the ability to be networked together and work in teams. These distributed, or “swarm,” robots could eventually be used for dangerous tasks such as search and rescue operations.

Finally, advances in interfaces, sensors (including sophisticated tactile sensors), and actuators, combined with improved materials and ergonomic designs, are furthering robotic surgery and dramatically improving the quality and usefulness of human prosthetic devices. Ultraprecise surgical robots are making new forms of minimally invasive surgery possible that can reduce postsurgical complications, enable faster recovery, and possibly reduce surgical death rates. Robotic prosthetics and exoskeletons are able to take precise directions and make increasingly accurate and delicate movements. New interfaces have been developed that can operate robotic limbs using small electrical signals produced when muscles contract or using signals from nerve endings or even brain waves. The capabilities of these prosthetics may soon come to rival or exceed those of actual human limbs. These advances could eventually include prosthetic hands with independently moving fingers and prosthetic body parts that mimic the sense of touch using a neural interface.⁶⁵

These technological advances, combined with declining costs, are making entirely new uses for robots possible. For example, El Dulze, a Spanish food processor, now uses highly agile robots to gently pick up heads of lettuce from a conveyor belt, measure their density (rejecting heads that don’t meet company standards), and replace them on the belt, where other robots position the heads for a machine that removes their roots. The company says the robots are better than humans at assessing lettuce quality (the reject rate has fallen from 20 percent to 5 percent), and hygiene at the facility has also improved.⁶⁶

POTENTIAL FOR ACCELERATION

Adoption rates for advanced robots will be determined by many factors, including labor market conditions. For example, in China, where wages and living standards are rising, workers are pressing for better working conditions, including relief from long hours of precise piecework that can lead to repetitive stress injuries. As education levels rise, fewer workers are willing to take such jobs. As a result, Foxconn, a contract manufacturer that employs 1.2 million workers, is investing in robots to assemble products such as the Apple iPhone.⁶⁷ According to the International Federation of Robotics (a major robotics industry group), China is expected to become the world’s largest consumer of industrial robots by 2014.

65 Megan Scudellari, “Missing touch,” *The Scientist*, September 1, 2012.

66 *68 robots perform farmer’s work*, case study of Fanuc Robotics Europe S.A., International Federation of Robotics, September 2012.

67 John Markoff, “Skilled work, without the worker,” *The New York Times*, August 18, 2012.

Global manufacturing labor costs today are \$6 trillion annually, so additional automation represents a huge opportunity.

Demographics will also play a role in determining demand for advanced robotics. Robotic surgical systems and prosthetics could help meet the large and growing need (particularly in advanced, aging economies) to provide quality health care. And many manufacturers still rely on legions of low-skill workers (often in developing countries) to do work that involves precise operations on irregular objects, such as bending tiny wires to assemble mobile phones or deboning chicken breasts; over the coming decade, many of these tasks could be automated.

New applications for advanced robotics, particularly in services, are also emerging. Robots are now poised to take on dirty, dangerous, and labor-intensive service work, such as inspecting and cleaning underground pipes, cleaning office buildings, or collecting trash. Domestic service robots are another expanding market. Though robotic vacuum cleaners have been around for years, sales of these and similar household robots are now growing rapidly, by about 15 to 20 percent annually. Adoption could accelerate even further by 2025 as these machines become more capable and consumers consider the trade-offs between buying robots, sacrificing leisure time, or hiring professional cleaners or gardeners to perform these tasks.

Advanced robots are also of great interest to military planners, who see opportunities to both automate combat (similar to remotely piloted drone aircraft) and support human troops. DARPA is investing in a range of advanced robotics programs, from a full robotics “challenge” (similar to the DARPA Grand Challenge that pioneered self-driving cars) to four-legged robots for carrying supplies, robotic exoskeletons and suits to strengthen and protect troops, and advanced prosthetic limbs to help injured soldiers. This type of military investment could greatly speed further advancement.

Robot prices are dropping, placing them within reach of more users. Industrial robots with features such as machine vision and high-precision dexterity typically cost \$100,000 to \$150,000. By 2025, it is possible that very advanced robots with a high level of machine intelligence and other capabilities could be available for \$50,000 to \$75,000 or less. In recent decades, robot prices have fallen about 10 percent annually (adjusted for quality improvements) and may decline at a similar or faster rate through 2025.⁶⁸ Accelerated price declines could be made possible by scale efficiencies in robot production (due in large part to rising demand by Chinese and other Asian manufacturers), the decreasing cost of advanced sensors (partly driven by demand for inexpensive sensors in smartphones and tablets), and by the rapidly increasing performance of computers and software. Some entrepreneurs are focusing on developing inexpensive general purpose robots that can be easily trained to do simple tasks (see Box 8, “Your new coworker, Baxter”).

The rate at which robots could proliferate is a subject of intense debate. According to the International Federation of Robotics, industrial robot sales reached a record 166,000 units in 2011, a 40 percent jump over 2010; sales in China grew by more than 50 percent in 2011. Since 1995 global sales have grown by 6.7 percent per year on average. It is possible that there could be even faster

68 *World robotics 2012*, International Federation of Robotics, August 30, 2012.

growth ahead if Baxter and other low-priced, general-purpose models can drive rapid adoption in simple manufacturing and service work. At the same time, installations of advanced industrial robots could accelerate beyond historic rates if robotics technology continues to accelerate. Adoption scenarios will depend both on improvements in capability and price and receptivity to automation; in addition, significant organizational and societal barriers may stand in the way.

Box 8. Your new coworker, Baxter

To make robots useful in low-end manufacturing, they not only have to be priced attractively, but they also need to fit into the workplace. They can't take up too much space, they have to work well and safely with humans, and they have to be easy to program. These were some of the goals for "Baxter," a \$22,000 general-purpose robot developed by startup company Rethink Robotics. Another goal was to put a friendly face on robots—literally. Baxter features an LCD display screen mounted on a "neck" above its body. The screen shows a pair of eyes that take on different expressions depending on the situation. The eyes follow what the robot's two arms are doing, as a human worker would.

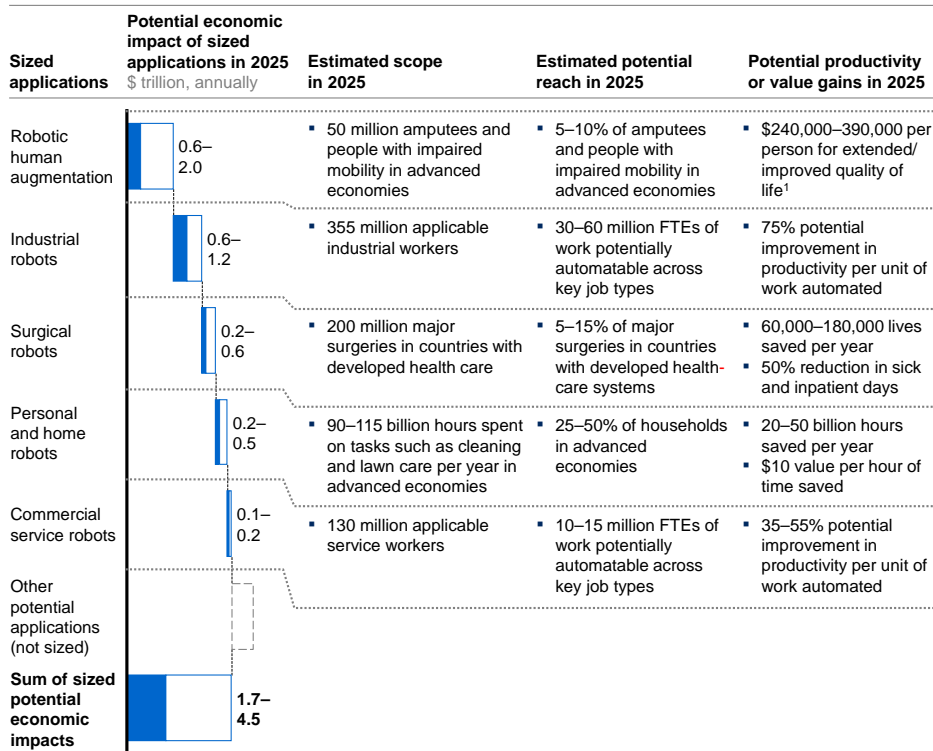
While Baxter's functionality is somewhat limited—it is best at performing simple operations such as picking up objects, moving them, and putting them down—it makes up for these limitations with superior adaptability and modularity created by the ability to install different standard attachments on its arms. When the robot is first installed or needs a new routine, it "learns" without the need for programming. A human simply guides the robot arms through the motions that will be needed for the task, which Baxter memorizes. It even nods its "head" to indicate that it has understood its new instructions.

POTENTIAL ECONOMIC IMPACT

We estimate that by 2025 advanced robotics could have a worldwide economic impact of \$1.7 trillion to \$4.5 trillion annually across the applications we have sized (Exhibit 7). Much of this impact—\$800 billion to \$2.6 trillion—could come from improving and extending people's lives. An additional \$700 billion to \$1.4 trillion could arise from automating manufacturing and commercial service tasks. We estimate that the use of advanced robots for industrial and service tasks could take on work in 2025 that could be equivalent to the output of 40 million to 75 million full-time equivalents (FTEs). This could potentially have annual economic impact of \$600 billion to \$1.2 trillion in developed countries and \$100 billion to \$200 billion in developing economies. Finally, \$200 billion to \$500 billion in impact could arise from the use of time-saving household service robots.

Exhibit 7

Sized applications of advanced robotics could have direct economic impact of \$1.7 trillion to \$4.5 trillion per year in 2025



1 Using QALY (quality-adjusted life years) estimates.

NOTE: Estimates of potential economic impact are for some applications only and are not comprehensive estimates of total potential impact. Estimates include consumer surplus and cannot be related to potential company revenue, market size, or GDP impact. We do not size possible surplus shifts among companies and industries, or between companies and consumers. These estimates are not risk- or probability-adjusted. Numbers may not sum due to rounding.

SOURCE: McKinsey Global Institute analysis

Health care

We estimated the potential economic impact of robotic surgery and robotic prosthetics to be as much as \$800 billion to \$2.6 trillion annually by 2025, based on saving lives and improving quality of life. For estimating the potential economic impact of robotics for human augmentation, we considered potential uses of robotic prosthetics and exoskeletons.⁶⁹ By 2025 there could be more than 50 million people with impaired mobility in the developed world, including amputees and elderly people, for whom robotic devices could restore mobility, improve quality of life, and increase lifespan. It is possible that 5 to 10 percent of these people could have access to robotic augmentation by 2025 given the current penetration of alternatives such as traditional prosthetics and motorized wheelchairs. Studies indicate that impaired mobility contributes significantly to reduced life expectancy due to increased health risks such as injury and osteoporosis.⁷⁰

If it were possible to extend life by one to two years for each disabled person and provide a 20 to 30 percent improvement in quality of life over eight years using

69 Robotic mechanisms that can be worn by physically handicapped people to help move limbs (or even entire bodies).

70 For more on the effects of disabilities on life expectancy, see R. Thomas and M. Barnes, “Life expectancy for people with disabilities,” *NeuroRehabilitation*, May 2007.

robotic assistance (assuming substantial restoration of normal function) the result could be a potential impact of \$240,000 to \$390,000 per person, using a quality-adjusted life year (QALY) approach. If these results can be achieved, robotics for human augmentation could lead to a potential economic impact of \$600 billion to \$2 trillion per year by 2025, much of which could be consumer surplus accruing to the users of these robotic devices.

As the technology for robotic surgery improves, it could have the potential to prevent deaths and significantly reduce both in-patient care time and missed work days. Robotic surgical “platforms” are already being used for minimally invasive procedures such as laparoscopic surgery. It is possible that with advances in robotic technology, by 2025 robotic surgery could be widely used for these and other procedures. Approximately 200 million major surgeries could be performed every year in countries with developed health-care systems in 2025.⁷¹ Currently, about 3 percent of all major surgeries result in death, but it is possible that by 2025, advanced robotic surgical systems could help reduce these deaths substantially, perhaps by as much as 20 percent, by reducing common complications such as bleeding or internal bruising.

This improvement in outcomes could be enabled by more flexible surgical robots with a greater range of motion that could perform more types of operations, or from new features such as AI-assisted autocorrect systems that could warn surgeons when they are about to cut the wrong tissue or apply too much pressure. Declining costs in robotic surgery systems could allow more hospitals and surgeons to use the technology, potentially increasing the performance of many surgeons. We estimate that if 5 to 15 percent of all major surgeries in countries with developed health-care systems could be performed with the assistance of robots by 2025, it could result in 60,000 to 180,000 lives saved each year. Robot-assisted surgery could also cut in-patient stays and sick days associated with surgery by 50 percent. If these results can be achieved, we estimate that robotic surgery could have an economic impact of \$200 billion to \$600 billion per year by 2025.⁷²

Industrial robots

For industrial robots, we analyzed data regarding job tasks, occupations, and distribution across countries.⁷³ We then considered which tasks could be fully or partially automated economically by advanced robots by 2025, assuming a high level of robot performance and continued reductions in cost. In developed countries, across occupations such as manufacturing, packing, construction, maintenance, and agriculture, we estimate that 15 to 25 percent of industrial worker tasks could be automated cost-effectively (based on estimated 2025 wage rates) by 2025. We estimate that in developing countries, on average, 5 to 15 percent of manufacturing worker tasks could be automated across relevant occupations by 2025.

71 Based on analysis by Thomas G. Weiser et al., “An estimation of the global volume of surgery: A modeling strategy based on available data,” *Lancet*, volume 372, number 9633, July 12, 2008.

72 We use a quality-adjusted life year (QALY) of \$100,000 and assume that surgical patients avoiding death are restored to a normal life expectancy.

73 Analysis of job occupations and tasks is based on data from a variety of sources, including labor and wage data from the Economist Intelligence Unit, International Labour Organisation, IHS Global Insight, Eurostat, and various national labor bureaus.

We calculated the potential cost savings using the estimated annual cost of advanced robots compared with the annual employment cost of an equivalent number of workers. This yields a potential economic impact of \$600 billion to \$1.2 trillion per year by 2025. This would imply a substantial increase in the number of industrial robots installed globally by 2025, by about 15 million to 25 million robots, requiring investments totaling about \$900 billion to \$1.2 trillion. Realizing all of this potential impact would therefore imply 25 to 30 percent average annual growth in robot sales, significantly higher than the average growth rate over the past two decades, but lower than the growth rate in 2010 and 2011.

Service robots

Service robots fall into two categories: those used in commercial settings and personal robots. For personal and household service robots, we focused on the potential to automate cleaning and domestic tasks such as vacuuming, mopping, lawn mowing, and gutter cleaning. The use of advanced robots for these types of tasks has significant potential given the current trajectory of technology improvement, the relatively low cost of the robots required, and the already increasing rate of adoption. Sales of household robots used largely for the above-mentioned tasks are already growing by about 20 percent annually. To estimate the potential impact of household robots, we considered the amount of time spent on relevant cleaning and domestic tasks, focusing on the developed world, where significant adoption is most likely. Based on US and European labor studies, we estimate that 90 billion to 115 billion hours per year are spent performing relevant household tasks in the developed world.⁷⁴ If 25 to 50 percent of people in the developed world were to adopt the use of these robots by 2025, \$200 billion to \$500 billion worth of time savings could be realized. We believe this level of adoption is possible given the rapid advances in low-cost robotics technology, the relatively limited sophistication of the robots required for these applications, and the demonstrated willingness of many consumers to pay for household time-saving devices.

For commercial service robots, we analyzed data on job tasks, occupations, and distribution across countries.⁷⁵ We then considered which tasks could be fully or partially automated economically by advanced robots by 2025, assuming a high level of robot performance and continued reductions in cost. We estimate that in developed economies, across occupations such as food preparation, health care, commercial cleaning, and elder care, as much as 7 to 12 percent of commercial service worker tasks could be automated cost-effectively by 2025. For example, nurses spend up to 20 percent of their shift time wheeling equipment and carts from one location to another or waiting for a cart to arrive. So-called courier robots (self-guided, motorized carts) can take on these tasks. We estimate that in developing countries, 4 to 8 percent of commercial service worker tasks could be automated across relevant occupations by 2025. To achieve this, we estimate that 2.5 million to eight million advanced robots would be necessary, requiring an estimated investment of \$200 billion to \$400 billion globally by 2025.

74 Estimates based on data from Rachel Krantz-Kent, "Measuring time spent in unpaid household work: Results from the American time use survey," *Monthly Labor Review*, volume 132, number 7, July 2009.

75 Analysis of job occupations and tasks based on data from a variety of sources, including labor and wage data from the Economist Intelligence Unit, International Labour Organisation, IHS Global Insight, Eurostat, and various national labor bureaus.

BARRIERS AND ENABLERS

There are several important barriers that could limit adoption of advanced robotics by 2025. First, although costs are declining, most industrial and many commercial service robots remain expensive, costing tens or hundreds of thousands of dollars per robot. Surgical robots often cost more than \$1 million (although these costs could come down and few of these might be needed compared with industrial and service robots). Large-scale adoption of industrial and service robots could require investments of perhaps \$1.1 trillion to \$1.6 trillion by 2025. Before making these investments, companies would likely require strong evidence of positive returns on investment, and establishing a clear track record of performance could take years. And once robots are purchased and installed, it can still take time to redesign processes and flows to fully take advantage of their capabilities.

Surgical robots have already seen significant growth in adoption, but additional trials and data will be required to fully demonstrate their benefits, particularly given concerns about health-care costs in the United States and other advanced economies. There are also questions about whether robotically assisted surgery has demonstrated significantly better performance than nonrobotic minimally invasive surgery techniques, which are less costly. While the capabilities and performance of the technology could improve significantly by 2025, adoption may be constrained until definitive proof of results is available.

The talent required to operate and maintain advanced robots is an important enabler that will be required to fully capture their potential. Some advanced robots could be designed to be very user-friendly and able to work naturally side-by-side with humans, but advanced robots may still require a high level of expertise to maintain their hardware and software.

Finally, the potential effect of advanced robots on employment could generate social and political resistance, particularly if robots are perceived as destroying more jobs than they create. Although the productivity improvements that advanced robots would create would drive growth in the economy, the workers who would be displaced might not be easily re-employed. Policies discouraging adoption of advanced robots—for example, by protecting manual worker jobs or levying taxes on robots—could limit their potential economic impact. Policy makers will face difficult questions regarding legal liability, such as determining who is at fault when service or household robots contribute to accidents or injuries.

IMPLICATIONS

Over the coming decade, advanced robotics could deliver tremendous value for robot creators, health-care providers, manufacturers, service providers, entrepreneurs, consumers, and societies. For many businesses, advanced robotics promises significantly reduced labor costs, greater flexibility, and reduced time to deliver products to the marketplace. Business leaders should look for opportunities to leverage growing technology capabilities to help automate difficult, labor-intensive, and dangerous tasks in ways that are simple, user-friendly, and cost-effective, whether for treating patients or automating manual work.

For hospitals and health-care providers, advanced robotics could ultimately offer substantial improvements in patient care and outcomes. As a result, providers of robotic systems and supporting tools or services could see large growth opportunities over the coming decade. Makers of robotic surgical systems could see strong demand for increasingly advanced systems but also feel pressure to minimize costs and clearly demonstrate improved outcomes for patients. Makers of robotic prosthetics and exoskeletons could experience similarly high demand and may want to look for ways to reach disabled and elderly people around the world, even in less-developed regions.

Manufacturing and service companies with large workforces could benefit from reduced costs, reduced injuries, and lower overhead, as well as reducing payrolls in human resources, labor relations, and factory supervisory roles. Factories might no longer need to be located near sources of low-cost labor, allowing them to be located closer to final assembly and consumers, simplifying supply chains and reducing warehousing and transportation costs.

However, business leaders will face challenges in capturing the full productivity and quality improvements that could be afforded by advanced robots. Advanced robotics requires substantial capital investments, and businesses will need clear evidence of positive return on investment. Reconfiguring manufacturing processes, service delivery channels, and supply chains is difficult and time-consuming. Training employees to work effectively alongside robots is also no small task. To maximize value capture and stay ahead of the curve, businesses should continually experiment with advanced robotics and additional automation, identify promising technologies, rethink business processes, and develop in-house talent. They should also consider how their supply chains could be redesigned to leverage automation, and how additional speed to market, flexibility, and quality could help differentiate their offerings from those of competitors.

For some entrepreneurs, decreasing robot cost and increasing capabilities could make entirely new business models possible or decrease barriers to entry in the manufacturing and service industries. Robotically enabled production facilities, fast-food restaurants, self-service laundries, and medical clinics might offer superior efficiency and quality and could scale quickly. Established manufacturers may need to accelerate automation to meet the competition while investing in innovative product development or superior service quality to better differentiate their offerings.

For societies and policy makers, the prospect of increasingly capable robots brings potential benefits: growing national productivity, higher-quality goods, safer surgeries, and better quality of life for the elderly and disabled. But it also poses new challenges in employment, education, and skill training. In some cases, access to advanced robotics could cause companies to repatriate manufacturing operations from low-wage offshore locations. And the spread of robotics could create new high-skill employment opportunities. But the larger effect could be to redefine or eliminate jobs. By 2025, tens of millions of jobs in both developing and advanced economies could be affected. Many of these employees could require economic assistance and retraining. Part of the solution will be to place even more emphasis on educating workers in high-skill, high-value fields such as math, science, and engineering.

6. Autonomous and near-autonomous vehicles



For years, almost all commercial aircraft have had the ability to operate on autopilot. Onboard computers can manage most aspects of flying, including even aspects of takeoff and landing. The tankers and cargo ships that transport most of the goods for the global economy are highly automated, allowing them to operate with very small crews. Now partly or completely self-driving cars and trucks are also becoming a reality, enabling a potential revolution in ground transportation that could, if regulations allow, be well under way by 2025.

Autonomous vehicles offer several potential benefits, including reducing deaths from motor vehicle crashes and reducing CO₂ emissions. With computers controlling acceleration, braking, and steering, tightly spaced cars and trucks can safely travel at higher speeds; when one vehicle in line brakes or accelerates, they all do. Since most driving accidents are caused by human error, removing drivers could actually increase traffic safety and reduce deaths, injuries, and property losses. Convoys of trucks could speed down the highway with no driver needed (or just one driver in the lead truck), with as little as one foot of space between them.⁷⁶ Roadways could accommodate more vehicles without expansion, and acceleration and braking could be optimized to reduce fuel consumption and CO₂ emissions. In addition, closely spaced vehicles have much lower aerodynamic drag, which further reduces fuel consumption. Drivers could be free to use their drive time to work, relax, or socialize while being transported.

If regulators approve autonomous driving and the public accepts the concept, the benefits provided by improved safety, time savings, productivity increases, and lower fuel consumption and emissions could have a total economic impact of \$200 billion to \$1.9 trillion per year by 2025. Technology is not likely to be the biggest hurdle in realizing these benefits. In fact, after 20 years of work on advanced machine vision systems, artificial intelligence, and sensors, the technology to build autonomous vehicles is within reach—as a growing number of successful experimental vehicles have demonstrated. What is more likely to slow adoption is establishing the necessary regulatory frameworks and winning public support. In order to realize other benefits (which we have not sized), such as reduced congestion, infrastructure investments would be needed to create special lanes and install sensors to control traffic flow on major arteries. And there will be legal and ethical questions to address, such as who bears responsibility when an autonomous vehicle causes an accident and how to program a computer to make life-and-death decisions (such as weighing whether to swerve to avoid a pedestrian against the chance of injuring passengers).

Nevertheless, autonomous vehicles are coming, in fact, some autonomous features, such as self-parking systems, are already available in production vehicles. While the economic impact driven by this technology could be quite large, it may take many years to fully materialize.

76 Brian Dumaine, “The driverless revolution rolls on,” *Fortune*, November 12, 2012.

DEFINITION

An autonomous vehicle is one that can maneuver with reduced or no human intervention. In this report, we focus on autonomous cars and trucks, which we believe have the greatest potential for significant economic impact by 2025. Other forms of autonomous vehicles—such as crop-spraying drone aircraft, self-guided forklift trucks, and law enforcement drones—may also become widely used, but we believe they have more limited applications and less incremental impact within our time frame. Also, we have chosen not to include estimates of the potential value of autonomous military vehicles and drones in the context of this report.

Machine vision is a key enabling technology for autonomous vehicles. Using cameras and other sensors, a computer constantly monitors the road and the surrounding environment, acquiring an image and then extracting relevant information (such as stop signs or objects in its path) on which to base actions. Advances in machine vision include 3D cameras that gather additional information regarding distances that two-dimensional cameras cannot provide. Pattern recognition software, including optical character recognition programs, can interpret symbols, numbers, and the edges of objects in an image. LIDAR (laser-imaging detection and ranging), which is similar to radar but uses laser light bounced off of objects rather than radio signals to measure distance, is also being used by autonomous vehicles, along with advanced GPS (global positioning system) technologies and spatial data. When combined with sensor data, this information enables autonomous vehicles to pinpoint their current locations, follow the road, and navigate to their destinations.

Input signals from machine vision and sensors are integrated with stored spatial data by artificial-intelligence software to decide how the vehicle should operate based on traffic rules (for example, obeying speed limits and yields signs) and knowledge of exceptions (such as stopping when the light is green if a pedestrian is in the intersection). Control engineering software does the “driving,” giving instructions to the actuators that perform the task needed for the desired action, such as accelerating, braking, or turning.

With these capabilities, a fully autonomous vehicle can navigate to a specified destination, moving safely among other vehicles, obstacles, and pedestrians. These vehicles’ computers can also optimize fuel economy by accelerating and braking smoothly, remaining within the speed limit, and never taking a wrong turn. Google has demonstrated these capabilities with a Toyota Prius that has been equipped with computers, sensors, actuators, and other technology; this vehicle has been driven for 300,000 miles with only one accident (which was human-caused).⁷⁷

Partly autonomous driving features—including steering assistance (maintaining the car’s position between lane markers), braking and accelerating to maintain distance from vehicles ahead, and automatic braking when obstacles appear ahead—are already being offered or will soon be offered on production vehicles. In the next decade, we can expect autonomous driving to be offered as an option on new automobiles, initially on high-end models and later on mid-priced vehicles.

Eventually, autonomous driving could give rise to new kinds of vehicles. These might include driverless passenger vehicles (which would not require a driver to

⁷⁷ Frederic Lardinois, “Google’s self-driving cars complete 300K miles without accident, deemed ready for commuting,” *TechCrunch*, August 7, 2012.

sit behind the wheel) that could be configured to maximize work space or even provide beds for passengers; new concepts involving car sharing in which a car could arrive or leave and park wherever and whenever needed; or new public transportation vehicles that would allow for greater flexibility and personalization.

POTENTIAL FOR ACCELERATION

Autonomous driving would herald a new era for automobiles. During the past century, the automobile was a breakthrough general-purpose technology that provided the means for getting workers to their jobs and consumers and goods to markets. Automobiles enabled economic development and higher living standards around the world. Trucks have spread economic development and markets to locations that railroads, rivers, and canals have never been able to reach. However, these machines have also caused pollution, soaring demand for fossil fuels, and congestion and related productivity losses, as well as death and injury. The average American car owner spends 750 hours per year driving—the equivalent of four months of work days—while the average European spends about 300 hours.⁷⁸ More than one million people are killed in traffic accidents every year around the world, and it is estimated that 70 to 90 percent of all automobile accidents are caused by human behavior.⁷⁹ The majority of this waste and destruction could be avoided by using autonomous vehicles.

Around the world, autonomous vehicles have the potential to improve the economics of trucking. Self-driving trucks that transport goods long distances could fit easily into intermodal transportation and logistics systems. Trucks moving in convoys could transport goods on major arteries, then transfer their cargos at regional distribution centers, from which other vehicles could take the cargo to its final destinations. On their long hauls, autonomous trucks would not have to stop for their drivers to sleep or eat.

The technology for autonomous vehicles has evolved at lightning speed. In 2004 DARPA sponsored a \$1 million prize for driverless vehicles to navigate a course in the Mojave Desert called the “DARPA Grand Challenge.” No teams finished the race. One year later, in 2005, five cars successfully crossed the finish line. In 2007 a more urban version of the race was held incorporating street signs, obstacles, and traffic; six teams finished.⁸⁰ Today, Google’s self-driving cars are driving on city streets and freeways (with a human driver behind the wheel as backup in case the system has a problem) in the US states of California and Nevada. Google has announced that it expects to have a commercially available version of its technology ready in three to five years. The self-driving technology that is being tested today would add thousands of dollars to the price of a car, but the cost of these systems is expected to drop. For example, researchers at Oxford University are aiming to develop an autonomous system that would cost as little as \$150.⁸¹

Even though the regulatory framework for autonomous vehicles is not yet in place (California and Nevada are permitting testing on public roads), major automakers

78 *Mobility choices: Consumers at the wheel*, McKinsey & Company survey, June 2012.

79 Hans von Holst, ed., *Transportation, traffic safety and health: The new mobility*, Springer Publishing, 1997.

80 Darpagrandchallenge.com.

81 “Researchers testing frugal autonomous car systems, aim for \$150 price tag,” Engadget.com; R. W. Wall, J. Bennett, G. Eis, “Creating a low-cost autonomous vehicle,” presented at Industrial Electronics Society annual conference in Sevilla, Spain, November 5–8, 2002.

are moving ahead with development. General Motors, Toyota, Mercedes-Benz, Audi, BMW, and Volvo are testing their own autonomous systems. Audi is testing what it calls a “piloted” car that can handle starts and stops in heavy traffic and park itself.⁸² The driver can take over control of the vehicle at any time and is expected to always monitor the vehicle’s driving. Cadillac has demonstrated an enhanced cruise-control system that not only controls speed but also provides steering assistance on highways.

The 2014 Mercedes-Benz S-class is arriving soon with a range of advanced, though not full, autonomous driving capabilities standard, including keeping in a lane and maintaining speed and distance from other cars. These capabilities will be accessible only under certain driving conditions and drivers will need to keep their hands on the wheel, but its developers claim the onboard vision system can keep the car in its lane and maintain safe distances to other vehicles at speeds up to 124 miles per hour. The driver needs to step in when the car changes driving environments (such as when exiting a freeway). In congested traffic, the car will be able to track the environment and understand when to accelerate and when to brake.⁸³

Japan’s New Energy and Industrial Technology Development Organization, a research organization, has successfully tested an autonomous trucking system in which a single driver leads three other trucks that are equipped with roof-mounted radar systems, traveling at 50 miles per hour, spaced about four meters apart. On-site autonomous vehicles are also being tested by mining giant Rio Tinto. The company has used 150 partly autonomous trucks in Australian mining operations. The trucks follow a predefined route and load and unload material without an operator.

POTENTIAL ECONOMIC IMPACT

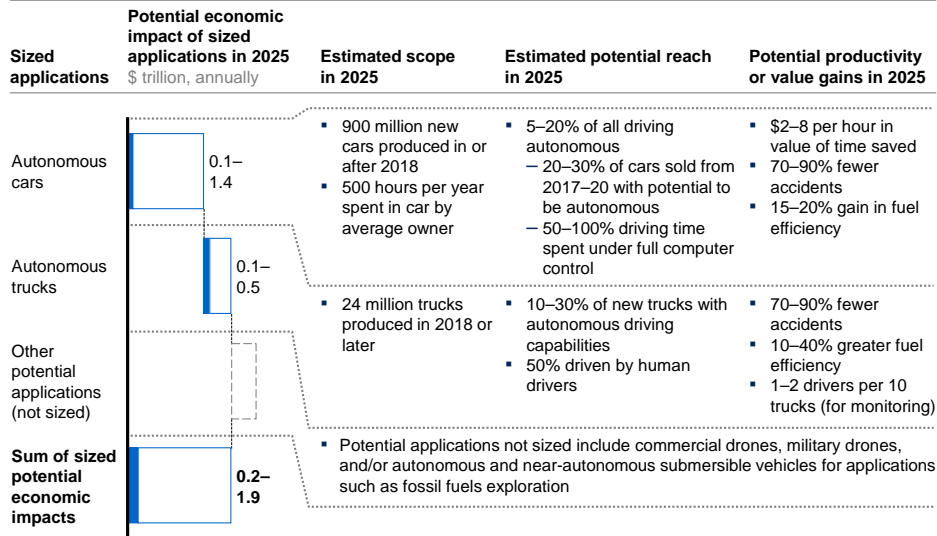
The potential economic impact of autonomous cars and trucks could be \$200 billion to \$1.9 trillion per year by 2025 (Exhibit 8). This is an indicative value estimation of the benefits of the technology that could be realized if autonomous vehicles are allowed by regulations and adopted by consumers. The largest impact would come from freeing up time for drivers, increased road safety, and the reduced cost of operation of vehicles. We estimate that 30,000 to 150,000 lives could be saved per year in 2025 if this technology is adopted and that CO₂ emissions could be reduced by as much as 300 million tons per year. That amount is equivalent to 50 percent of CO₂ emissions from current commercial aviation.⁸⁴

Self-driving cars could have a potential economic impact of \$100 billion to \$1.4 trillion per year in 2025. This assumes that 75 to 90 percent of cars sold from 2017 to 2020 in the high-end auto segment, as well as 20 to 30 percent of midpriced cars, could have self-driving capability. That would translate into approximately 10 to 20 percent of the 1.2 billion private cars projected to be on the road in 2025 having the ability to self-drive in at least half of all traffic situations.

82 Angus MacKenzie, “The future is here: Piloted driving in Audi’s autonomous A6,” *MotorTrend*, January 2013.

83 Andrew English, “New car tech: 2014 Mercedes-Benz S-class,” *Road & Track*, November 2012.

84 *Introduction of aviation into the European Union emissions trading scheme*, Econometrica Press summary paper, May 2009.

Exhibit 8**Sized applications of autonomous and near-autonomous vehicles could have direct economic impact of \$200 billion to \$1.9 trillion per year in 2025**

NOTE: Estimates of potential economic impact are for some applications only and are not comprehensive estimates of total potential impact. Estimates include consumer surplus and cannot be related to potential company revenue, market size, or GDP impact. We do not size possible surplus shifts among companies and industries, or between companies and consumers. These estimates are not risk- or probability-adjusted. Numbers may not sum due to rounding.

SOURCE: McKinsey Global Institute analysis

Assigning a value of \$2 to \$8 per hour of driving time that could be regained (depending on factors such as degree of car autonomy and potential legislation requiring the driver to pay attention to the road), we estimate that \$100 billion to \$1.0 trillion in saved time could be freed up per year by 2025.⁸⁵ We calculate the second-largest source of savings—reducing vehicular deaths—by estimating that self-driving technology can reduce road accidents by 5 to 20 percent overall. This assumes that autonomous cars will not be subject to the type of accidents that are caused by human behavior. This could reduce annual automobile deaths by 30,000 to 140,000 a year globally in 2025.⁸⁶

Fuel savings of 15 to 20 percent could be possible through the use of self-driving technology. Autonomous vehicles can be programmed to eliminate the 10 to 15 percent of fuel waste that occurs with rapid acceleration, speeding, and speed variation. Also, because sensors on each car respond instantly to the actions of the cars they follow, autonomous cars could travel more closely together, reducing air resistance and improving fuel efficiency by 15 to 20 percent when vehicles travel in convoy style.⁸⁷ The consequent CO₂ emission reduction could be approximately 20 million to 100 million tons per year.

85 Based on US Department of Transportation estimates of the value of transportation time (\$7 to \$19 per hour) for different countries. The US Bureau of Labor Statistics estimates the value of work time at \$16 per hour. We have chosen \$2 to \$8 per hour, because the full value of the time cannot be recaptured while still in the car.

86 We use a value per full QALY (quality-adjusted life year) value of \$100,000 for advanced economies and \$50,000 in the developing world, with discount rate of 4 percent per year.

87 Kevin Bullis, "How vehicle automation will cut fuel consumption," *MIT Technology Review*, October 24, 2011.

Assuming that autonomous trucks could travel long distances in tightly spaced caravans and that drivers would not be needed in most vehicles, self-driven trucking could have a potential economic impact of \$100 billion to \$500 billion per year in 2025. We think it is possible that between 2017 and 2025, 10 to 30 percent of trucks sold could be at least partially autonomous. Self-driving trucks potentially could be used for long-distance highway driving. However, over shorter distances, or for local deliveries, a driver would still be needed. But even local delivery trucking could benefit from autonomous driving features that improve fuel efficiency and safety.

We assume that half of autonomous trucks could still have a driver (to provide service or make deliveries, for example); for convoys of fully self-driving trucks, there might be one or two drivers for every ten trucks. If adoption of autonomous trucks occurs at the rates calculated here, we estimate economic impact of higher driver productivity could be \$100 billion to \$300 billion per year in 2025. Autonomous trucks could also prevent 2,000 to 10,000 traffic deaths per year in 2025 (as with passenger cars, 70 to 90 percent of trucking accidents are caused by human behavior, such as falling asleep at the wheel).

Based on evolving technology, it is possible that autonomous trucks could be spaced less than three feet apart while driving, reducing fuel consumption by 15 to 20 percent by sharply reducing air resistance. Combined with speed control optimized for fuel efficiency, we estimate that autonomous trucks can use 10 to 40 percent less fuel than non-autonomous trucks.

BARRIERS AND ENABLERS

Governments will have a central role in determining whether the potential value of autonomous vehicles will be realized. Government efforts to encourage the development and ultimate adoption of autonomous cars and trucks could greatly speed their impact by helping to overcome concerns about technology, safety, liability, and legal responsibilities. Laws regarding autonomous driving will be a critical enabler. If governments establish regulations early on that let autonomous vehicles travel on public roads, it will provide a foundation on which to build new approaches to ground transportation. However, if regulations forbid drivers to take their hands off the wheel under any circumstances, the consumer surplus derived from saved driving time will not materialize.

If policy makers decide that the benefits of autonomous vehicles constitute a valuable public good, they can maximize those benefits by investing in intelligent road infrastructure systems that would make hands-off driving safer. Intelligent roads would have embedded sensors to provide precise positioning information and unambiguous input about speed limits. Other elements would include sensors at intersections to tell the vehicle if it is safe to proceed or if a traffic light is red or green, for example. In this way, the smart road takes on many of the complex tasks involved in guiding a vehicle safely. We do not believe that it is likely that extensive investments in intelligent roads will be made by 2025. However, if the adoption of autonomous vehicles accelerates, the pressure to invest in autonomous-vehicle lanes and road sensors could rise as motorists seek to maximize the benefits of autonomous vehicles.

Despite the technological progress that is now being seen in experimental vehicles, these systems still require a great deal of improvement. Continuing work is required on vision, pattern recognition, and artificial-intelligence technologies to account for unexpected vagaries in infrastructure (for example, what to do when lane marker lines are obscured or traffic is rerouted around work crews).

IMPLICATIONS

Autonomous vehicles have significant potential to transform ground transportation, creating many opportunities for businesses and addressing many societal needs. They also have the potential to affect everyone who uses a car, all industries related to cars and trucks, and intermodal logistics systems. Autonomous vehicles could create great opportunities for new players in the automotive industry, including new types of competitors from technology and IT-related industries. In addition to providing vehicles with the input devices and onboard intelligence to maneuver independently, companies may find new business models that capitalize on the free time of drivers-turned-passengers (entertainment services or worker productivity tools designed for use in cars, for example).

There is the possibility of a few players dominating the autonomous vehicle market, and these early entrants could create standards for operating systems and programming interfaces that might influence regulatory requirements. Early entrants into the autonomous-vehicle “ecosystem” could therefore benefit. As fully autonomous vehicles become more accepted, there may also be opportunities for new types of driverless passenger cars (such as models designed for ride-sharing and carpooling that have no driver’s seat). This could provide an opening for new vehicle manufacturers or players in other industries to enter the market; it could also reduce rates of private car ownership.

The success of autonomous cars and trucks could change the auto insurance industry. A significant reduction in traffic accidents and insurance claims could lead to a corresponding reduction in premiums. Individuals will also have more complex risk profiles as they gain the ability to operate both self-driving and traditional cars. Eventually, this could even drive a shift from traditional personal auto insurance to product liability insurance. However, some degree of personal liability will likely remain.

Self-driving vehicles could have very disruptive effects on the trucking industry. In the United States, there are around 3.5 million truck drivers. Demand for long-haul truck drivers would decline significantly, relegating truck driving to final-mile transportation and delivery. Companies should begin to work with employees to manage this change before this transition. The job of truck driver may come to involve more customer service, for example. Other driving jobs, such as taxi drivers and bus drivers, could also be at risk in the long term.

Policy makers will need to devise thoughtful supporting regulations for autonomous vehicles. Car manufacturers might not risk taking on the liability of driverless vehicles until regulators establish appropriate rules; for example, systems such as those that will be available on the forthcoming Mercedes-Benz S-class are designed to disengage if the driver takes even one hand off the wheel above certain speeds.

Policy makers should also plan ways to maximize the value of autonomous vehicles to the economy and society. This should include long-term infrastructure planning that takes autonomous vehicles into account (for example, the creation of dedicated lanes for autonomous vehicles and sensor-embedded roads) and regulations that balance safety with the adoption of valuable technology.

Autonomous vehicles will also present legitimate security concerns. Like any computer system, a car's autonomous guidance system could be hacked, with potentially disastrous results. Robust cybersecurity systems will need to be in place before this technology hits the road.

7. Next-generation genomics



The science of genomics is at the beginning of a new era of innovation. The rapidly declining cost of gene sequencing is making huge amounts of genetic data available, and the full power of information technology is being applied to vastly speed up the process of analyzing these data to discover how genes determine traits or mutate to cause disease. Armed with this information, scientists and companies are developing new techniques to directly write DNA and insert it into cells, building custom organisms and developing new drugs to treat cancer and other diseases. Over the coming decade, next-generation genomics technology could power rapid acceleration in the field of biology and further alter health care. Desktop gene-sequencing machines are not far off, potentially making gene sequencing part of every doctor's diagnostic routine.

Longer term, these advances could lead to radical new possibilities, including fully tailoring or enhancing organisms (including humans) by precisely manipulating genes.⁸⁸ This could lead to novel disease treatments and new types of genetically engineered products (such as genetically engineered biofuels), while enabling the nascent field of synthetic biology—designing DNA from scratch to produce desired traits.⁸⁹

The potential economic impact of next-generation gene sequencing in the applications that we have sized in health care, agriculture, and the production of substances such as biofuels could be \$700 billion to \$1.6 trillion a year by 2025. About 80 percent of this potential value would be realized through extending and enhancing lives through faster disease detection, more precise diagnoses, new drugs, and more tailored disease treatments (customized both to the patient and to the disease). In agriculture, analyzing plant genomes could lead to more advanced genetically modified (GM) crops and further optimize the process of farming by tailoring growing conditions and farming processes to a seed's genetic characteristics. Furthermore, it may be possible to create high-value substances such as biofuels by modifying simple organisms such as *E. coli* bacteria. Easy access to gene-sequencing machines could not only put powerful genetic technology in the hands of researchers and physicians, but could also create a global community of co-creators that might advance biotechnology in unforeseeable ways, as hobbyists propelled the microcomputer revolution.

The technical challenges inherent in next-wave genetic engineering technology are great but may be less formidable than the social, ethical, and regulatory

88 The fundamental challenge of genomics and, arguably, biology itself, involves clearly understanding the processes that link DNA, RNA, proteins, and metabolics to determine cellular and organism behavior, a field of discovery often referred to as “omics.”

89 DNA can be modified through recombinant technology, combining DNA from two or more existing genomes, or through a process of DNA synthesis that involves chemically printing DNA (often called synthetic biology). Synthetic biology is at a relatively early stage of technological development; furthermore, precise editing of DNA is not required to achieve much of the impact made possible by next-generation genomics. For these reasons, we do not include synthetic biology in our estimated potential economic impact in this report.

concerns it may generate. While this technology has the potential to create huge benefits for society, it comes with an equally impressive set of risks. Genetically modified organisms could interfere with natural ecosystems, with potentially disastrous results including loss of species and habitats. Genomic technology raises privacy and security concerns related to the potential theft or misuse of personal genetic information stored on computers. And while the potential for widespread access to sequencing and, eventually, DNA synthesis technology will create opportunities for innovators, it also raises the specter of bioterrorism. Moreover, this technology could well unfold in a regulatory vacuum: governments have yet to address major questions concerning who should own genetic information, what it can be used for, and who should have access to next-generation genomic capabilities.

DEFINITION

Next-generation genomics can be described as the combination of next-generation sequencing technologies, big data analytics, and technologies with the ability to modify organisms, which include both recombinant techniques and DNA synthesis (that is, synthetic biology). Next-generation sequencing represents newer, lower-cost methods for sequencing—or decoding—DNA. It encompasses the second- and third-generation sequencing systems now coming into widespread use, both of which can sequence many different parts of a genome in parallel.

The rate of improvement in gene-sequencing technology over the past decade has been astonishing. When the first human genome was sequenced in 2003, it cost nearly \$3 billion and took 13 years of work by teams of scientists from all over the world collaborating on the Human Genome Project. Now a \$1,000 sequencing machine could soon be available that will be able to sequence a human genome in a few hours. In fact, over the past decade, the rate of improvement in sequencing speed has exceeded Moore's law, the famously fast rate of performance improvement achieved by computer processors. This improvement in performance has been achieved by creating highly parallel systems that can sequence millions of DNA base pairs in a very short time. As the DNA is read, the process generates massive data, which are passed on to powerful computers for decoding. Thus, progress in genomics and computing speed are evolving in tandem—a development that has been referred to as “wet” science meeting “dry” science.

This advance in DNA sequencing speed (along with simultaneous reductions in cost) promises to accelerate the process of biological discovery. Historically, biological research has relied largely on hypothesis-driven, trial-and-error testing. This approach is very time-consuming and difficult, so scientists' understanding of which genes drive specific outcomes (such as diseases) remains very limited. With growing access to large samples of fully sequenced genomes, researchers can employ more broad-based methods, performing correlation analysis on big data sets of sequenced genomes together with patient data, and testing combinations of genes, diseases, and organism characteristics to determine which genes drive which outcomes. These big data experiments can include data on genealogy, clinical studies, and any other statistics that could help link genotype (DNA) to phenotype (organism characteristics or behavior). Armed with this information, it could be possible to better identify and diagnose people at high risk for conditions such as heart disease or diabetes, allowing earlier, more effective intervention.

Next-generation sequencing also makes personalized medicine possible. Individual patients possess unique genomes and can be affected differently by the same disease or therapy. The ability to genetically sequence all patients, along with the viruses, bacteria, and cancers that affect them, can allow for better matching of therapy to the patient. Sequencing can also help physicians understand whether a set of symptoms currently treated as a single disease is, in fact, caused by multiple factors.

Advanced genomics will also facilitate advances in agriculture. Farmers might be better able to optimize soil types, watering schedules, crop rotations, and other growing conditions based on a more complete understanding of crop genomes. It may also be possible to produce genetically modified crops that can grow in locations where soil conditions and access to water cannot be easily improved; crops that can thrive in colder, drier climates; or crops that generate a larger portion of their weight as food. Crops might also be modified to serve as better raw materials for the production of biofuels. Modified animals in our food supply might also be on the horizon. For example, one US company is seeking approval for an Atlantic salmon modified with an eel gene that enables it to reach maturity in half the normal time.⁹⁰

Finally, next-generation genomic technology could be used to modify the DNA of common organisms to produce valuable substances. Using synthetic biology or even standard, well-established recombinant techniques, the metabolic systems of certain organisms can be modified to produce specific substances, potentially including fuels, pharmaceuticals, and chemicals for cosmetics.

POTENTIAL FOR ACCELERATION

Next-generation genomics has the potential to give humans far greater power over biology, allowing us to cure diseases or customize organisms to help meet the world's need for food, fuel, and medicine. With world population heading toward eight billion in 2025, there is a growing need for more efficient ways to provide fuel for heat, electricity generation, and transportation; to feed people; and to cure their ailments. Meanwhile, populations are aging in advanced economies. By 2025 approximately 15 percent of the world's population will be 60 years of age or older, multiplying health-care challenges.⁹¹

Next-generation genomics can address these needs. The falling cost of genome-sequencing technology will accelerate both knowledge and applications. In genomics, the relevant unit of performance measurement is the time and cost per sequenced base pair (the basic units of DNA). With newer generations of sequencing technology, the cost of sequencing a full human genome has fallen to around \$5,000, but the \$1,000 genome is widely expected to be achieved within the next few years. Counsyl, a Silicon Valley company, already offers a \$600 genetic test that can screen children for more than 400 mutations and 100 genetic disorders.⁹²

90 Andrew Pollack, "Engineered fish moves a step closer to approval," *The New York Times*, December 21, 2012.

91 David Hutton, *Older people in emergencies: Considerations for action and policy development*, World Health Organization, 2008.

92 Kim-Mai Cutler, "Through dirt-cheap genetic testing, Counsyl is pioneering a new bioinformatics wave," *TechCrunch.com*, April 23, 2013.

Cancer is a genetic disease that is caused when mutated cells grow out of control. Sequencing is already being used to tailor treatments that are customized to the genome of the patient and the mutated genome of the tumor. Studies have shown how specific cancer-causing mutations correlate with responses to different cancer treatments and there is a healthy pipeline of bio treatment and diagnostic drugs. However, given the rate at which drugs fail during testing, it is not likely that the number of drugs used with companion diagnostics over the next five years will rise rapidly.⁹³

Oncology remains at the forefront of genetic research and development in medicine, but applications for other types of diseases are on the radar. Researchers are also focusing on mutation-based links to widespread diseases such as cardiovascular disease to identify how different genomes correspond to different responses to therapies.

GM crops are playing an increasingly important role in improving agriculture in developing economies. The total area planted in GM crops has risen from 1.7 million hectares in 1996 to more than 170 million hectares in 2012, and for the first time farmers in developing economies planted more hectares of GM crops than did farmers in advanced countries. Planting of GM crops grew 11 percent in developing economies in 2012, more than three times the rate of such planting in advanced economies. Next-generation genomics could enable the creation of even more advanced varieties with even greater potential value.

Synthetic biology is still in a very early stage of development, but could become a source of growth. If the process can be perfected, modifying organisms could become as simple as writing computer code. While the technology is new, there is already evidence for applications in science and business. For example, a research team at Ginko Bioworks in Boston is working on developing the biological equivalent of a high-level programming language with the goal of enabling large-scale production of synthetically engineered organisms.

Companies are beginning to invest in synthetic biology capabilities. Joule Unlimited and Algenol Biofuels, for example, have created demonstration plants that can produce high-value substances using synthetically engineered organisms—diesel fuel in the case of Joule Unlimited and ethanol at Algenol. However, synthetic biology remains challenging, with high up-front capital investments required and difficulties in economically scaling production.

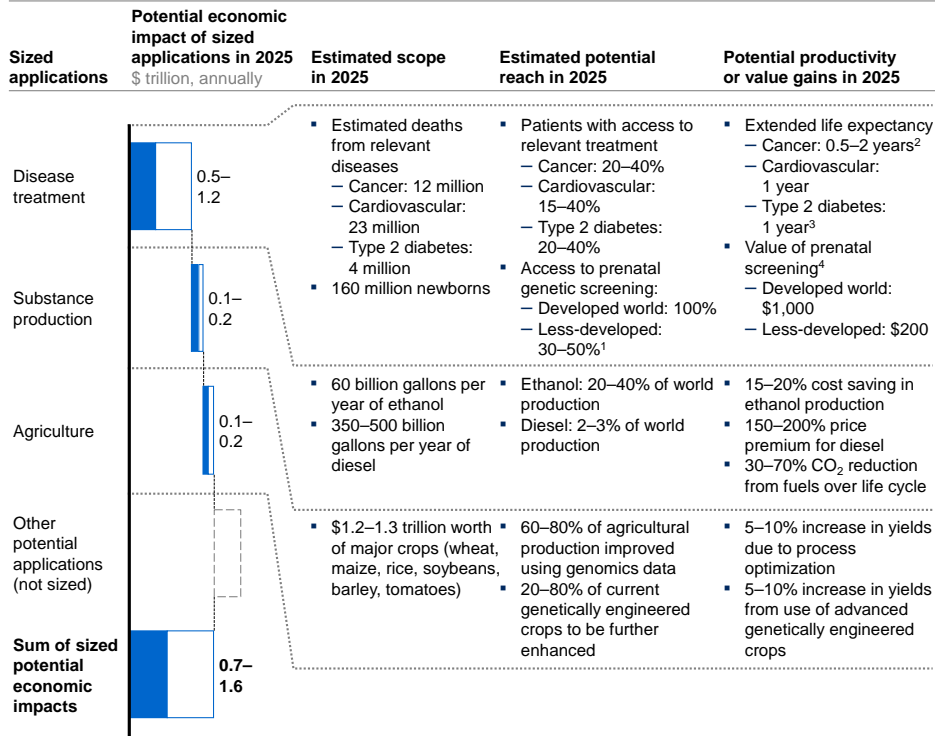
ECONOMIC IMPACT

In the applications we assessed, we estimate that next-generation genomics have a potential economic impact of \$700 billion to \$1.6 trillion per year by 2025. We estimate the impact of disease prevention and treatment applications that we size could be \$500 billion to \$1.2 trillion per year in 2025, based on extended life expectancy stemming from better and faster disease diagnosis and more tailored treatments (Exhibit 9). In particular, new technology has the potential to improve treatment of genetically linked diseases such as cancer and cardiovascular diseases, which currently kill around 26 million patients per year.

93 *Personalized medicine: The path forward*, McKinsey & Company, March 2013.

Exhibit 9

Sized applications of next-generation genomics could have direct economic impact of \$700 billion to \$1.6 trillion per year in 2025



1 Developing economies excluding the least developed.
 2 Will vary across cancer types.
 3 We take into account the overlap of diabetes- and cardiovascular-related deaths.
 4 Measured by parents' willingness to pay.
 NOTE: Estimates of potential economic impact are for some applications only and are not comprehensive estimates of total potential impact. Estimates include consumer surplus and cannot be related to potential company revenue, market size, or GDP impact. We do not size possible surplus shifts among companies and industries, or between companies and consumers. These estimates are not risk- or probability-adjusted. Numbers may not sum due to rounding.

SOURCE: McKinsey Global Institute analysis

Some 14 million new cases of life-threatening cancers can be expected to be diagnosed worldwide in 2025. Determining how many of these patients could have longer lives or better quality of life due to more effective treatment based on next-generation genomics is not straightforward. Most cancers still may not be curable even after sequencing identifies the genetic mutations that trigger disease. For some cancers, however, the process of identifying the mutations involved and then developing targeted therapy is moving ahead. For example, Herceptin, a breast cancer drug, acts only on tumors that contain cancer cells that, because of a gene mutation, make more of the HER2 tumor-creating protein than normal cells. Studies have shown that Herceptin can decrease fatalities by, for example, reducing the risk of recurring tumors. Some industry leaders believe that eventually most types of cancer could be treated with targeted therapies based on next-generation genetic sequencing.⁹⁴

To estimate the potential economic impact of these improved diagnostic and tailored treatment methods, we estimate the value to the patient of the extended life that might result. Based on the assessment of cancer experts, we estimate that genomic-based diagnoses and treatments can extend lives of cancer

94 *Personalized medicine*, McKinsey & Company, March 2013.

patients by six months to two years in 2025. We further estimate that 20 to 40 percent of patients would have access to such care in 2025. We note that any estimates of success rates are highly speculative, given the state of development of these therapies.

Longer term, advanced genomics may offer tremendous potential to develop personalized treatments for cardiovascular disease. Every patient responds differently to the mix of medicine they are exposed to, and today high-risk patients are often treated with preventive medications with dosages adjusted on a trial-and-error basis, creating high risks. While the technology is still in early stages, genetic testing could help doctors determine dosages and mixes of substances more precisely. Also, screening can enable customized preventive routines (lifestyle changes, for example), as well as tailored treatments. Based on expected growth rates in cardiovascular disease, 23 million people could be expected to die of cardiovascular disease in 2025.⁹⁵ For the purpose of sizing potential impact, we assume that 15 to 40 percent of patients could receive and benefit from genetic-based care and, on average, have one year of extended life.

Another major target for genetic medicine is type 2 diabetes, a growing health problem, especially in advanced economies. Based on current rates of diabetes incidence, some three million deaths could be caused by type 2 diabetes and related complications in 2025.⁹⁶ Genome sequencing could enable the creation of treatments that could control the disease more effectively and better reduce the risk of death than the currently imprecise science of daily insulin use. We estimate that 20 to 40 percent of patients could have access to such treatment and might have increased life expectancy of one year.⁹⁷ Other areas in which genetic sequencing holds promise, but for which we have not built estimates, include immunology and transplant medicine, central nervous system disorders, pediatric medicine, prenatal care, and infectious diseases.

Next-generation gene sequencing has application in prenatal care. Sequencing a fetus's DNA would make it possible to predict the health of the baby more accurately than current tests can. Surveys show that parents in advanced economies would be willing to pay \$1,000 to have their baby's genome sequenced.⁹⁸ Assuming close to 100 percent adoption in advanced economies and 30 to 50 percent adoption rates in less-developed economies (excluding least-developed nations), this testing could generate value of approximately \$30 billion per year in 2025.

Another source of potential economic impact could arise from altering the metabolism of common organisms such as *E. coli* and yeast to create biofuels; this could be less expensive and require less energy and other inputs than creating biofuels from plants. Production costs could be as much as 15 to 20 percent lower for ethanol produced in this manner. It is possible that the cost of producing diesel using this technology could reach parity with traditional diesel by 2025, and since biodiesel commands a price premium even today (due

95 Cancer Fact Sheet number 297, World Health Organization, January 2013.

96 Diabetes, Fact Sheet number 312, World Health Organization, March 2013.

97 There is an overlap in potential economic impact from diabetes- and cardiovascular-related deaths.

98 A. B. Caughey et. al., "Assessment of demand for prenatal diagnostic testing using willingness to pay," *Obstetrics and Gynecology*, volume 103, number 3, March 2004.

to factors like government policy and environmental concerns), this new source of biodiesel could see significant demand. We estimate that the price premium over traditional diesel might be as much as 150 to 200 percent, and that micro-organism produced biodiesel could potentially replace 2 to 3 percent of traditional diesel consumption. Producers claim that these fuels derived from microbes could contribute 70 to 90 percent less in CO₂ emissions in their production and use than traditional fuels. We estimate that the potential impact could be \$100 billion to \$200 trillion in 2025, including the savings associated with lower production costs, the value of lower CO₂ emissions, and the value of the fuel itself.

In agriculture, next-generation genomics has the potential to both raise productivity in places where food is in short supply and conserve water. Advances in genetic modification of seeds could increase yields by making crops more drought- and pest-resistant. Genomics can also provide information that can be used to optimize crops for specific soils and climates and guide precision farming practices such as “fertigation” (a process in which the exactly necessary amounts of water and fertilizer are delivered to crops). We assume potential increases of 5 to 10 percent from optimized processes and 5 to 10 percent from new genetically modified seeds, leading to a potential economic impact of \$100 billion to \$200 billion per year in 2025.

BARRIERS AND ENABLERS

There is still much that scientists do not understand about genomics. Deciphering the interrelationships between genes, cellular mechanisms, organism traits, and environment is a complex undertaking that next-generation gene sequencing can speed up. But that work is only just beginning. Fast and cheap sequencing is still a new technology, and much of the initial genome sequencing will likely have unknown or little immediate impact. Understanding and applications will grow once many genomes have been sequenced and sample sizes are big enough to enable advanced analytics. While next-generation genomics technology could speed up this learning process dramatically, it is less clear how quickly this will lead to breakthroughs in understanding biology.

What is more likely to slow progress, however, are the many unresolved regulatory and ethical issues that this technology poses. One issue is the ownership of the data of sequenced genomes, which will be a very valuable resource for performing analyses and testing pharmaceutical treatments, but which might not be available if patients own the data regarding their own genomes and are not willing to share it. In the fall of 2013, the US Supreme Court is scheduled to hand down a key ruling on whether pharmaceutical companies can patent human cells. There are also concerns regarding the confidentiality of patient DNA information: can it be used by health insurers to deny coverage or raise rates, and should patients be given all the information about disease-linked mutations found in their genomes that might someday lead to illness? If these questions are slow in being addressed or not addressed adequately, progress could be delayed, potentially by public resistance.

There is also widespread public apprehension about the possible unintended consequences of altering plant and animal DNA. The European Union’s 1998 ban on genetically modified corn remains in effect, and many consumers are concerned about the possible effects of “Frankenfood” on environments, biodiversity, and human health. Advanced recombinant technology and synthetic biology could certainly heighten such concerns. Regulators have imposed limits

on research on modified organisms, restricting them to closed environments. The continuation or strengthening of these types of restrictions could limit the potential economic impact of advanced genomics.

IMPLICATIONS

By 2025, continued advancement in gene sequencing speed and cost, along with equally rapid advances in the ability to understand and manipulate biological information, could create tremendous opportunities and risks for technology providers, physicians, health-care payers, biotechnology and pharmaceutical companies, entrepreneurs, and societies.

It is possible that genetic sequencing could become standard practice during medical exams by 2025. If it does, it could create major opportunities for companies and startups to manufacture and sell gene-sequencing equipment, along with the various supporting systems and tools that could be required (including big data analytics tools). The early entrants into this market could have the opportunity to define major industry standards and norms, including sequencing approaches, data standards, and integration with electronic health records. They will also need to win over payers, such as insurance companies and governments, by clearly demonstrating cost-effective efficacy improvements; the technology will also need to become user-friendly for physicians.

Insurers and other health-care payers (for example, state health insurance systems) will have a large interest in shaping how next-generation genomics and the resulting data are used. Improved treatments, reduced side effects, and reduced waste (due to avoiding incorrect diagnoses and treatments) could help reduce payer costs, which could provide the incentive for payers to subsidize routine genome screening. In some countries payers will also need to convince regulators and patients that genomic data will not be used against individual patients.

For biotech and pharmaceutical companies, the ability to sequence more material more quickly and to use the growing body of genetic data to isolate (or engineer) the best candidate substances for drug development has the potential to raise productivity and lower costs for new drugs and therapies. This could significantly impact the economics of drug discovery and testing. Simultaneously, the barriers to entry into biopharmaceuticals could fall when research becomes less capital-intensive and cycles for development decrease.

Next-generation genomics could drive a major wave of entrepreneurship. Alongside companies that are looking to produce and sell gene-sequencing systems, there are already a growing number of startups and laboratories offering home DNA testing, including results that identify predispositions for known genetic diseases and information on ancestry. Fast, cheap sequencing is making these types of services possible; however, as these technologies become widely available, specialized testing services may have a limited market. Other entrepreneurs are already coming to market with new, unexpected solutions based on next-generation sequencing. For example, a synthetic biology startup that used the peer-to-peer funding site Kickstarter to raise capital has produced a synthetically engineered light-emitting plant, which it says could lead to a new source of lighting.

Policy makers will have many issues to address surrounding the applications of genetic science. Governments have supported the development of genomics through investments in research but have not been as forward-thinking when it comes to crafting policy. Governments can play a critical role in helping next-generation genomics live up to its potential to save lives, feed people, and provide fuels that will be less harmful to the environment.

One possible step could be supporting independent research investigating questions regarding the environmental and health risks and benefits of genomic applications. Governments can also work on regulations and initiatives to enable the success of genome-based advances. For example, the regulatory environment for drugs and diagnostics is likely to have a significant impact on the evolution of personalized medicine. Most experts believe that regulation has not kept pace with the rapid advances in the field of personalized medicine. A more far-sighted regulatory approach could balance many of the objections, including concerns regarding personal privacy, with the potential benefits of these technologies. This would give next-generation genomics researchers the opportunity to continue developing these technologies.

In addition to clarifying rules about ownership of DNA data and confidentiality, governments can facilitate the accumulation of genetic information. Since 2006, the US National Cancer Institute and the National Human Genome Research Institute have been compiling the Cancer Genome Atlas, a project with the goal of collecting all data about what mutations have been linked to cancers. It may soon be possible for governments to sponsor a central database of millions of genome sequences and make the information accessible (with proper precautions) to researchers.

Perhaps the thorniest concern in the near future is prenatal genome sequencing. Prenatal genetic screening raises the specter of eugenics: will parents end pregnancies for reasons other than serious deformities and other congenital medical conditions?

Ever since the creation of Dolly the sheep in 1996 proved that cloning is possible, genetic engineering has inspired both visions of a better world and concerns about the risks of such advances. Recently, scientists revealed that they have successfully inserted mitochondrial DNA into the egg cells of women who have had trouble conceiving. The procedure has been used in 30 successful pregnancies, producing babies with genes from the child's two biological parents and the mitochondrial DNA donor; in effect, these children have three biological parents.⁹⁹ This particular modification was performed to aid in conception, but it could also represent the first step on the path to manipulating human DNA to produce babies with "desirable" traits.

99 Michael Hanlon, "World's first GM babies born," *Daily Mail*, April 25, 2013.

8. Energy storage



Since the late 1700s—a century before electricity became widely used—scientists have been working on ways to store electrical energy. Today, the technology of energy storage is advancing rapidly and being applied in new ways, creating significant potential for impact and disruption. Improved lithium-ion batteries are already powering electric and hybrid vehicles, as well as billions of portable consumer electronics products, including mobile Internet devices. Over the coming decade, battery-powered vehicles could become cost competitive with vehicles powered by internal-combustion engines, saving energy and reducing CO₂ emissions. Energy storage could also help bring electricity to remote areas in developing countries and boost the efficiency and quality of the electric grid while helping to reduce CO₂ emissions.

The potential economic impact of improved energy storage could be \$90 billion to \$635 billion per year by 2025. More than half of this impact could be driven by electric and hybrid vehicle adoption. Distributed energy (that is, using batteries to bring power to areas where wiring or reliable supply is not available) may have a relatively small direct economic impact but have a transformative effect on the lives of more than one billion people who currently live without electricity. Grid applications—placing storage capacity on the grid to reduce the cost of meeting peak demand and to facilitate feeds from wind or solar generators—may also have relatively modest impact by 2025, barring major technical breakthroughs in battery cost and performance that would improve gains.

In this chapter, we analyze the potential acceleration of energy storage use and its potential impact assuming the scenario that has the most realistic potential by 2025. However, it is possible to envision a scenario in which distributed storage has a faster rate of adoption and greater economic impact as a result of falling battery costs and higher energy prices, which could lead to significantly increased adoption of renewable power sources, particularly solar (see Chapter 12, “Renewable energy”) and drive demand for grid storage. While this scenario is more likely to occur after 2025, it nonetheless deserves mention.

DEFINITION

Energy storage systems convert electricity into a form that can be stored and converted back into electrical energy for later use, providing energy on demand. This enables utilities, for example, to generate extra electricity during times of low demand and use it to augment capacity at times of high demand. Today, about 3 to 4 percent of the electricity that is produced by utilities worldwide is stored, almost all of it through a technique called pumped hydro-electric storage (PHES), which involves pumping water uphill during times of low demand or low cost and releasing it downhill to turn power-generating turbines during times of high

demand and high cost. PHES currently accounts for approximately 120 gigawatts of storage capacity.¹⁰⁰

Batteries in their various forms constitute the most widely known energy storage technology and the main focus of our analysis. Lithium ion (Li-ion) batteries are widely used in consumer electronic devices such as laptop PCs, as well as in electric and plug-in hybrid vehicles. The Li-ion battery market is expected to double in the next four years to \$24 billion in global revenue.¹⁰¹ Significant performance and cost improvements are also expected in Li-ion batteries over the coming decade. Prices for complete automotive Li-ion battery packs could fall from \$500 to \$600 per kilowatt-hour today to about \$160 per kilowatt-hour in 2025, while cycle life could increase significantly at the same time, potentially making plug-in hybrids and electric vehicles cost competitive with traditional internal combustion engine vehicles on a total cost of ownership basis. The average cost of owning and operating Li-ion batteries for utility grid applications (a function of multiple variables including battery prices and cycle life) could fall from \$500 per MWh to between \$85 and \$125 per MWh by 2025. This could make Li-ion batteries cost competitive for some grid applications and for providing distributed energy, based on the levelized cost of electricity (LCOE), a standard measure of electricity costs.¹⁰²

Other important energy storage technologies include molten salt, flow cells, fly wheels, supercapacitors, and even conventional lead acid batteries (including recycled batteries). Other promising battery technologies to watch that are currently under development but may not be commercially viable by 2025 include liquid metal, lithium-air, lithium-sulfur, sodium-ion, nano-based supercapacitors (see Chapter 10, “Advanced materials”), and energy cache technology.

Compressed air energy storage (CAES) is a fairly mature energy storage technology useful for utility grid applications. Similar to PHES, CAES typically uses natural formations, but instead of pumping water uphill, air is pumped into caverns, salt domes, or other underground spaces and maintained under pressure until it is released to help drive a turbine. By 2025, the next generation of PHES and CAES energy storage could enable construction methods that are less dependent on naturally occurring geographic formations (making use instead of sea water, mine shafts, and cargo containers, for example), as well as variable-speed turbines, giving more output control and higher round-trip efficiencies.

POTENTIAL FOR ACCELERATION

Energy storage systems play an important role in integrating alternatives to fossil fuels into the energy mix and also can help improve the reliability of the electric supply and bring electricity to new users. With growing energy demand and growing concerns over CO₂ emissions and climate change, there is growing demand for less harmful means of energy production. Today, 13 billion tons

100 *Electricity storage*, International Energy Agency/Energy Technology Systems Analysis Program and International Renewable Energy Agency technology policy brief E-18, April 2012.

101 Malavika Tohani, *Global lithium-ion battery market: Growth trends and application analysis*, Frost & Sullivan, February 2013.

102 Cost is often measured as the levelized cost of electricity (LCOE), the constant unit cost (per KWh or MWh) of electricity generated by different sources using a present value payment stream of the total cost of capital, return on investment, operating costs, fuel, and maintenance over a technology's useful life. This measure is useful for comparing the prices of technologies with different operating characteristics.

of CO₂ are released annually from electricity generation. Seven billion tons are released annually through transportation.¹⁰³ The energy and transportation sectors are beginning to add more sustainable energy sources and, in both sectors, these efforts rely on energy storage: on the energy grid, storage systems can help accommodate electricity from renewable sources such as solar and advanced batteries make electric and partially electric vehicles possible.

Several other factors are leading to increased interest in energy storage. Energy storage costs have declined in recent years and are expected to decline even more by 2025—particularly for Li-ion batteries—although experts disagree as to exactly how much. This has enabled increased adoption of hybrid and battery-operated vehicles, as well as higher-performance portable consumer electronics.

Improved energy storage technologies could help rapidly growing developing economies meet their energy needs. China's electricity consumption is growing by 11 percent per year, India's by 5 percent, and Africa's by 4 percent.¹⁰⁴ Advanced energy storage technologies may be able to bring power to areas that are not currently wired and may not be for many years to come, and can be used within power grids to stretch capacity until new infrastructure is built.

Utilities in advanced economies may also invest more in energy storage during the coming decade in order to deal with peak capacity issues, to accommodate renewables (taking electricity from solar and wind farms, for example), and as part of smart grid installations. The rising use of electricity from solar and wind, which are intermittent sources of power, will likely require new forms of energy storage.¹⁰⁵ To meet peak demand without adding permanent new capacity, utilities have a range of choices, including PHES, CAES, and other non-battery technologies. Battery storage could become more competitive in these applications, but may apply only in limited circumstances. Battery storage in smart grid applications can help with frequency regulation and guaranteed peak power services.

Major advances in battery technology are occurring in important components, which could double battery capacity over the next 10 to 15 years.¹⁰⁶ Batteries have three elements: a positive terminal (the cathode), a negative terminal (the anode), and an electrolyte (a chemical medium that allows the flow of electrical charge between the cathode and anode). Next-generation cathodes incorporate “layered-layered” structures, eliminating dead zones that impede ion transfer. Silicon anodes could increase cell capacity by 30 percent compared with graphite anodes (although they are currently susceptible to cracks).¹⁰⁷ In addition, researchers are trying to identify cathode-electrolyte pairs that can sustain higher voltages, thereby boosting capacity. These advances, combined with increased production efficiency, are widely expected to significantly reduce the LCOE of batteries over the coming decade.

103 *World energy outlook 2011*, International Energy Agency, November 2011.

104 *Annual energy outlook 2012*, US Energy Information Administration, April 5–May 2, 2013.

105 Many renewable energy sources, such as solar and wind power, provide intermittent power (when wind velocity drops or the sun is obstructed by clouds, for example).

106 Russell Hensley, John Newman, and Matt Rogers, “Battery technology charges ahead,” *The McKinsey Quarterly*, July 2012.

107 *Ibid.*

POTENTIAL ECONOMIC IMPACT

The economic impact of energy storage technologies in the applications we analyzed has the potential to reach \$90 billion to \$635 billion annually in 2025 (Exhibit 10). This value could arise from three primary applications: electric and hybrid vehicles, distributed energy, and utility grid storage. While energy storage for consumer electronics also has significant economic value, a major portion of this value is effectively included within our estimated potential economic impact for mobile Internet technology (see Chapter 1), and therefore we do not include it here.

Exhibit 10

Sized applications of energy storage could have economic impact of \$90 billion to \$635 billion per year in 2025, including consumer surplus



Sized applications	Potential economic impact of sized applications in 2025 \$ billion, annually	Estimated scope in 2025	Estimated potential reach in 2025	Potential productivity or value gains in 2025
Electric and hybrid vehicles	20–415	<ul style="list-style-type: none"> 115 million passenger vehicles sold Over 1 billion vehicles in the market 	<ul style="list-style-type: none"> 40–100% of vehicles sold in 2025 could be electric or hybrid 	<ul style="list-style-type: none"> Fuel price: \$2.80–7.60 per gallon 0.22 KWh per mile fuel efficiency for EVs
		<ul style="list-style-type: none"> 13,000 TWh electricity consumption in emerging markets 2–70 hours per month without electricity 	<ul style="list-style-type: none"> 35–55% adoption with solar and battery combination 35–55% of companies in Africa, Middle East, and South Asia own diesel generators 	<ul style="list-style-type: none"> \$0.75–2.10 per KWh value of uninterrupted power supply to an enterprise \$0.20–0.60 per KWh value per household
Distributed energy	25–100	<ul style="list-style-type: none"> 60–65% rural electrification rate 1.2 billion people without electricity access 	<ul style="list-style-type: none"> 50–55% adoption based on number of people projected to earn above \$2 per day 	<ul style="list-style-type: none"> \$0.20–0.60 per KWh value per household for direct lighting, TV, and radio benefits
		<ul style="list-style-type: none"> 60 KWh monthly electricity requirement of average household 		
Electrifying new areas	0–50			
Utility grid				
Frequency regulation	25–35	<ul style="list-style-type: none"> 27,000–31,000 TWh global electricity consumption 1.5% electricity production reserved for frequency regulation 	<ul style="list-style-type: none"> 100% technology adoption, more efficient, and cost competitive with incumbent solutions 	<ul style="list-style-type: none"> \$30 per MWh weighted average frequency-regulation price
Peak load shifting	10–25	<ul style="list-style-type: none"> 2.5% additional reserved for renewable integration 		
Infrastructure deferral	~10	<ul style="list-style-type: none"> 12% of total electricity production possible to shift 850 million tons additional CO₂ release 	<ul style="list-style-type: none"> 10–20% adoption of energy storage, given costs compared with combined cycle gas turbines 	<ul style="list-style-type: none"> \$65–80 per MWh between non-renewable peak and base load \$45–65 per MWh between peak and average wind price \$30–45 per MWh between peak and average solar price
Other potential applications (not sized)				
Sum of sized potential economic impacts	90–635	<ul style="list-style-type: none"> \$295 billion per year investment in infrastructure T&D deferral 10% spent to reduce congestion 	<ul style="list-style-type: none"> 15% adoption based on share of transmission lines economical for energy storage 	<ul style="list-style-type: none"> Possible deferral of infrastructure investment by 2.5 years

NOTE: Estimates of potential economic impact are for some applications only and are not comprehensive estimates of total potential impact. Estimates include consumer surplus and cannot be related to potential company revenue, market size, or GDP impact. We do not size possible surplus shifts among companies and industries, or between companies and consumers. These estimates are not risk- or probability-adjusted. Numbers may not sum due to rounding.

SOURCE: McKinsey Global Institute analysis

Electric and hybrid vehicles

Based on an expected doubling of lithium-ion battery capacity in the next decade, electric-powered vehicles (EVs) could become cost competitive with internal combustion engine (ICE) vehicles by 2025 on a total cost of ownership basis. The cost of energy from lithium-ion battery packs (which usually include battery cells, a battery management system to control cell balancing during cycles, and thermal protection) could drop to \$165 per KWh by 2025, from \$560 per KWh in 2011.¹⁰⁸ This decrease could be the result of improvements in battery capacity and manufacturing efficiency, as well as falling component costs. Cell capacity could improve by 110 percent due to innovations such as layered-layered cathodes and silicon anodes and as volumes rise, we estimate that margins for suppliers of raw materials and parts could fall by 20 to 40 percent from today's levels, reducing costs for automakers. Given these factors, the potential economic impact of energy storage for electric vehicles could be approximately \$20 billion to \$415 billion annually by 2025.

For the purposes of calculating the magnitude of this impact, we estimated the number of battery-powered vehicles that could be sold annually in 2025 based on historic adoption trends and expected battery improvements that would alter the cost comparison between EVs and ICEs. For this analysis, we assume that the adoption of hybrid, plug-in hybrid, or battery-powered vehicles will be highly dependent on retail fuel prices. Using these assumptions, and accounting for wide regional fuel price variation (plus or minus 50 percent of current fuel prices), 20 to 40 percent of new cars bought globally in 2025 could be hybrid electric vehicles. This could occur if the total cost of ownership of hybrid vehicles makes them cost competitive with ICEs when fuel prices are \$2.85 per gallon or more. This also assumes that hybrids use electricity about 40 percent of the time. As much as 55 percent of new cars could be plug-in hybrid vehicles by 2025, which could be cost competitive with internal-combustion and hybrid vehicles at fuel prices above \$5.50 per gallon (these cars use electricity during approximately 75 percent of driving time). Finally, up to 25 percent of new cars could be all-electric, which would be competitive at fuel prices above \$9.50 per gallon.¹⁰⁹

Electricity distribution in underserved markets

Bringing electricity to developing economies is a significant challenge. In many nations, power plants operate below their rated capacities due to fuel shortages or dropping water levels in hydro-electric systems. In addition, there may be limited or highly unreliable grid infrastructure, particularly transmission and distribution lines reaching rural areas. For distributed energy, the total potential economic value of energy storage could be between \$25 billion and \$150 billion in 2025. This estimate is based on two sources of impact: improving the reliability of electric power in developing economies and bringing electric power (at least on a part-time basis) to the poorest citizens living in the most remote areas.

108 Russell Hensley, John Newman, and Matt Rogers, "Battery technology," *The McKinsey Quarterly*, July 2012.

109 These are ranges of maximum market share per electric-vehicle type and are interdependent (i.e., if plug-in hybrids achieve 55 percent share in 2025, plug-in hybrids cannot have 40 percent share). Therefore, these shares do not add up to more than 100 percent in any scenario.

Unstable electricity supply

About 43 percent of the electricity consumed in developing economies is used by industry.¹¹⁰ In a survey undertaken by the World Bank, 55 percent of Middle Eastern and North African firms, 54 percent of South Asian firms, and 49 percent of sub-Saharan African firms identified electricity as a major constraint to doing business. The smallest firms, which cannot afford backup generators, are most affected by erratic electricity supply; however, large firms still feel the impact, since they are forced to commit resources to generating capacity in order to keep running.¹¹¹ The potential for improvement of electricity reliability in developing economies is vast: developing economies consume 13,000 TWh of electricity annually, even though outages in such nations are persistent, lasting from two to 70 hours per month on average.¹¹²

Using energy storage to create distributed sources of additional power could have an economic impact of \$25 billion to \$100 billion annually in 2025 (less the cost of storage) by preventing outages. We base this estimate on an adoption rate of 35 to 55 percent. We place the value of uninterrupted electricity at 75 cents to \$2.10 per kilowatt-hour for businesses and of 20 to 60 cents for consumers, based on developing country outage reports.¹¹³

New electricity supply

Today only 63 percent of rural populations in emerging markets have access to electricity. More than one billion people could still be without electricity in 2025, based on population growth and current levels of electrification.¹¹⁴ In remote, sparsely populated areas, local energy generation is often the only solution for electricity access. The value of providing electricity access to remote areas in developing economies could be as much as \$50 billion annually in 2025. We base our estimate on a solar-plus energy storage solution, providing 60 KWh of electricity per month per household for lighting and some television, cell phone charging, radio, fan, and iron usage. The value to rural households of this electricity access is estimated to be between 20 to 60 cents per KWh (based on World Bank and IEG projections, and an estimated 55 percent adoption rate, based on the proportion of rural populations that could potentially afford system lease fees).¹¹⁵

Grid storage

Today, electricity is generated seconds before it is used on the grid. As a result, the electricity industry must invest in and maintain capacity for peak usage—usually during the heat of summer as millions of air conditioners run at full power—even though peak demand is infrequent. Energy storage could enable peak load shifting (tapping additional sources of supply during times of peak demand), higher utilization of existing grid infrastructure, and efficient balancing of small fluctuations in power output, as well as providing temporary power in the

110 Russell Hensley, John Newman, and Matt Rogers, “Battery technology,” *The McKinsey Quarterly*, July 2012.

111 World Bank Group, *Enterprise surveys: What businesses experience*.

112 *World energy outlook 2011*, International Energy Agency, November 2011.

113 Musiliu O. Oseni, *Power outages and the costs of unsupplied electricity: Evidence from backup generation among firms in Africa*, University of Cambridge research paper.

114 *World energy outlook 2011*, International Energy Agency, November 2011.

115 *The welfare impact of rural electrification: A reassessment of the costs and benefits*, Independent Evaluation Group (IEG) and World Bank, 2008.

event of an outage. However, for these benefits to be realized, energy storage must be cost competitive with other methods of addressing these issues, such as combined cycle gas turbine technology (the type of generating plant used for peaker applications) and demand-side management (that is, getting consumers and businesses to voluntarily reduce use during peak periods). Even by 2025, battery storage may not be competitive in many circumstances. Given these limitations, grid-based energy storage could have a moderate economic impact of \$45 billion to \$70 billion annually in 2025. This value could be realized primarily from three applications: frequency regulation, peak load shifting, and deferral of investments in new transmission and distribution infrastructure.

Frequency regulation

A wide range of devices, such as motors used in manufacturing, rely on constant frequency of alternating current electricity (50 to 60 Hz for most of the world). When generation and load are out of balance, frequency deviates from its set point. Significant load increases cause frequency to slow and voltage to drop. Similarly, frequency increases are caused by loss of load, which can happen with renewables (when a cloud passes over the sun during solar production, for example). Conventional generating facilities powered by gas or coal provide their own frequency regulation—a constant flow—by setting aside a portion of generating capacity (typically 1 to 4 percent) that can be ramped up to regulate frequency. By committing to reserve a portion of capacity in this way, utilities limit their output, losing some production efficiency.

Today, batteries are already competitive in the frequency regulation market where they are permitted by regulations, which often require reserve generating capacity to fulfill this role. Batteries will become more competitive as prices decline. The potential economic impact of energy storage on frequency regulation could be \$25 billion to \$35 billion annually in 2025, net of storage costs. This assumes that battery storage could replace all of the 4 percent of generation capacity set aside for frequency regulation. We have used an average price of frequency regulation of \$30 per MWh.

Peak load shifting

Electricity usage varies by time of day and by season; usually, the highest demand occurs in the afternoon and early evening, when people come home from work, and during the summer. To meet peak demand (when generation prices are highest), utilities can either build excess generation capacity or purchase electricity from other utilities or from specialized peaker plant suppliers. Energy storage could save costs by enabling utilities to avoid purchasing electricity at peak prices, instead buying (or generating) when it is least expensive, regardless of when it will be used. The ability to store energy for use at a later time is also useful for integrating energy from renewable sources (wind and solar power, for example) into the electricity supply, due to the intermittent nature of these power sources.

The economic impact of using energy storage for peak load shifting could be \$10 billion to \$25 billion annually in 2025. This assumes an LCOE of \$55 to \$85 per megawatt-hour in 2025 for relevant energy storage solutions and an estimated LCOE of between \$25 to \$65 per megawatt-hour for on-demand generation (using peaker plants). The generally lower cost of on-demand generation compared with energy storage will often make peaker plants a more economical choice for utilities. However, at the upper end of the cost range for peak costs,

energy storage is competitive. Therefore, energy storage could be used for 10 to 20 percent of the roughly 10 to 15 percent of all electricity generation that could be beneficially shifted.

While not included in our estimate of potential economic impact, batteries from electric vehicles could also be used as low-cost energy storage mechanisms for peak load shifting and frequency regulation. Recent studies have found minimal economic benefit to consumers from participating in peak load shifting, but there may still be an opportunity for providing frequency regulation services.¹¹⁶

Infrastructure deferral

Energy storage systems can save money by allowing utilities to delay building transmission and distribution capacity. If peak load will push a transmission line beyond capacity, energy storage can be placed on the transmission line close to the load source (that is, the area where demand exceeds line capacity) to accommodate peak demand. However, energy storage is financially viable for this use only in a small number of cases, such as when lines cannot be upgraded quickly due to long distances, where there are strict permitting requirements due to environmental concerns, or in urban hubs where distribution infrastructure upgrades are exceptionally expensive. Even by 2025, only about 15 percent of electric transmission and distribution infrastructure would be expensive enough to justify investing in storage systems to defer additional investment. As a result of these limitations, the potential economic impact of using energy storage for infrastructure deferral could be approximately \$10 billion annually by 2025.

BARRIERS AND ENABLERS

For the full economic impact of advanced energy storage to be realized, storage technology will need to reach cost and performance levels that meet or exceed those of existing alternatives. For electric and hybrid vehicles, for example, this not only means narrowing the gap with conventional ICEs on a cost-of-ownership basis, but also improving responsiveness and driving range between charges. Electric vehicles may also have to become less expensive to purchase and own, since the majority of new car sales in 2025 could be in developing markets. In addition, there will need to be adequate infrastructure in the form of recharging stations. Governments could facilitate electric and hybrid vehicle adoption through subsidies.

In grid applications, there are obstacles to advanced storage options beyond technology cost and performance. In deregulated electricity markets, where generation is separate from transmission and distribution (T&D), some applications for grid energy storage face an uphill battle. Batteries can be used for short-duration load shifting (a generation function) as well as distribution deferral (a T&D function), but utilities have limited incentives to adopt this solution. Performing each of these services in isolation is less cost competitive than existing solutions; however, when generation and T&D uses are combined, the economic case improves significantly. Regulatory policy is also critical. Regulations can prevent energy storage solutions from competing with generation assets (such as gas-powered peaker plants) for frequency regulation and peak

116 Scott Peterson, Jay Whitacre, and Jay Apt, "The economics of using plug-in hybrid electric vehicle battery packs for grid storage," *Journal of Power Sources*, volume 195, number 8, April 2010; Corey D. White and K. Max Zhang, "Using vehicle-to-grid technology for frequency regulation and peak-load reduction," *Journal of Power Sources*, volume 196, number 8, 2011.

load generation, and prevent batteries from being employed beyond single-use applications.

IMPLICATIONS

The potential of advancing energy storage technology to power EVs, make electricity more reliable and available in developing nations, and improve power grid efficiency has implications for the auto and energy industries, commercial and residential energy users, and policy makers.

For producers of energy storage technology and systems, the coming decade could provide great opportunity; however, for many applications, it will be up to the industry to make the case for their solutions. Emphasizing the lifetime benefits from investments in energy storage will be essential for gaining the support of utility company leaders, who tend to invest on decade timescales. Suppliers can also raise the odds for adoption by making energy storage systems work seamlessly with existing grid infrastructure and renewable generation systems, potentially requiring partnerships with companies with core competencies in software, process control systems, and grid integration. To get utilities comfortable with newer, relatively untested battery technology, companies may also want to consider co-investing in initial pilot projects.

The onus will also be on energy storage technology producers to reduce battery costs while improving performance. Governments and research institutions are funding and conducting energy storage research—a potential option for companies looking for cofunding support of this potentially research. Storage solution providers that are not involved in research will need to keep abreast of how battery component technologies and manufacturing processes are evolving and build flexibility into their manufacturing processes in order to be able to embrace emerging innovations.

Vehicle manufacturers will have opportunities to establish market leadership in providing electric and hybrid vehicles that satisfy consumer expectations regarding performance, utility, safety, convenience, and design. As they do, these manufacturers will need to plan for multiple scenarios of energy storage technology improvement, improvement of other technologies (for example, advances in ICE technology or the wide adoption of natural gas as a fuel), and oil prices. These scenarios, combined with changing consumer expectations, should determine the pace at which the market embraces electric and hybrid vehicles.

Utilities face both risks and opportunities due to advanced energy storage. While energy storage may help improve the quality, reliability, and efficiency of the electricity supply, other uses could affect overall demand, both positively and negatively. As electric and hybrid vehicle adoption accelerates, peak load energy demand could grow by as much as 150 percent if charging is unconstrained (that is, if most drivers come home after work and charge their vehicles when demand is highest). This could place new strain on capacity, requiring new investment in infrastructure. Conversely, rooftop solar and small-scale wind generation could reduce demand from the grid. In many regions, regulators may require utilities to pay a “green energy premium” for electricity uploaded to the grid from these sources.

Alongside these challenges, utilities could have some important opportunities. With the adoption of EVs, utilities could partner with consumers to use car batteries as remote energy storage solutions, effectively using consumers' plugged in cars as utility storage, especially for frequency regulation. There is also an opportunity to establish the market for home and road charging bundles, combining energy and hardware at a fee. Finally, to take advantage of distributed generation, utilities could provide long-term leases for storage equipment.

Consumers are likely to become increasingly aware of the issues and trade-offs relating to energy storage. As motorists, their decision to buy a hybrid or plug-in vehicle today is not about economics (at least in the absence of tax incentives), but rather about factors such as concern about climate change. In the future, however, electric and hybrid vehicles could become much more cost competitive. As residential utility customers, consumers will face choices about whether to invest in rooftop solar or small-scale wind capacity or whether to participate in demand-management schemes. These decisions have implications for the demand for energy storage.

Policy makers will play an important role in determining how much impact energy storage technologies have. Utility regulation should be reviewed to see whether there are incentives or disincentives for investment in grid storage and other relevant applications. The overall goal should be to ensure that energy storage is permitted to compete on an equal footing with other solutions. For example, grid storage should be allowed to compete with generation for frequency regulation and with peaker plants for peak load electricity supply. Introduction of renewable energy quotas could also promote investment in energy storage.

Governments can play an important role in supporting energy storage research and development. Many energy storage solutions are still in the developmental stages and are dependent on investments in basic science research, meaning it can take many years for technologies to be commercialized. Alongside investment in basic science R&D, policy makers may also want to support investment in improving the manufacturing processes of energy storage devices.

Advances in energy storage technology could significantly boost the utility and adoption of electric and hybrid vehicles, generating enormous economic impact by 2025. The realization of this potential impact is highly dependent upon retail fuel prices, which are often affected by taxes and other instruments of policy. Policy makers should seriously consider the impact of fuel pricing policies on the future of EVs and carefully weigh the trade-offs.

The potential of energy storage for grid applications could be limited by 2025, but this technology nonetheless has longer-term potential to disrupt energy generation and distribution. It is possible to envision a scenario in which distributed renewable generation, combined with cheap storage, and in the presence of higher energy prices, could eventually lead to significantly increased adoption of distributed renewable power, particularly solar. Eventually, this could vastly alter the utility industry; the use of oil, gas, coal, and nuclear generation; and the transport industry, ushering in an era of localized energy independence along with drastically reduced emission levels. Finally, there is little doubt that consumers and many businesses stand to benefit greatly from advances in energy storage technologies, whether they are used to power mobile Internet devices, vehicles, or entire households.

9. 3D printing



In recent years, 3D printing has attracted increasing attention. The prospect of machines that can print objects much the same way that an inkjet printer creates images on paper has inspired enthusiasts to proclaim that 3D printing will bring “the next industrial revolution.” Other observers have reacted with skepticism and point to the technology’s current limitations and relatively low level of adoption.

Our research leads us to a more nuanced view. While 3D printing does have the potential for disruptive impact on how products are designed, built, distributed, and sold, it could take years before that impact is felt beyond a limited range of goods. Nonetheless, rapidly improving technology and a variety of possible delivery channels for 3D-printed goods (such as using the local print shop) could ultimately result in many products being 3D-printed. In fact, personal 3D printers are already becoming available for less than \$1,000.

3D printing could proliferate rapidly over the coming decade. Sales of personal 3D printers grew 200 to 400 percent every year between 2007 and 2011, and 3D printers are already commonplace for designers, engineers, and architects, who use them to create product designs and prototypes.¹¹⁷ 3D printing is also gaining traction for direct production of tools, molds, and even final products. These newer uses of 3D printing could enable unprecedented levels of mass customization, shrinking and less-costly supply chains, and even the “democratization” of manufacturing as consumers and entrepreneurs begin to print their own products. Looking longer term, perhaps beyond 2025, one category of 3D printing—bioprinting of living organs—has long-term potential to save or extend many lives.

We estimate that 3D printing could generate economic impact of \$230 billion to \$550 billion per year by 2025 in the applications we have sized. The largest source of potential impact among sized applications would be from consumer uses, followed by direct manufacturing and the use of 3D printing to create tools and molds.

117 *Wohlers report 2012: Additive manufacturing and 3D printing state of the industry*, Wohlers Associates, 2012.

DEFINITION

3D printing belongs to a class of techniques known as additive manufacturing. Additive processes build objects layer-by-layer rather than through molding or subtractive techniques (such as machining). Today, 3D printing can create objects from a variety of materials, including plastic, metal, ceramics, glass, paper, and even living cells. These materials can come in the form of powders, filaments, liquids, or sheets. With some techniques, a single object can be printed in multiple materials and colors, and a single print job can even produce interconnected moving parts (such as hinges, chain links, or mesh).

A variety of 3D printing techniques are in use today, each with its own advantages and drawbacks. Major techniques include selective laser sintering, direct metal laser sintering, fused deposition modeling, stereolithography, and inkjet bioprinting (see Box 9, “Additive manufacturing techniques”). In all cases, objects are formed one layer at a time, each layer on top of the previous, until the final object is complete. With some techniques this is accomplished by melting material and depositing it in layers, while other techniques solidify material in each layer using lasers. In the case of inkjet bioprinting, a combination of scaffolding material and live cells is sprayed or deposited one tiny dot at a time.¹¹⁸

3D printing has several advantages over conventional construction methods. With 3D printing, an idea can go directly from a file on a designer’s computer to a finished part or product, potentially skipping many traditional manufacturing steps, including procurement of individual parts, creation of parts using molds, machining to carve parts from blocks of material, welding metal parts together, and assembly. 3D printing can also reduce the amount of material wasted in manufacturing and create objects that are difficult or impossible to produce with traditional techniques, including objects with complex internal structures that add strength, reduce weight, or increase functionality. In metal manufacturing, for example, 3D printing can create objects with an internal honeycomb structure, while bioprinting can create organs with an internal network of blood vessels. Current limitations of 3D printing, which vary by printing technique, include relatively slow build speed, limited object size, limited object detail or resolution, high materials cost, and, in some cases, limited object strength. However, in recent years rapid progress has been made in reducing these limitations.

118 See Savas Tasoglu and Utkan Demirci, “Bioprinting for stem cell research,” *Trends in Biotechnology*, volume 31, number 1, January 2013.

Box 9. Additive manufacturing techniques

- **Selective laser sintering (SLS).** In this technique, a layer of powder is deposited on the build platform, and then a laser “draws” a single layer of the object into the powder, fusing the powder together in the right shape. The build platform then moves down and more powder is deposited to draw the next layer. SLS does not require any supporting structure, which makes it capable of producing very complex parts. SLS has been used mostly to create prototypes but recently has become practical for limited-run manufacturing. General Electric, for example, recently bought an SLS engineering company to build parts for its new short-haul commercial jet engine.
- **Direct metal laser sintering (DMLS).** DMLS is similar to selective laser sintering but deposits completely melted metal powder free of binder or fluxing agent, thus building a part with all of the desirable properties of the original metal material. DMLS is used for rapid tooling development, medical implants, and aerospace parts for high-heat applications.
- **Fused deposition modeling (FDM).** A filament of plastic resin, wax, or another material is extruded through a heated nozzle in a process in which each layer of the part is traced on top of the previous layer. If a supporting structure is required, the system uses a second nozzle to build that structure from a material that is later discarded (such as polyvinyl alcohol). FDM is mainly used for single- and multipart prototyping and low-volume manufacturing of parts, including structural components.
- **Stereolithography (SLA).** A laser or other UV light source is aimed onto the surface of a pool of photopolymer (light-sensitive resin). The laser draws a single layer on the liquid surface; the build platform then moves down, and more fluid is released to draw the next layer. SLA is widely used for rapid prototyping and for creating intricate shapes with high-quality finishes, such as jewelry.
- **Laminated Object Manufacturing (LOM).** A sheet of material (paper, plastic, or metal) is fed over the build platform, adhered to the layer below by a heated roller, and a laser cuts the outline of the part in the current layer. LOM is typically used for form/fit testing, rapid tooling patterns, and producing less detailed parts, potentially in full color.
- **Inkjet-bioprinting.** Bioprinting uses a technique similar to that of inkjet printers, in which a precisely positioned nozzle deposits one tiny dot of ink at a time to form shapes. In the case of bioprinting, the material used is human cells rather than ink. The object is built by spraying a combination of scaffolding material (such as sugar-based hydrogel) and living cells grown from a patient’s own tissues. After printing, the tissue is placed in a chamber with the right temperature and oxygen conditions to facilitate cell growth. When the cells have combined, the scaffolding material is removed and the tissue is ready to be transplanted.

POTENTIAL FOR ACCELERATION

Until now, 3D printing has been used primarily for rapid prototyping. However, the technology has been evolving since the 1980s, and it may have reached a tipping point at which much more widespread adoption could occur. Advances include improvement in the performance of additive manufacturing machinery, an expanding range of possible materials, and falling prices for both printers and materials. Importantly, major initial patents have expired or will expire soon. When the original patent for fused deposition modeling (FDM) expired in 2009, 3D printing systems created through an open source project called RepRap (for replicating rapid prototyper) started to become commercially available. This has helped to spread free software and encourage rapid innovation for 3D printing using a variation on the FDM process. The last of the original selective laser sintering patents filed by the process's inventors (Carl Deckard and Joe Beaman) will expire in June 2014, which could spawn another round of innovation and low-cost commercialization.¹¹⁹

3D printing for producing complex, low volume, and highly customizable products is already accelerating. Boeing currently prints 200 different parts for ten aircraft platforms.¹²⁰ In health care, manufacturers have been offering printed custom hearing aid earpieces, selling more than one million units in 2011. In addition, more than 40,000 acetabular hip cups (the socket for hip joint replacements) have been built using 3D printing.¹²¹ The dental appliance maker Invisalign produces 50,000 to 60,000 appliances per day using stereolithography printers. Entrepreneurs are also designing and selling 3D-printed products, such as iPhone cases, often using services like Sculpteo and Shapeways that allow designers to upload designs that the company then prints and ships to consumers.

As 3D printing continues to mature and grow, it has the potential to address many important needs. In intensely competitive consumer products markets, 3D printing can meet rising expectations for quality design and personalization, including better fit for items such as shoes or helmets (see Box 10, "Vision: Everything made to order in one step"). 3D printing also has the potential to address concerns about the waste and environmental impact of traditional manufacturing processes and supply chains. Direct product manufacturing using printing can reduce the number of steps required for parts production, transportation, assembly, and distribution, and it can reduce the amount of material wasted in comparison with subtractive methods. In medicine, the ability to print body parts from the patient's own cells could improve transplant success rates and prevent deaths that occur due to patients having to wait for donor organs.

Improvements in speed and performance and falling costs will likely accelerate the spread of 3D printing in the coming decade. The average industrial printer now sells for about \$75,000, and some machines cost more than \$1 million. However, these costs are widely expected to decline rapidly in coming years as production volumes grow. Advances are also under way that could dramatically improve the output speed and quality of 3D printers. For example, recent work at the Fraunhofer Institute for Laser Technology points to the potential for a fourfold increase in printing speeds for metal objects.

119 *Wohlers report 2012: Additive manufacturing and 3D printing state of the industry*, Wohlers Associates, 2012.

120 *Ibid.*

121 *Ibid.*

On the consumer side, prices for basic 3D printers using fused deposition modeling technology have declined from \$30,000 a few years ago to less than \$1,000 for some models. Unit sales of consumer 3D printers remain small, with about 23,000 printers sold in 2011, but these sales are growing rapidly, with more than 300 percent in average annual growth between 2007 and 2011.

Meanwhile, 3D printing services are spreading rapidly. Shapeways already has more than 8,000 online shops and shipped 1 million parts in 2012. In late 2012, Staples announced plans to roll out a new 3D printing service in the Netherlands and Belgium that will allow customers to upload 3D designs and pick up the finished items at their local Staples store.¹²²

The materials used in 3D printing still remain costly (generally about 50 to 100 times greater than materials used for injection molding), but prices are declining rapidly and can be expected to decline further as volumes increase. Chinese plastics suppliers have already started to sell plastic filaments at very competitive prices—just five times the price of production grade plastics—and new extruders have been developed that can turn production-grade plastics into filaments. In addition, new types of materials are being adapted for additive manufacturing every year. Some newer polymer types that can work in 3D printers offer flexibility, electrical conductivity, and even biocompatibility (e.g., for implants). An important step could be the development of standardized materials that can be used by 3D printing systems from different vendors; today, each manufacturer requires its own certified materials.

Box 10. Vision: Everything made to order in one step

Imagine that you need new shoes. Instead of going to the store, you go online and buy a cool shoe design for a few dollars, or just download one for free. With a few clicks, you use a mobile phone app to scan your foot, select a few colors, and upload the design to print at a local 3D printing shop. Next you log on to a popular furniture site, browse for a while, and select an interesting metal and plastic chair, specifying a few adjustments to the size. A few hours later, on the way to the gym, you visit the 3D printing shop and try on your new shoes, which fit perfectly. Your new 3D-printed chair is delivered to your doorstep later that week.

On the way to work, one of those new passenger planes passes overhead. In its ads, the airline promises to get you there faster and with lower carbon emissions than with the older planes in its fleet. They can make this boast because of the way 3D printing has changed aerospace products. The strength and durability of airplane parts has increased. The jet engine block is made from a single piece of metal with an internal structure that removes weight with little loss of strength. To top it off, these 3D-printed parts are made using far fewer resources and with almost no waste.

You also think about your father, who needed a knee joint replacement last year. Amazingly, the doctors were able to scan his leg and 3D print a titanium replacement joint that fit perfectly. They even bioprinted replacement ligaments for the knee using a sample of his own cells, and after rehabilitation, he's back to playing basketball with his grandkids.

¹²² Objects printed using laminating object manufacturing and paper material have similar material characteristics to wood and can be worked in a similar way (e.g., by sanding, carving, and drilling).

POTENTIAL ECONOMIC IMPACT BY 2025

We estimate that 3D printing could generate economic impact of \$230 billion to \$550 billion per year across our sized applications by 2025 (Exhibit 11). The largest source of potential impact among the sized applications would come from consumer uses, followed by direct manufacturing (i.e., using 3D printing to produce finished goods) and using 3D printing to make molds.

Exhibit 11

Sized applications of 3D printing could have direct economic impact of \$230 billion to \$550 billion per year in 2025



Sized applications	Potential economic impact of sized applications in 2025 \$ billion, annually	Estimated scope in 2025	Estimated potential reach in 2025	Potential productivity or value gains in 2025
Consumer use of 3D printing	100–300	<ul style="list-style-type: none"> \$4 trillion in sales of consumer products that might be 3D printed 	<ul style="list-style-type: none"> 5–10% of relevant products (e.g., toys) could be 3D printable, assuming easy consumer access 	<ul style="list-style-type: none"> 60–80% value increase per 3D-printed product – 35–60% cost savings to consumers – 10% added value from customization
Direct product manufacturing ¹	100–200	<ul style="list-style-type: none"> \$300 billion spending on complex, low-volume items such as implants and tools \$470 billion spending on complex, low-volume parts in transportation 	<ul style="list-style-type: none"> 30–50% of products in relevant categories replaceable with 3D printing 	<ul style="list-style-type: none"> 40–55% cost savings to buyers of 3D-printed products
Tool and mold manufacturing	30–50	<ul style="list-style-type: none"> \$360 billion global market for injection-molded plastics 	<ul style="list-style-type: none"> 30–50% of injection-molded plastics produced with 3D-printed molds 	<ul style="list-style-type: none"> 30% production cost reduction using superior 3D-printed molds
Other potential applications (not sized)				
Sum of sized potential economic impacts	230–550			

¹ Focuses on use of 3D printing to directly manufacture low-volume, high-value parts in the medical and transport manufacturing industries. Other potentially impactful applications might include manufacturing of low-volume, high-value replacement parts for other industries.

NOTE: Estimates of potential economic impact are for some applications only and are not comprehensive estimates of total potential impact. Estimates include consumer surplus and cannot be related to potential company revenue, market size, or GDP impact. We do not size possible surplus shifts among companies and industries, or between companies and consumers. These estimates are not risk- or probability-adjusted. Numbers may not sum due to rounding.

SOURCE: McKinsey Global Institute analysis

Consumer uses

We estimate that consumer use of 3D printing could have potential economic impact of \$100 billion to \$300 billion per year by 2025, based on reduced cost (compared with buying items through retailers) and the value of customization. 3D printing could have meaningful impact on certain consumer product categories, including toys, accessories, jewelry, footwear, ceramics, and simple apparel. These products are relatively easy to make using 3D printing technology and could have high customization value for consumers.

Global sales of products in these categories could grow to \$4 trillion a year (at retail prices) by 2025. It is possible that most, if not all, consumers of these products could have access to 3D printing by 2025, whether by owning a 3D printer, using a 3D printer in a local store, or ordering 3D-printed products online. We estimate that consumers might 3D print 5 to 10 percent of these products by 2025, based on the products' material composition, complexity, cost, and the potential convenience and enjoyment of printing compared with buying for consumers. A potential 35 to 60 percent cost savings is possible for consumers self-printing these goods despite higher material costs (the materials required for the products we focus on here, primarily plastics, are relatively inexpensive and

getting cheaper). The savings over retail come not only from eliminating the costs of wholesale and retail distribution, but also from reducing the costs of design and advertising embedded in the price of products. It is possible that consumers will pay for 3D printing designs, but it is also possible that many free designs will be available online. Finally, customization might be worth 10 percent or even more of the value for some 3D-printed consumer products.¹²³

Direct manufacturing

Even in 2025, traditional manufacturing techniques will almost certainly have a large cost advantage over additive manufacturing for most high-volume products. However, 3D printing could become an increasingly common approach for highly complex, low-volume, highly customizable parts. If used in this way, we estimate that 3D printing could generate \$100 billion to \$200 billion in economic impact per year by 2025 from direct manufacturing of parts. The market for complex, low-volume, highly customizable parts, such as medical implants and engine components, could be \$770 billion annually by 2025, and it is possible that some 30 to 50 percent of these products could be 3D-printed. These products could cost 40 to 55 percent less due to the elimination of tooling costs, reduction in wasted material, and reduced handling costs.

Tool and mold manufacturing

Even by 2025, the large majority of parts and products will still be manufactured more efficiently with techniques such as injection molding. 3D printing, however, has the potential to create significant value by shortening setup times, eliminating tooling errors, and producing molds that can actually increase the productivity of the injection molding process. For example, 3D-printed molds can more easily include “conformal” cooling channels, which allow for more rapid cooling, significantly reducing cycle times and improving part quality.¹²⁴ We estimate that 3D printing of tools and molds could generate \$30 billion to \$50 billion in economic impact per year by 2025, based on an estimated \$360 billion cost base for production of injection molded plastics in 2025 and assuming that about 30 to 50 percent of these plastics could be produced with 3D-printed molds at around 30 percent less cost.

BARRIERS AND ENABLERS

Despite improvements in 3D printing technology, remaining limitations, particularly material costs and build speeds, could constrain wide-scale adoption. However, both materials costs and speed could improve dramatically by 2025 for many techniques based on the current evolution of the technology. If materials costs and build speeds fail to improve significantly, it could substantially lessen the economic impact of 3D printing.

Much of the potential value of 3D printing for consumers and entrepreneurs will depend on the emergence of an “ecosystem” to support users. Online 3D object exchanges like thingiverse point to a potential future in which object designs are widely exchanged and purchased like music files, greatly facilitating the spread of 3D printing adoption. The success of 3D printing also depends on improvements in products such as design software, 3D scanners, and supporting

¹²³ For example, Nike currently offers customizable NikeiD shoes at a surcharge of approximately 30 percent over the price of standard designs of similar quality.

¹²⁴ *Wohlers report 2012: Additive manufacturing and 3D printing state of the industry*, Wohlers Associates, 2012.

software applications and tools. Commercial 3D scanners are an important enabling technology. Hobbyists are currently using Microsoft's Xbox Kinect to create 3D scans, and smartphones can be converted into basic 3D scanners via the use of an app. Consumer-oriented, sub-\$1,000 3D scanners could soon be coming to market as well. The expiration of key patents for printing technologies could inspire waves of low-cost, highly capable 3D printers for businesses and consumers.

IMPLICATIONS

While the range of products that consumers and companies choose to 3D print could be limited at first, the ability to easily design and self-manufacture products could create significant consumer surplus and even influence consumer culture. Access to 3D printers is already inspiring a "maker" subculture in which enthusiasts share designs and ideas. For example, the 3D printing service Shapeways already has more than 10,000 crowd-sourced 3D models for jewelry and other items that have been uploaded by consumers. 3D printing could eventually spawn the same kind of dynamic, complex ecosystem that exists in software and Web development—in which developers can easily share and collaborate with one another—extending this kind of innovation ecosystem to the creation of physical objects.

Budding product designers and entrepreneurs can use 3D printing to quickly reach a mass, even global, audience. Makers of 3D printing devices and service providers should consider how best to stake out the most favorable positions within this ecosystem, whether by establishing a brand for consumer 3D printers, establishing a marketplace for 3D designs, or opening go-to 3D print shops (either online or in brick-and-mortar locations).

Ultimately, a gradually rising share of sales in categories such as toys and personal accessories could shift to either home production or 3D printing centers. Leaders in these categories should identify how to add value for consumers in ways that home-printed products cannot. Manufacturers of consumer products that could become 3D-printable should consider new ways to customize products to match some of the advantages of home printing. At the same time, they should follow closely the evolution of online exchanges for 3D printable designs and carefully manage their intellectual property rights while proactively leveraging these exchanges to distribute their products. Internally, these manufacturers should take advantage of 3D printing for rapid prototyping to speed designs to market and keep careful watch for the moment when improvements in technology might make 3D printing an economically viable production method for them.

Materials, manufacturing, and logistics value chains related to products that are candidates for 3D printing could also be affected by this technology. Direct production of goods by consumers could affect demand for some materials and global shipping volumes (although only in a small way initially). Leaders of businesses that could be affected by this new production ecosystem should think about what role they want to play and develop strategies to compete. For example, Staples' decision to experiment with 3D printing services suggests that there may be opportunities to offer other services and products to entrepreneurs and consumers who use 3D printing.

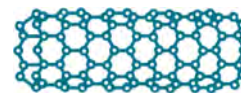
Access to 3D printing could actually make some manufacturing sectors more competitive. For industries with high-value goods, in which rapid innovation is more important than absolute cost, the combination of 3D printing of products and advanced robotics (see Chapter 5, “Advanced robotics”) could make proximity to end markets and access to highly skilled talent more important than hourly labor rates in determining where production is located. This could lead some advanced economy companies to produce more goods domestically, boosting local economies. However, this may not create many manufacturing jobs, as the 3D printing process is highly automated.

3D printing poses opportunities as well as challenges for policy makers in both advanced and developing economies. Societies can benefit from products that are made with less waste that do not require transport over great distances and, therefore, have less impact on the environment.¹²⁵ Policy makers should consider supporting the development of 3D printing, in particular by funding research in 3D printing technologies.

The challenges for policy makers include addressing regulatory issues—such as approving new materials for use—ensuring appropriate intellectual property protections, and assigning legal liability for problems and accidents caused by 3D-printed products. Governments will also be called upon to clarify how intellectual property rights will be protected. 3D printers have already been used to make handguns, raising another set of issues. Policy makers face the challenge of evaluating and addressing these risks without stifling innovation or limiting the value that this technology can provide.

125 According to the US Department of Energy, 3D printing can significantly reduce energy and materials use compared with traditional manufacturing methods. See www1.eere.energy.gov/manufacturing/pdfs/additive_manufacturing.pdf.

10. Advanced materials



History shows that breakthroughs in the quality or cost of basic materials can drive cycles of disruptive growth. For example, the so-called Second Industrial Revolution, a period of rapid innovation and expansion from about 1860 to 1920, was enabled in part by advances in steel manufacturing technologies that provided a lighter, stronger, and more versatile material that went into thousands of mass-produced products, as well as into bridges, skyscrapers, and ships.

A new revolution in materials has been taking shape in research laboratories around the world during the past few decades. Scientists are perfecting new ways to manipulate matter to produce advanced materials with unheard-of attributes that could enable innovations in fields ranging from infrastructure construction to medicine. These advances include so-called smart materials that are self-healing or self-cleaning, memory metals that can revert to their original shapes, piezoelectric ceramics and crystals that turn pressure into energy, and nanomaterials.

While many of these advanced materials may have interesting and potentially high-impact applications, it remains far from clear whether most will be capable of driving significant impact by 2025. We therefore focus here on advanced nanomaterials, which could be used to create many other smart materials (including those mentioned above) and for a host of other important applications (see Box 11, “Vision: A new dimension”).

Nanomaterials are made possible by manipulating matter at nanoscale (less than 100 nanometers, or approximately molecular scale). At nanoscale, ordinary substances like carbon and clay take on surprising properties—including greater reactivity, unusual electrical properties, and enormous strength per unit of weight—that can enable the creation of new types of medicine, super-slick coatings, and stronger composites. Invisible to the naked eye, nanomaterials have already found their way into products as varied as pharmaceuticals, sunscreens, bacteria-killing socks, and composite bicycle frames. And recent generations of semiconductors have features in the tens of nanometers, in effect making them nanotechnology.

Nanomaterials could have wide applications across health care, electronics, composites, solar cells, water desalination and filtration, chemicals, and catalysts. However, producing the nanomaterials required for many of these applications remains extremely expensive. The nanomaterials in use today are mostly particles (silver, clay, and metal oxides) that are relatively simple and easy to produce.¹²⁶

¹²⁶ Relatively simple nanoparticles are already being used in products such as car bumpers, scratch-resistant coatings, bacteria-killing socks, and sunscreen. This has led some to describe nanotechnology as a trillion-dollar industry, referring to the total revenue of products that incorporate some form of nanomaterials. See Mihail C. Roco and William Sims Bainbridge, *Societal implications of nanoscience and nanotechnology*, National Science Foundation, March 2001.

Box 11. Vision: A new dimension

Imagine a world in which advanced nanomaterials have revolutionized medical diagnostics and treatment. Using a simple blood test and inexpensive gene sequencing (see Chapter 7, “Next-generation genomics”), patients would be checked for illnesses, including various cancers. When cancer is detected, a customized dose of cancer-killing chemicals would be attached to nanoparticles that would deliver the treatment to the cancer cells without affecting healthy cells. Nano-based drug delivery could make chemotherapy more effective, helping to save lives while reducing the side effects.

Advanced nanomaterials could someday be used to manufacture all sorts of goods. Consumer electronic devices would have unprecedented levels of speed and power because their circuitry would be based on highly conductive graphene. With graphene-based supercapacitor batteries, it would take only a few minutes to give a mobile Internet device a charge that would last for a week. And thanks to nanocomposites, your self-driving electric car can go 300 miles without recharging and is still lighter and stronger than old-fashioned steel and plastic vehicles.

Your tablet computer would no longer be a stiff, clunky, book-shaped device, but rather a thin sheet that can be rolled up and put in a pocket. In homes and offices, walls are covered with ultra-thin nanomaterial-based displays that can be used to view information, enjoy entertainment, or simply to place a pretty picture on the wall. And there would be no need to worry about wasting electricity: these displays consume low levels of power and the highly efficient, graphene-based solar cells and energy storage systems in homes would supply most consumer power needs.

Nanomaterials may also hold the key to solving the world’s water shortage issues. Graphene-based filters could both turn salt water into freshwater and remove all impurities, making water shortages a thing of the past.

More advanced nanomaterials such as graphene (ultrathin sheets of graphite) and carbon nanotubes (tubular graphene) could eventually be used to create superefficient batteries; thin, flexible, energy efficient displays; ultralight, superstrong structural materials; and even the next generation of semiconductor chips. However, producing graphene and nanotubes in large quantities remains prohibitively expensive (as much as \$700 per gram for carbon nanotubes) and is expected to remain so for years. Over the coming decade, the most important application of advanced nanomaterials could be the use of nanoparticles to create new targeted treatments for cancer. We estimate that the use of advanced nanomaterials for targeted drug delivery for cancer alone could generate an economic impact of \$150 billion to \$500 billion annually by 2025.

After many years of delivering more promise than visible progress, nanotechnology is often viewed as overhyped. The truth is that nanotechnology, albeit in its more basic, invisible forms, is already a reality today and will have a growing role in industry, medicine, and the lives of consumers in years to come. Over the coming decade, the full potential of advanced nanomaterials may only begin to be felt, but these materials will likely continue to attract considerable interest and R&D investment. Nanomaterials could begin to open up major opportunities for health-care technology companies, pharmaceutical companies, and health-care providers. Business leaders, particularly in health care, manufacturing, and electronics, should consider now how these materials could be used to create new products or make existing products better, and invest accordingly. Meanwhile, policy makers will need to address unanswered questions regarding the safety of nanomaterials.

DEFINITION

Any use or manipulation of materials with features at a scale of less than 100 nanometers (roughly molecular scale) can qualify as nanotechnology. This is a very, very small scale indeed. Each nanometer is one-billionth of a meter; the width of a human hair is typically 20,000 to 80,000 nanometers. Nanoscale objects and machines can be created in a variety of ways, including direct manipulation of molecule-sized nanoparticles using tools such as atomic-force microscopes, or electron beam or laser lithography capable of printing two- or three-dimensional structures with nanoscale features.¹²⁷ Since complex nanoscale structures such as nanomachines (including nano electromechanical machines, or NEMS) are currently experimental and very difficult to construct, and methods for large-scale production may not be developed for another decade, we focus in this chapter on nearer-term applications of advanced nanomaterials.

Nanomaterials can have amazing properties. At nanoscale, science enters the strange realm of quantum mechanics. Nanoparticles, for example, generally have far greater surface area per unit of volume (up to 2,000 square meters per gram) than other materials and are thus highly reactive (and bio-reactive), making them useful in medicine. Nanoscale materials can also have unusual electromagnetic, thermal, and optical characteristics, which could enable advances across many of the technologies described in other chapters of this report, including the next-generation sensors and actuators use in advanced robotics and in Internet of Things applications (see Chapters 5 and 3). The properties of nanomaterials could make them useful in creating a variety of other advanced materials (see Box 12, “Living in a materials world”).

¹²⁷ “3D-printer with nano-precision,” Phys, <http://phys.org/news/2012-03-3d-printer-nano-precision.html>.

Box 12. Living in a materials world

While nanomaterials offer considerable promise, particularly long term, they are by no means the only type of advanced materials that could drive economic impact over the coming decades. Below are some other types of materials that could help build a better, cleaner world, though each has its own engineering, production, and performance challenges to overcome.

- **“Green” materials** attempt to solve environmental issues. Low-CO₂ concrete, for example, could reduce emissions from concrete production, which are estimated to account for 5 percent of total CO₂ emissions.¹ Adding advanced materials reduces the amount of fuel required to burn and grind the ingredients of concrete and reduce the need to de-carbonate limestone within the kiln.
- **Self-healing materials** take their inspiration from biological systems that can self-organize and self-repair. Self-healing materials would reduce the need for costly maintenance by healing themselves when damage occurs. One example is self-healing concrete, which would include ingredients that are automatically released or that expand to fill cracks when they appear.
- **Piezoelectric materials** that turn pressure into electricity are not new, but researchers continue to find new potential applications, such as generating electrical energy from movement. Eventually, it could be possible to capture electricity from the movement of pedestrians to generate electricity or to incorporate piezoelectric materials into clothing to power mobile Internet devices.
- **Memory metals** revert to a prior shape when heated to a specific temperature. These materials are being considered as a way of producing movement in light, inexpensive robots—using a charge to expand or contract the material, imitating muscle movement. Some versions of memory metals can even be “programmed” to take on multiple shapes at different temperatures.
- **Advanced composites** could help build strong, lighter components for vehicles, including aircraft. In addition to next-generation nanocomposites, ongoing advances in composites made from carbon fiber and other materials could make it possible to substitute composites for materials such as aluminum in more applications. These advances include new ways of producing and binding carbon fiber, allowing for less expensive fabrication.

1 David Bradley, “10 Technology Breakthroughs,” *MIT Technology Review*, 2010.

Today, simple nanoparticles are the most widely used nanomaterials. They are used in coatings, paints, sensors, chemical catalysts, and food packaging. Silver nanoparticles, which have antimicrobial properties, have been added to laundry detergents and even woven into socks. Zinc oxide nanoparticles have interesting optical properties (allowing some wavelengths through while blocking others), making them useful ingredients in some sunscreens. Clay nanoparticles can make lighter, stronger, and more elastic composites, in part by reducing the amount of filler material required and increasing binding, and are used in some car bumpers. Clay nanoparticles also improve barrier properties and are therefore used in some plastic food packaging to increase shelf life.

In the near term, medicine could be the most promising area for adoption of advanced nanomaterials. The large surface area and high reactivity of many nanomaterials could make them powerful diagnostic tools for many diseases, including cancer. Nanoparticles can also be used to create potentially lifesaving medicines that can target specific tissues or cells. This can create therapies that are more effective and reduce harmful side effects. For example, researchers are working on ways to use gold and silver nanoparticles, as well as liposomes (nano-sized bubbles made from the material of cell membranes) for targeted drug delivery. Nanomaterials can be combined with cancer-killing substances and then delivered to a tumor in a more precise way than current options, reducing the damage to healthy cells and other side effects of conventional chemotherapy.

In late 2012, AstraZeneca announced that it is developing a treatment that uses gold nanoparticles to convey the cancer-killing drug TNF (tumor necrosis factor) to specific cancer sites. TNF is normally highly toxic but might be safely delivered using nanoparticles because it would be targeted directly to tumors.¹²⁸ Nanoparticles can be used to target cancer cells passively (by taking advantage of these cells' increased tendency to absorb such particles relative to normal cells) or actively (by attaching molecules designed to specifically seek out or bind to cancer cells, such as peptides).¹²⁹

Graphene, which is composed of one-atom-thick sheets of carbon hexagons, is being produced today, but only in limited quantities and at high cost. When this material can be mass-produced cost-effectively, its impact could be quite disruptive. Graphene is one-sixth the weight of steel per unit of volume but more than 100 times as strong. Graphene can be compressed without fracturing, recovering its original shape after being pressurized to more than 3,000 atmospheres. Graphene also has 35 percent less electrical resistance than copper and ten times the conductivity of copper and aluminum, making it an excellent material for building electrical circuits; it has been estimated that graphene could yield terahertz processor speeds (about 1,000 times faster than today's fastest microchips) and could one day replace silicon entirely. In 2011 IBM created the first integrated circuit based on a graphene transistor.¹³⁰ However, integrating graphene into chips at scale has so far proven challenging.

128 Karen Weintraub, "Gold particles could deliver cancer drugs," *Boston Globe*, December 24, 2012.

129 Peptides are biological molecules made of amino acids that can perform many functions, including killing cells or selectively delivering drugs to specific types of cells or tissues.

130 Yu-Ming Lin et al., "Wafer-scale graphene integrated circuit," June 2011.

Graphene and carbon nanotubes have a host of potential applications. Because of their unique chemical and electrical properties, including large surface area and high reactivity, carbon nanotubes could act as extremely powerful sensors, allowing the detection of trace molecules of dangerous substances or biomarkers for diseases such as cancer. Graphene-based supercapacitors are being developed with the goal of producing ultra-efficient batteries that could charge in seconds yet power a smartphone or other device for days.¹³¹ Graphene could also potentially be used to create highly efficient solar cells (see Chapter 12, “Renewable energy”), or as a coating in lithium-ion battery electrodes, enabling faster charging and greater storage capacity, a potential boost to the adoption of electric vehicles (see Chapter 8, “Energy storage”). And both graphene and carbon nanotubes can be used as electron emitters to build anodes for highly efficient, super thin, and (with graphene) possibly flexible and transparent displays. Finally, because of its unique absorptive qualities, graphene may help improve access to potable water, a growing issue in many parts of the world. Lockheed Martin recently announced progress in creating graphene-based filters that could produce drinking water from sea water at a small fraction of the cost of current methods, such as reverse osmosis.¹³²

However, even as potential applications multiply, it remains unclear whether graphene and carbon nanotube production and handling processes can be scaled up cost-effectively. Perfecting scalable, cost-effective production techniques could well take more than a decade. Graphene and carbon nanotube prices vary widely based on purity, size, form, and (for graphene) substrate material. Today, the selling price for 50 millimeter x 5 millimeter monolayer graphene thin films manufactured by the company Graphene Square ranges from \$264 to \$819. Graphene nanoplatelets (five to eight nanometers thick) manufactured by XG Sciences are sold for about \$220 to \$230 per kilogram. Prices for carbon nanotubes range from \$50 per gram to more than \$700.

Another promising nanomaterial is quantum dots—nanoparticle semiconductors with unique optical properties. Quantum dots can efficiently produce colored light, potentially making them useful in electronic displays. They could also be used as medical diagnostic tools in place of traditional organic dyes, targeting tumors and lighting up under imaging (if toxicity risks can be addressed). Quantum dots are also a possible candidate for creating qubits (quantum bits), the informational unit for quantum computers.¹³³ Quantum computers could, in effect, perform many operations simultaneously by exploiting quantum mechanics.

POTENTIAL FOR ACCELERATION

In the coming decade, it is possible that nano-based materials and processes could help meet needs in medicine and perhaps see adoption in electronic products, such as displays. Medical diagnostics and treatments enabled by graphene, carbon nanotubes, quantum dots, gold nanoparticles, or biological nanomaterials such as liposomes and peptides could save and extend many lives. There is ever-growing demand for better portable electronic devices and displays (see Chapter 1, “Mobile Internet”). Nanotubes, graphene, and quantum dots could

131 Maher El-Kady and Richard Kaner, “Scalable fabrication of high-power graphene micro-supercapacitors for flexible and on-chip energy storage,” *Nature Communications*, volume 4, February 2013.

132 Company press release, March 18, 2013.

133 T. D. Ladd et al., “Quantum computers,” *Nature*, volume 464, number 7285, March 2010.

help make these displays brighter, thinner, and more energy efficient, possibly even allowing these displays to be made transparent and flexible—capable of being “papered” onto walls, windows, or curved surfaces. However, it is far from clear whether the use of nanomaterials for such displays will be economical by 2025, given their high cost and the availability of substitute technologies, such as LCD and OLED.

Research is bringing the technology for large-scale manufacturing of graphene and nanotubes nearer. In 2012, researchers at Universiti Sains Malaysia announced advances in creating carbon nanotubes that they claim could reduce the price of this material to \$15 to \$35 per gram.¹³⁴ In 2011 Lockheed Martin announced that its F-35 fighter jet will use carbon nanotube composite plastics in some structural parts thanks to an improved manufacturing process, which the company says reduces the cost of producing nanotube-based parts by 90 percent.¹³⁵ Samsung and IBM are funding R&D in commercial applications of graphene and nanotubes, and several major research institutions are also investigating graphene.

Some of the biggest challenges this research addresses include manufacturing large sheets of graphene and long strands of nanotubes. Another concern is the possible health effects of loose nanomaterials. There is evidence that nanotubes, when inhaled, can have damaging health effects similar to asbestos, though the risk of inhalation could be low for many applications.¹³⁶

Despite the difficulties of large-scale production, it is expected that the global market for graphene will grow rapidly in the coming decade, though estimates range widely. According to BCC Research, the global market for commercial products made using graphene is negligible today, but the company predicts that it will grow to \$123 million by 2017 and to \$987 million by 2022, with the largest markets being for capacitors, structural materials, and computing.¹³⁷ BCC also estimates that the global market for carbon nanotubes could reach \$527 million by 2016.¹³⁸ By comparison, world aluminum production in 2012 was 45 million tons, for a total market value of \$112 billion.¹³⁹

POTENTIAL ECONOMIC IMPACT BY 2025

For the purposes of estimating the potential economic impact of advanced nanomaterials, we focus on applications in medicine, specifically drug delivery for cancer patients. The application of advanced nanomaterials for medical purposes has relatively high potential by 2025 given the types of advanced nanomaterials likely to be used, the limited quantities needed, the maturity of the production processes for these materials, and the high willingness of consumers

134 Jasmine Leong, “New method for continuous production of carbon nanotubes by USM researchers,” *Scientific Malaysian*, April 23, 2012.

135 Stephen Trimble, “Lockheed Martin reveals F-35 to feature nanocomposite structures,” *Flight International*, May 26, 2011.

136 Paul Borm and Wolfgang Kreyling, “Toxicological hazards of inhaled nanoparticles—Potential implications for drug delivery,” *Journal of Nanoscience and Nanotechnology*, volume 4, number 5, October 2004.

137 Andrew McWilliams, *Graphene: Technologies, applications, and markets*, BCC Research, July 2012.

138 John Oliver, *Global markets and technologies for carbon nanotubes*, BCC Research, July 2012.

139 *The aluminium market analysis, financials and forecasting 2012–2017*, ASDReports, May 2012.

to pay for potentially life-saving treatments. For this application, we estimate that advanced nanomaterials could have a potential economic impact of \$150 billion to \$500 billion annually by 2025 (Exhibit 12).

Exhibit 12

Sized applications of advanced materials could have direct economic impact of \$150 billion to \$500 billion per year in 2025



Sized applications	Potential economic impact of sized applications in 2025 \$ billion, annually	Estimated scope in 2025	Estimated potential reach in 2025	Potential productivity or value gains in 2025
Drug delivery	150–500	20 million new cancer cases worldwide in 2025	5–10% of cancer patients could benefit from nano-based drug delivery treatments	\$130,000–230,000 QALY value created per patient ¹ <ul style="list-style-type: none"> \$100,000–200,000 for 1–2 years increased life expectancy \$30,000 from reduced chemotherapy side effects
Other potential applications (not sized)		Example applications not sized include nanomaterials for electronics and composites and applications of other advanced and smart materials, such as self-healing concrete or memory metals		
Sum of sized potential economic impacts	150–500			

1 QALY is quality-adjusted life year.

NOTE: Estimates of potential economic impact are for some applications only and are not comprehensive estimates of total potential impact. Estimates include consumer surplus and cannot be related to potential company revenue, market size, or GDP impact. We do not size possible surplus shifts among companies and industries, or between companies and consumers. These estimates are not risk- or probability-adjusted.

SOURCE: McKinsey Global Institute analysis

Other uses may be developed for nanomaterials in electronics, solar cells, composites, and water systems during this decade; however, their potential economic impact could be limited through 2025 due to the engineering and production challenges involved, the cost of the nanomaterials required, and the cost and effectiveness of existing or expected substitutes. We also do not size the potential impact from nano-based therapies that seem to be farther from potential use than cancer treatments (for example, HIV treatment).

Drug delivery for cancer patients

Our estimate of potential impact of \$150 billion to \$500 billion annually by 2025 is based on the assumption that 5 to 10 percent of the 20 million new cancer cases that could be expected in 2025 could be treated with nano-based therapies. Conclusive data on the relative efficacy of such treatments remains limited given the newness of this technology. However, based on current research, it seems possible that future nano-based drug delivery treatments could significantly improve outcomes and reduce side effects for many cancer patients. Here we assume that nano-based treatments could add one to two years of life expectancy and significantly improve quality of life during one year of treatment. We estimate the value of these impacts to be \$130,000 to \$230,000 per patient.¹⁴⁰

140 We use a quality-adjusted life year (QALY) value of \$100,000 and assume one to two years of extended life; we value the improved quality of life for patients undergoing treatment at \$30,000 per patient, assuming an average 30 percent quality of life improvement during one year of treatment.

Significant R&D spending is already going into the development of nanomaterials for drug delivery, particularly liposomes and gold nanoparticles. Celgene, a pharmaceuticals company, is seeking approval for a pancreatic cancer therapy that would use nanoparticles to deliver the chemotherapy drug paclitaxel to targeted cells. Celgene has said that it expects sales of \$2 billion a year by 2017 for this treatment, which would make it the first nano-blockbuster.¹⁴¹ According to data from PharmaProjects, as of March 2013 there were 80 nano-based drugs in the development pipeline, with seven in phase 3 clinical trials. Of the 80 drugs in the pipeline, 43 were for cancer treatments. The nanotechnology-enabled drug delivery market is expected to grow to \$136 billion by 2021, with liposomes and gold nanoparticles accounting for 45 percent of this market, according to market researcher Cientifica.¹⁴²

BARRIERS AND ENABLERS

The use of advanced nanomaterials in medicine could drive significant economic impact by 2025, but realizing this potential depends on whether specific nano-based drugs can be successfully developed and approved at reasonable cost. Drug development of any kind is generally very costly, and the vast majority of new drug candidates are never approved. However, given the number of nano-based drugs in various stages of development, it is possible that a number of them will come to market within several years. Unfortunately, many of these drugs may be very expensive. Abraxane, Celgene's nano-based drug, will reportedly cost pancreatic cancer patients \$6,000 to \$8,000 per month. Given growing concerns about rising health-care costs, prices like these could limit adoption. At the same time, many patients may be willing to pay a high price for such potentially life-saving drugs.

For advanced nanomaterials to deliver their full potential through 2025 and beyond, reliable and far less expensive methods will have to be developed for producing substances such as graphene, carbon nanotubes, and quantum dots in high volumes. Major challenges persist in producing high-quality forms (long strands of nanotubes or large sheets of grapheme, for example) and effectively handling small, delicate, chemically reactive, and potentially toxic nanomaterials. Until these production challenges can be overcome, the potential economic impact of advanced nanomaterials will remain limited.

Nanomaterials also raise a range of regulatory issues that will need to be resolved before widespread adoption is possible. Some nanomaterials can have high toxicity and could cause environmental damage, and many remain untested. Regulations will be needed to guide nanomaterial use not only in medicine, but also in other applications in which the material is not encapsulated. Products containing nanomaterials may require special end-of-life recycling procedures.

141 Matthew Herper, "Celgene's Abraxane extends life by 1.8 months in advanced pancreatic cancer," *Forbes*, January 22, 2013.

142 *Nanotechnology for drug delivery: Global market for nanocarriers*, Cientifica, February 7, 2012.

IMPLICATIONS

Over the coming decade, advanced nanomaterials will continue to attract considerable interest and R&D investment. These materials could also create major opportunities for health-care technology companies, pharmaceutical companies, and health-care providers. As the use of advanced nanomaterials becomes increasingly widespread, they have the potential to deliver enormous value to consumers, both in health care and eventually across a wide array of products. However, policy makers will need to address unanswered questions regarding the safety of nanomaterials.

In industries such as semiconductors, consumer electronics, and chemicals, nanomaterials are already being explored, developed, and even used to produce some products. Nanomaterials are enabling these industries to move past the limitations that traditional materials impose on how fast a circuit can be or how efficient a chemical process can become. Across all of manufacturing, the cost/benefit trade-offs of using nanomaterials for applications such as composites, paints, and coatings will continue to shift as the technology evolves. For example, in the automotive industry, advanced nanocomposites and graphene-enhanced batteries could play a large role in enabling more cost-competitive electric vehicles. Business leaders should consider how these materials could ultimately be used to create revolutionary new products or make existing products better, and invest accordingly.

As industries develop more products that use advanced nanomaterials—whether for electronic parts, composite materials, medicines, or other applications—companies that develop techniques for producing large quantities of high-quality nanomaterials like graphene and nanotubes could benefit greatly. Companies in many industries, particularly electronics and aerospace, should look for opportunities to invest in nanomaterials R&D, including through partnerships and sponsorships. Today, pure graphene producers are typically smaller startup companies, such as Angstrom Materials, Graphenea, Graphene Square, Graphene Supermarket, Graphene Technologies, and XG Sciences. Carbon nanotubes also are produced by several major chemical companies, including Showa Denko and Arkema.

Consumers stand to benefit greatly from advanced nanomaterials. Besides offering potential breakthroughs in disease diagnosis and treatment over the coming decade, over the long term nanomaterials could also lead to new electronics products that are more powerful, more energy efficient, and more useful. Advanced nanocomposites using materials such as graphene and carbon nanotubes could eventually be used to make many objects, including cars and airplanes, lighter and stronger.

Nanomaterials might also help build a more sustainable future if they live up to their potential to create highly efficient batteries, solar cells, and water purification systems. Policy makers will need to consider both the costs and benefits of nanotechnology to their citizens, as well as the economic implications of advanced nanomaterials. Large advanced economies have been funding nanotechnology research for two decades; in fact, in 2011 accumulated government investment over the previous decade totaled more than \$67.5 billion. Including private investment, the total investment is estimated to be close to a

quarter of a trillion dollars.¹⁴³ In 2011 China surpassed the United States as the largest funder of nanotechnology research. The objective of this research is to establish leadership and enable early adoption of nano-based products and processes by Chinese industry. Realizing the full, long-term potential of advanced nanomaterials will require sustained funding and support. The US National Nanotechnology Initiative tracks and supports progress in key areas, but funding is vulnerable to congressional action and department budgets.

Finally, serious studies need to be conducted to identify any environmental and health risks posed by nanomaterials. So far, research suggests that nanomaterials exhibit widely varying levels of toxicity depending on the type of materials and their configuration, with some materials appearing benign and others potentially highly toxic. As science and industry continue to pursue the economic and societal benefits of nanomaterials, policy makers and citizens should be informed about the potential environmental and health risks.

143 2011 report on global nanotechnology funding and impact, Cientifica, July 13, 2011.

11. Advanced oil and gas exploration and recovery



After the first global oil shock during the 1970s, nations and energy companies around the world were forced to consider what a future with dwindling fossil fuel supplies might look like. One response was to look for new types of fossil fuel reserves and develop ways to reach them. Forty years later, these efforts are finally beginning to pay off. Horizontal drilling and hydraulic fracturing, the technologies for reaching “unconventional” reserves such as the natural gas and “light tight” (LTO) oil trapped in rock formations (often shale) are now at the point of widespread adoption.¹⁴⁴ These extraction techniques have the ability to unlock both newly discovered reserves and previously known deposits that could not be economically extracted using conventional methods.

North American energy companies, particularly those in the United States, are furthest along in exploration and development of unconventional reserves, and could maintain a sizable lead through 2025. Other countries are also believed to possess sizable reserves, but it could take many years to develop them.¹⁴⁵ Globally, accessing these unconventional oil and gas resources could deliver significant economic impact by 2025. Shale gas production is already well under way, and LTO is becoming part of the North American oil supply. These developments will clearly have an impact in the coming decade, which is why they are the focus of this analysis. However, they are not the only unconventional reserves; in fact, improved technologies could eventually unleash yet another fossil fuel revolution.

In this chapter, we examine the economic impact of advanced oil and gas exploration and recovery in five major regions with the potential to produce unconventional oil and gas in large quantities by 2025: North America, China, Argentina, Australia, and Europe. In these regions, we estimate that unconventional oil and gas could have a direct economic impact of \$95 billion to \$460 billion annually by 2025.¹⁴⁶ We estimate the bulk of this impact could come from North America due to the relative maturity of its industry. Moreover, most of that value could come from recovery of unconventional oil reserves due to greater incremental production over the coming decade (that is to say, oil reserves are starting from a smaller base than unconventional gas) and could have higher margins than shale gas.

144 Light tight oil is called “light” because it is a variety of crude oil that is relatively lower in specific gravity; it is termed “tight” because it is found in deposits with low permeability.

145 *World shale gas resources: An initial assessment of 14 regions outside the United States*, US Energy Information Administration, April 2011.

146 Direct economic impact for this technology refers to the value added (GDP) to the economy by the oil and gas sector due to increased output from shale gas and LTO. Indirect impact refers to the value added to sectors of the economy that benefit from increased output in oil and gas, both upstream (oil-field equipment providers) and downstream (chemicals manufacturers). Induced impact refers to the value added to the economy due to increases in household incomes of people connected with the sector, such as employees of oil and gas companies and suppliers, as well as their dependents and employees.

In addition to providing direct economic impact, increased access to unconventional deposits could also create significant indirect and induced impact. Additional benefits could include lower input costs for downstream industries such as chemicals, which could raise output. However, recovering unconventional oil and gas could be constrained by political and regulatory actions spurred by environmental risks. As a result, realization of the full potential economic impact may depend on choices made by societies and policy makers in the coming years.

The implications of advanced oil and gas exploration and recovery are important and complex. Not only are there opportunities for energy players and suppliers, but there could also be substantial impact on downstream manufacturing industries and consumers. For some countries, these newly available resources promise greater self-reliance, which could alter their geopolitical postures. However, many citizens and leaders are concerned about the potential damage that hydraulic fracturing can have on local environments and ecosystems, leading some countries to ban the process entirely. There are also concerns that unconventional oil and gas could affect the development of renewable energy sources such as solar and wind by making fossil fuels once again cheaper by comparison. Over the coming decade, businesses, societies, and policy makers will have to decide how best to benefit from new sources of fossil fuels while managing risks and concerns. If unconventional reserves can be safely and cost-effectively exploited, the pattern of growing energy scarcity may be reversed for many decades.

DEFINITION

Unconventional oil and gas reserves are defined as reserves that cannot be extracted by conventional drilling methods. In these reserves, oil or gas is trapped in natural fractures in rock (often shale) or adsorbed by nearby organic material. Besides shale gas and LTO, unconventional fossil fuel deposits include coalbed methane, tight sandstone, and methane clathrates (also known as methane hydrates). Proven reserves of coalbed methane in Canada's Alberta Province have been estimated to be equivalent to nearly 13 percent of the world's shale gas reserves, and methane clathrate deposits are estimated to be many times larger than shale gas reserves.¹⁴⁷ However, extraction of these reserves has thus far been difficult. The enormous methane clathrate deposits are located on the ocean floor, making them too expensive to recover in most cases.¹⁴⁸ Development of coalbed methane has been set back by falling natural gas prices due to shale gas availability in North America. Therefore, this report focuses on only shale gas and LTO, which have the greatest potential for successful development through 2025, to estimate the economic impact of unconventional reserves. However, new technologies may lead to more rapid advances in the development of methane clathrates or coalbed methane, possibly ushering in the next energy "revolution."

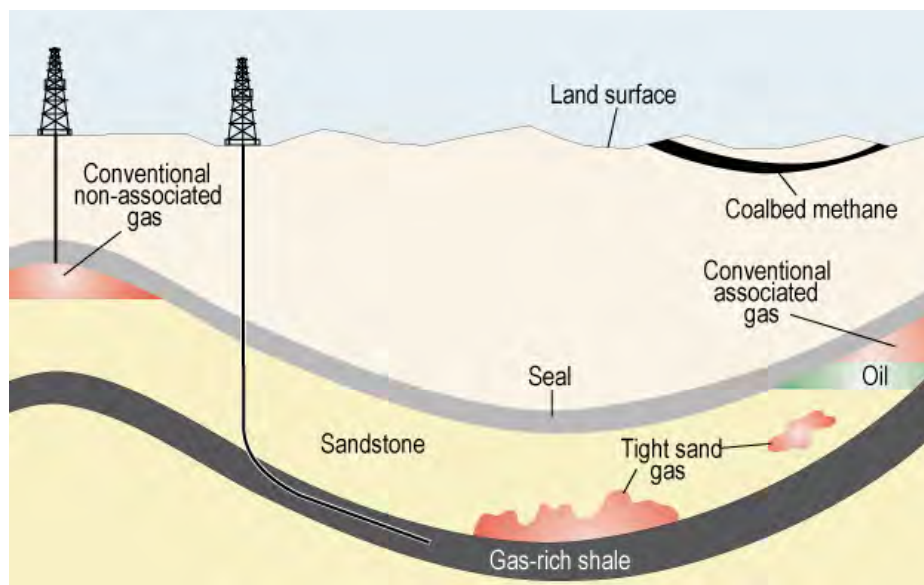
¹⁴⁷ *Potential of gas hydrates is great, but practical development is far off*, US Energy Information Administration, November 2012; *World shale gas resources*, USEIA, April 2011; *Alberta's energy reserves 2007 and supply/demand outlook 2008–2017*, Energy Resources Conservation Board, June 2008.

¹⁴⁸ A notable promising development is the extraction of natural gas from methane clathrate deposits off the coast of Japan: "Japan extracts gas from methane hydrate in world first," BBC News Business, March 12, 2013.

Today, the core technologies used to access unconventional oil and gas reserves are hydraulic fracturing and horizontal drilling. When used together, these technologies are able to overcome many of the challenges of extracting shale gas and LTO. Gas- and petroleum-rich shale rock is typically located much deeper below the surface than conventional reserves (two to three miles). Because of shale's low permeability, which prevents oil and gas from flowing from the rock, fracturing is required to release the pressure of overlying and surrounding rock. Fracturing involves pumping up to five millions of gallons of fluid (usually water-based with some additives) at high pressure into rock fractures to release gas or oil held in pores.¹⁴⁹ Horizontal drilling is the method by which the well bore—the tube that carries the oil or gas up from the earth—is drilled to the appropriate depth and then extended parallel to the surface up to a few kilometers. Horizontal drilling allows recovery of fuel in multiple stages along the length of the well bore, making it much more economical than drilling repeatedly to a great depth (Exhibit 13).

Exhibit 13

Shale gas is located in pores and fractures 2 to 3 miles below the surface, requiring horizontal drilling and fracturing for extraction



SOURCE: US Energy Information Administration; US Geological Survey

In order to reach high levels of output from each shale basin and well, large amounts of investment, experimentation, and data are required, often through a trial-and-error process of drilling hundreds of trial wells. Due to the varied characteristics of each basin, 500 to 1,500 wells are typically needed to fully understand basin behavior. It can take up to \$10 billion in capital investment and many years to scale up production of a basin, including building the infrastructure to transport the extracted oil or gas.

149 For more on the composition of fracturing fluids and additives, see *Modern shale gas development in the United States*, US Department of Energy, April 2009.

POTENTIAL FOR ACCELERATION

The potential for rapid development of shale gas and LTO is great given the world's nearly insatiable appetite for fossil fuels to enable economic activity as populations grow and economies develop. As the massive populations of China and India grow richer, they can be expected to follow the rising pattern in per capita energy consumption that has been seen in other nations (Exhibit 14). Other drivers of demand for unconventional oil and gas are declining yields in some major fields and the desire by some nations to be more self-reliant for economic and political reasons.

Exhibit 14

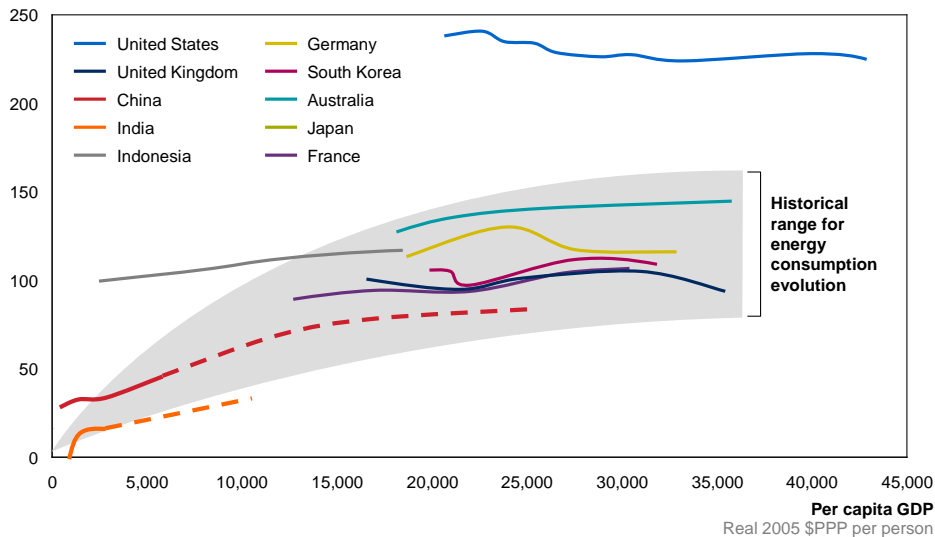
As incomes rise, demand for resources increases; China and India may follow the same pattern

ENERGY EXAMPLE

— Historic (1970–2008)
- - 2030 projected

Per capita energy consumption, 1970–2008, projected to 2030 for India and China

Million British thermal units per person



SOURCE: International Energy Agency; IHS Global Insight; McKinsey Global Institute analysis

The technology for extracting unconventional oil and gas is advancing rapidly, pointing to the potential to significantly reduce costs and increase production. For example, it may be possible to double the productivity of fracturing by using microseismic data and well log data in predictive fracture modeling. Such modeling techniques could cut the time it takes to understand basin behavior by half, enabling companies to scale up production faster. Replacing the diesel generators that power fracturing pumps with natural gas generators could reduce fuel costs for operating wells and decrease nitric oxide and carbon dioxide emissions by up to 80 percent. Water reuse and treatment technologies could reduce freshwater needs by as much as 50 percent, saving up to \$1 million over the life of a well. Fracturing with previously used and untreated water has helped reduce water treatment requirements and costs by more than 70 percent in the past few years. Longer term, use of non-water fluids such as vapor, refrigerated gas, or petroleum could increase productivity by as much as 20 percent per well and make production easier in water-constrained areas (although the environmental effects of using alternative fracturing fluids are yet to be fully studied).

Development of unconventional oil and gas fields is most advanced in the United States and Canada, but other nations are also beginning to develop their reserves. To get at China's huge shale gas reserves, the Chinese government awarded exploration rights in January 2013 in 19 areas and has entered into an agreement with the US government to share technological know-how.¹⁵⁰ To spur development in Argentina, the government has doubled the price of natural gas by raising its price cap and has invited foreign players to help explore unconventional reserves in Vaca Muerta, where conventional extraction has already spurred the creation of infrastructure. In Russia, which is believed to be one of the largest potential sources of unconventional oil and gas in the world, the energy industry has launched major exploration projects.¹⁵¹ The British government has allowed fracturing to resume in Lancashire (after it was stopped in 2012 following tremors in nearby Blackpool), while South Africa and Romania have lifted their moratoria on exploration of shale fields.¹⁵² If these countries push aggressively to develop these resources, it is possible that the potential economic impact could be even greater than we are estimating here.

POTENTIAL ECONOMIC IMPACT BY 2025

Over the long term, unconventional oil and gas could have significant economic impact on the global energy market. Based on current estimates of production for the five regions we studied—North America (the United States and Canada), China, Argentina, Australia, and Europe—we estimate potential direct economic impact of \$95 billion to \$460 billion a year by 2025 (Exhibit 15). The bulk of this potential direct economic impact could be in North America, where much of the incremental value would come from LTO production. Annual output of LTO could grow to five to seven times the current rate of production by 2025. Shale gas, by contrast, is already produced in large volumes in North America and therefore will likely grow more moderately. Moreover, since oil prices are determined by international markets, increased local production has a smaller impact on prices and therefore on margins. Natural gas, meanwhile, is priced locally; in fact, the addition of shale gas to the supply has depressed prices in North America.

Technically recoverable reserves (known reserves) of shale gas are estimated to be 220 trillion cubic meters (Tcm), equivalent to 1,350 billion barrels of oil, and unconventional oil reserves are estimated at 195 billion barrels.¹⁵³ It should be noted that estimates of what is technically recoverable have changed frequently as countries have explored their potential deposits. In North America, oil and gas deposits are well documented and production in unconventional fields is under way; in the rest of the world, however, estimates of potential output are harder to predict and could change based on evolving national policies and changing understanding of the commercial viability of the basins being explored. It is very possible that estimates of reserves will change significantly for many countries in coming years.

150 "Dozens line up for Chinese shale," *UP.com*, January 22, 2013.

151 Anna Shiryaevskaya and Jake Rudnitsky, "Russia may hold 680 trillion cubic meters of unconventional gas," *Bloomberg.com*, December 24, 2012.

152 "UK gives backing for fracking—shale gas go ahead," *Materials World Magazine*, February 2013.

153 One Tcm is equal to 35.31 Tcf (trillion cubic feet) and 6.09 billion barrels of oil equivalent; for global reserves, see *World shale gas resources*, USEIA, April 2011.

Exhibit 15**Sized applications of advanced oil and gas exploration and recovery could have direct economic impact of \$95 billion to \$460 billion per year in 2025**

Sized regions and applications	Potential economic impact of sized applications in 2025 \$ billion, annually	Currently estimated reserves	Estimated potential incremental annual production in 2025	Assumed price in 2025
North America – shale gas ¹	10–35	<ul style="list-style-type: none"> 71 trillion cubic meters (Tcm) of reserves <ul style="list-style-type: none"> – 60 Tcm in United States – 11 Tcm in Canada 	145 billion cubic meters (Bcm)	\$2–8 per million British thermal unit (MMBtu); nearly \$70–280 million per Bcm
North America – light tight oil	60–300	<ul style="list-style-type: none"> 64 billion barrels of reserves <ul style="list-style-type: none"> – 57 billion barrels in United States – 7 billion barrels in Canada 	5.4–9.0 million barrels per day	\$50–150 per barrel
Rest of the world – shale gas	15–65	<ul style="list-style-type: none"> More than 150 Tcm of reserves <ul style="list-style-type: none"> – 36 Tcm in China – 22 Tcm in Argentina 	70–220 Bcm	Regional pricing (per MMBtu) <ul style="list-style-type: none"> – China, Australia: \$8–10 – Argentina: \$7–8 – Europe: \$6–11
Rest of the world – light tight oil	10–60	<ul style="list-style-type: none"> More than 130 billion barrels of reserves <ul style="list-style-type: none"> – 24 billion barrels in Russia – 13 billion barrels in Argentina 	0.5–1.7 million barrels per day	\$50–150 per barrel
Other potential applications (not sized)		<ul style="list-style-type: none"> Potential unsized applications include coalbed methane and methane clathrate 		
Sum of sized potential economic impacts²	95–460			

1 Potential economic impact estimated by calculating incremental gross output from 2025 production and prices, and converting into value added through GDP multiplier tables; currently estimated reserves are for information only.

2 Only direct value added—indirect and induced impact, as well as downstream benefits, could nearly double the impact. NOTE: Potential economic impact not comprehensive; includes potential impact of sized applications only. Numbers may not sum due to rounding.

SOURCE: McKinsey Energy Insights; US Energy Information Administration; McKinsey Global Institute analysis

Some of these estimates are highly sensitive to assumptions about the speed of development and future market prices. Our production estimates for how quickly nations will gear up production could prove to be too conservative if these countries overcome regulatory, environmental, technological, and infrastructural (e.g., pipeline building) challenges that typically delay production. In addition, the price of oil in 2025 is dependent on many factors besides supply and demand, such as possible actions by current oil exporters to maintain price or the use of increased oil supply by new producers for geopolitical leverage. We have assumed a range of oil prices of \$50 to \$150 per barrel in 2025 for all countries (since it is a globally traded commodity) to show the sensitivity of the range of economic impact to this crucial assumption.

In addition to the direct economic impact created in the energy industry, advanced oil and gas exploration and recovery could yield indirect and induced economic impact that we estimate at between \$85 billion and \$420 billion annually in 2025.¹⁵⁴ For purposes of consistency with the other technologies in this report, we have focused on estimating the direct economic impact of extracting these reserves. In general, we have not estimated the impact on increasing output of other industries, though in the case of the United States, we have referenced a forthcoming McKinsey Global Institute report in laying out what it might be.

North America (United States and Canada)

Declining natural gas reserves during the 1970s prompted the United States government to fund research into extracting shale gas, leading to many advances in technology, including microseismic imaging. The government encouraged drilling for shale gas through tax credits, research dissemination, and industry support. In 1991, it supported the first horizontal drilling project, and in 1998, the first commercial shale fracture in the Barnett Shale basin in the US state of Texas. The first combination of hydraulic fracturing and horizontal drilling followed in the Barnett basin in 2005.

US development of unconventional oil and gas also benefits from the nation's long history of oil exploration, more than a century's worth of geological records, and a deep understanding of various technologies. Also, since any US landowner can sell mineral rights without government approval, it is relatively easy for developers to secure well sites. Canada's evolution in this regard has matched that of the United States, and it is currently the only other country producing shale gas or LTO in significant quantities.

North American shale gas production has already reached 350 billion cubic meters (Bcm) annually, supplying more than a quarter of its domestic natural gas production, and LTO production is currently about 1.5 million barrels a day, or nearly 20 percent of total oil production. McKinsey's proprietary Energy Insights model for unconvensionals estimates that annual shale gas production could potentially reach 495 Bcm and that LTO could reach 6.9 million to 10.5 million barrels a day in 2025.¹⁵⁵

To reflect the potential for great volatility in fuel prices, we have chosen a wide range for natural gas and oil prices to estimate impact. Therefore, having ranged shale gas prices from \$2 to \$8 per MMBtu and crude oil from \$50 to \$150 per barrel, we estimate direct economic impact on the North American economy from unconventional oil and gas at \$70 billion to \$335 billion per year by 2025.¹⁵⁶ The indirect impact could be \$30 billion to \$150 billion, while the additional impact

154 For each country, we have used a combination of proprietary models, public sources, guidance from internal and external experts, and national planning targets to estimate the value added of incremental production of shale gas and oil by 2025. Using the same sources, we have ranged the price of these fuels in 2025 and used incremental production and price estimates to determine incremental gross output. We have then used standard GDP multiplier tables to convert gross output into incremental value added.

155 Energy Insights is part of McKinsey Solutions and provides distinctive analysis that enables energy players to make key decisions on strategy, investment, and performance. For more information on Energy Insights, visit <http://solutions.mckinsey.com>.

156 The unit of measurement MMBtu refers to million British Thermal Units, traditionally the amount of energy required to heat one pound of water by one degree Fahrenheit, and often used for natural gas pricing; 1 MMBtu = 998.12 cubic feet.

induced in the economy could be \$45 billion to \$220 billion. The total economic impact of increased shale gas and LTO production is therefore estimated to be between \$145 billion and \$705 billion in 2025.

As mentioned earlier, an additional source of potential impact is the value added to the economy due to incremental output from energy-intensive industries such as petrochemicals. This is particularly relevant in the United States, as industry has benefited immensely from increased availability of cheap natural gas. According to research done for a forthcoming McKinsey Global Institute report on major sources of growth in the US economy, the petrochemicals industry is expected to add \$60 billion to \$80 billion of gross output in 2025 as a result of increased availability of cheap feedstock due to shale gas, and the manufacturing sector as a whole could add more than \$100 billion in gross output, leading to billions in value added to the economy. In addition, other industries could be impacted; for example, in the long-haul transportation sector, some companies are now considering fueling trucks with natural gas.¹⁵⁷

The rest of the world

Many countries besides the United States and Canada are estimated to have substantial unconventional reserves and could realize significant economic benefits by developing them. However, most experts believe that by 2025 these nations will reach only limited production. We have ranged our estimates of production and economic impact to reflect the differing views of experts, but it is possible that countries included in our estimates (such as China) or not included (such as Russia) could accelerate growth beyond our estimates.

By 2025, the top producers outside North America are expected to be producing 70 Bcm to 220 Bcm of shale gas and 0.5 million to 1.7 million barrels per day of LTO. China could be among the biggest producers of shale gas in this group, while Argentina and Australia could be the biggest producers of LTO.

Unlike crude oil, natural gas is not a freely traded commodity in international markets; its pricing is regional. Therefore, while we standardize on a global oil price estimate in 2025, we use regional estimates of shale gas prices to reflect conditions in different regions. Shale gas prices for China and Australia in 2025 are estimated at \$8 to \$10 per MMBtu, placing shale gas just below imported gas in price. Argentina's government has mandated all new unconventional gas to be priced at \$7.5 per MMBtu, while Europe's natural gas pricing is more uncertain; we therefore use a wide range of \$6 to \$11 per MMBtu.

The direct economic impact on these regions together is estimated to be \$25 billion to \$125 billion in 2025, with an additional \$5 billion to \$25 billion in indirect economic impact and nearly as much induced economic impact.

¹⁵⁷ Diane Cardwell and Clifford Krauss, "Trucking industry is set to expand its use of natural gas," *The New York Times*, April 22, 2013.

BARRIERS AND ENABLERS

The extraction of unconventional deposits of oil and gas requires a range of enabling conditions and capabilities. If policy makers and societies are not aligned on the need for un conventionals, the full impact of these resources will not be realized. Large quantities of water (or advances in fracturing technologies that use other fluids) are required, as are access roads (often in remote areas) to move workers and equipment to drilling sites. Several high-potential regions, such as China, Australia, and North Africa, suffer from water scarcity and could therefore find it difficult to allocate water for fracturing. Australia and China also have limited transportation infrastructure in place to reach remote basins. The environmental risks of hydraulic fracturing, which include potential contamination of groundwater, air pollution from equipment, greenhouse gas emissions from “fugitive” methane, and increased land use, are often cited as reasons for resistance to adoption of un conventionals.

Basic horizontal drilling and hydraulic fracturing technologies are not yet fully developed in most regions outside North America. Recognizing this situation as a challenge, the Chinese government recently signed a technology-sharing agreement with the United States.¹⁵⁸ Access to capital is another potential barrier. Argentina has among the world’s largest unconventional reserves, but Argentinian companies could find it difficult to finance unconventional oil and gas development due to the country’s fiscal situation.

National energy policies can work as either enablers or barriers. The United States government helped its industry take the lead by offering tax credits to companies that were willing to invest in shale exploration. Some Russian energy companies have been asking their government to consider similar tax credits for exploration.¹⁵⁹ Meanwhile, many European countries impose economic barriers via the imposition of high costs and strict regulations. France and Bulgaria have imposed moratoria on shale gas exploration, although the United Kingdom and Romania have recently lifted such bans.

IMPLICATIONS

Businesses that participate in the energy value chain, especially energy companies and oil-field services, could find enormous global opportunities in advanced oil and gas exploration and recovery. They could gain positions of strength by bringing the latest technological know-how to key players in these growing markets (often governments and state companies), and strike partnerships to explore unconventional basins together. Simultaneously, providers could consider investing in developing new techniques that could improve productivity or shorten learning curves for developing basins. For example, building expertise regarding water reuse could yield very high returns when production begins in earnest in water-scarce regions of the world such as parts of China or Africa. These players should also master big data analytics to improve their research. Shell, for example, is already collecting up to a petabyte (one million gigabytes) of geological data per well using its advanced seismic monitoring sensors (codeveloped with Hewlett-Packard), and plans to use the sensors on 10,000 wells.

158 “The US and China: Towards a clean energy economy,” *Whitehouse.gov.*, November 17, 2009.

159 Guy Chazan, “‘Red Lenin’ leads Russia’s oil revolution,” *Financial Times*, March 31, 2013.

Other businesses in the unconventional oil and gas value chain can anticipate growth in demand for products and services and prepare accordingly. In addition to suppliers of fracturing equipment and drilling rigs, new fields will need cement for casings, steel for pipelines, water disposal systems, and geological consulting services. Meanwhile, downstream players such as petrochemical manufacturers can make decisions regarding locating new plant capacity or product planning in anticipation of gas being more abundantly available in some areas. Dow, BASF, and Methanex have already announced plans to set up new manufacturing capacity in the United States to take advantage of cheap natural gas prices.

Businesses related to the renewable energy industry will need to keep a close watch on the impact of unconventional oil and gas on solar and wind power development. Shale gas production has already helped drive natural gas prices in the United States down from over \$10 per MMBtu in mid-2008 to less than \$5 in 2013. The shift from coal to gas for electricity generation is reducing greenhouse emissions while simultaneously leaching urgency from the drive to develop renewable energy sources. However, it has been argued that greater deployment of natural gas instead of coal for power generation could create more “peaker” plants that can flexibly adjust their generation, replacing inflexible “baseload” plants (which are usually coal-based). This could prepare grids for greater renewables capacity in the medium term by accommodating intermittent sources such as solar and wind power.

Policy makers and citizens will need to work together to weigh the benefits and risks of new oil and gas recovery technologies and determine whether they are, on aggregate, beneficial to society. Although the nature and extent of exposure is still a topic of debate, exploration and recovery carry environmental risks, including potential contamination of groundwater and air and greenhouse gas emissions from fugitive methane. Technology for extracting unconventional also requires huge amounts of resources—up to five million gallons of water in a single fracturing and hundreds of trips made by trucks to sites every day in the first few months. Many of these risks can be mitigated to a large extent through the use of new technologies and strong environmental policies. At the same time, development of shale plays can benefit areas where deposits exist, potentially creating jobs and economic development.

If citizens, industry, and policy makers agree that exploiting unconventional reserves is a national economic and political priority, then governments could provide appropriate systematic support. Where reserves are not yet proven, governments could consider creating tax incentives for exploration and research. Land acquisition is a barrier in many nations, which governments can help to lower. In many European countries, all mineral wealth from approximately 1.5 meters (or five feet) below the surface and lower belongs to the state, reducing the incentive for land owners to permit access and forcing exploration companies to negotiate with the government—and the government to negotiate with landowners. Governments could consider changing these conditions to accelerate development. If resource-rich countries are able to support development of unconventional oil and gas by adopting the latest technologies, building necessary infrastructure, mitigating environmental risks, investing in research, and removing administrative obstacles, they could start their own shale revolutions, potentially realizing much larger economic impact than current estimates.

Access to energy sources has shaped the global geopolitical landscape for more than a century. The role of energy in defining foreign policy agendas could change as countries around the world begin to develop new local sources of energy. Some analysts have suggested that increased US production of unconventional gas and oil could affect economic relations with energy exporters around the world and, therefore, could lead to a redefinition of US foreign policy priorities.¹⁶⁰ Similarly, if Europe is able to develop large unconventional reserves or diversify its sources of supply with new LNG (liquid natural gas) exports from North America or other countries, its trade and economic relationship with Russia could be affected.¹⁶¹ No one can predict the geopolitical implications of such developments: there are simply too many variables in play. With that being said, governments, businesses, and citizens should anticipate that shifts in international energy flows will have foreign policy implications. They should avoid any single “point prediction” and instead consider a range of possible scenarios when planning for the future.

While acting on the possibilities and challenges of the current situation, all stakeholders—including energy companies and suppliers, entrepreneurs, governments and policy makers—should be alert to the possibility that another revolution in unconventional energy production could be right around the corner. Just as the current potential has been made possible by incremental changes in technology over several years, the steps required to access the next big pool of value may already be under way.

¹⁶⁰ Daniel Pipes et al., “The geopolitics of US energy independence,” *International Economy*, volume 26, issue 3, summer 2012.

¹⁶¹ “Unconventional gas in Europe: Frack to the future: Extracting Europe’s shale gas and oil will be a slow and difficult business,” *The Economist*, February 2, 2013.

12. Renewable energy



Renewable energy holds a simple but tantalizing promise: an endless source of power to drive the machinery of modern life without stripping resources from the earth; contributing to pollution and climate change; or incurring the economic, social, and political toll associated with the competition for fossil fuels. This promise has been elusive because of the relatively high cost of renewable energy sources such as solar and wind compared with fossil fuels such as coal, oil, and gas. Despite some high-profile failures in the renewables sector and occasionally halting adoption, we see potential for rapidly accelerating growth in the next decade driven by both technological advances that could narrow the cost gap with fossil fuels and a growing desire to find energy sources that reduce human impact on the environment.

While meeting future energy demands in a more sustainable way could involve many forms of renewable energy, solar and wind power could have particularly high potential over the coming decade. These sources of energy are finally beginning to be adopted at scale in advanced economies such as the United States and the European Union. Even more importantly, developing giants China and India have ambitious plans for renewable energy that could enable further rapid economic growth while mitigating growing concerns about pollution.

Although solar and wind energy could continue to be uncompetitive with fossil fuels on a pure cost basis in some regions through 2025, significant additional adoption is widely expected.¹⁶² This adoption could be driven by reduced costs, as well as by continued government subsidies prompted by growing concerns over global climate change. In this chapter, we have estimated the potential economic impact of improving solar and wind technologies by comparing two scenarios—one that incorporates significant technological breakthroughs by 2025, and another in which technology is “frozen” at current levels. In comparing these two scenarios, we have included estimates of future government subsidies as a determinant of the levelized cost of electricity (LCOE), the metric that would be used when considering adoption.¹⁶³

162 The International Energy Agency's *World energy outlook 2012* and Bloomberg's *Global renewable energy market outlook* both estimate growth in renewables adoption from 4 to 5 percent to 11 to 15 percent. This is in line with the McKinsey *Global Energy Perspective* model estimates used in this chapter.

163 LCOE represents the overall cost of producing electricity, taking into account factors such as capital investment, operating and maintenance costs, capacity utilization, system efficiency, CO₂ credits, exchange rates, and other factors.

We also consider multiple possible subsidy levels. The highest of these assumes a consensus among world governments to limit CO₂ emissions to a specific level in order to meet global climate change targets.¹⁶⁴ Solar and wind power could represent 15 to 16 percent of global electricity generation in 2025, up from only 2 percent today. The incremental economic impact of this growth could be \$165 billion to \$275 billion annually by 2025. Of this, \$145 billion to \$155 billion could be the direct value added to the world economy from this power, less the cost of subsidies.¹⁶⁵ The remaining \$20 billion to \$120 billion per year reflects the possible value of the reduction in CO₂ emissions.

Solar and wind power could generate enormous benefits for businesses that provide or consume energy, as well as consumers and society, but this could still require strong government support, including continued subsidies. Increasing adoption of solar and wind power will also be affected by patterns in fossil fuel prices, as well as the actions of energy players, citizens, and policy makers. Greater demand for renewables could provide opportunities for technology providers and suppliers of ancillary equipment. This demand could arise from concerns about environmental sustainability both by consumers and companies, including those adopting “triple bottom-line” approaches to governance (requiring social and environmental responsibility as well as profits). Greater availability of renewables could create opportunities for companies to set up more environmentally responsible operations. For some businesses, solar or wind energy could make remote operations energy self-sufficient, expanding the range of possible locations. This would also depend to some degree on advances in energy storage (see Chapter 8).

Utility companies could play a major role in the adoption of renewable energies. They may need to make some investments in storage capacity to accommodate intermittent flows of solar and wind-based power into their grids. However, distributed renewables—power bought from local, small-scale operations or from commercial or residential users—could help defer investment in transmission and distribution infrastructure.

Technological advances in renewable energies and in fossil fuel production are highly linked; progress in wind and solar power could reduce demand for fossil fuels, while advances in unconventional sources of oil and gas that expand supply and reduce prices (see Chapter 11, “Advanced oil and gas exploration and recovery”) could make renewables less competitive. However, it is also possible that greater use of gas to power electric plants could increase the share of peaker plants in the grid, making it more suitable for adoption of intermittent sources such as renewables in the medium and long term. An overarching question for the growth of wind and solar power is whether the environmental concerns of citizens will be a sufficiently powerful force to motivate governments to continue

164 Most of the world’s major energy producers (except the United States and Canada) are signatories to the Kyoto Protocol and are legally bound to reduce or limit their greenhouse gas emissions; the United States, Canada, and many other countries are signatories to the Copenhagen Accord, which includes nonbinding emission targets.

165 Direct economic impact here refers to the value added to the economy (GDP) due to increased output of electricity from solar and wind sources. The economy also benefits from indirect and induced impact, which we have not estimated here. Indirect impact refers to the value added to other sectors, such as manufacturers of transmission towers or gearboxes. Induced impact refers to the value added due to increases in the household incomes of people connected with the sector.

to subsidize renewables (through environmental taxes on companies, for example) even if fossil fuel supplies rise and prices fall.

DEFINITION

Renewable energy is energy that is derived from a source that is continuously replenished, such as the sun, a river, wind, or the thermal power of the world's oceans. While we have focused on solar photovoltaic (PV) technology and wind power in this chapter due to their potential to be disruptive over the next decade, other renewable sources of energy also have the potential to be transformative if technological development and adoption accelerate (see Box 13, "Other potential sources of renewable energy"). A source of renewable energy that we have not considered here is hydro-electric power, which holds a significant share of global power generation capacity but is generally not expected to see major technological advancements or increased adoption by 2025.¹⁶⁶

Solar energy can be harnessed through many technologies, including concentrated solar and induced photosynthesis. We have sized the potential impact of the increased use of photovoltaics, the technology that accounts for the largest share of solar power production currently and which will most likely do so in the future. PV panels are made of photosensitive materials such as crystalline silicon. This technology converts sunlight into electric energy using the photoelectric effect.¹⁶⁷ Solar panels can be used in small arrays to power a single building or home, or deployed in massive solar "farms" that feed into the power grid. While the cost of solar PV cells and the overall cost of solar power generation have dropped dramatically in the past decade, solar power is still not cost competitive with fossil fuels on a global basis, although in some regions it has achieved grid parity, or soon will. The typical LCOE of conventional electric plants (coal and combined cycle gas) is around \$50 per MWh, compared with nearly \$150 per MWh for solar.

Wind power has been harnessed by civilizations dating back to the ancient Egyptians. Modern wind power uses the same principles but attempts to maximize the effect with large blades and highly efficient turbines that turn more than 45 percent of the kinetic energy of wind into electricity. Wind farms can contain hundreds of turbines arrayed over hilltops, in rivers, or offshore in oceans. Offshore wind is stronger and more reliable than onshore, but it is more expensive to set up wind turbines in riverbeds or beneath the ocean. Western European countries are the leading users of wind power, followed by China. The LCOE for onshore wind, which includes CO₂ credits, is now close to parity with coal and oil, especially in regions with large-scale wind power generation, but still high on a global basis at \$70 per MWh. The next waves of innovation in this technology may be focused on lowering the cost of wind turbines for offshore generation and designs that reduce the cost of nonturbine components, as well as installation and maintenance costs.

166 The IEA's *World energy outlook 2012*, Bloomberg's *Global renewable energy market outlook*, and McKinsey's *Global Energy Perspective* model all estimate the current share of hydro-electric power at 16 to 19 percent of global electricity generation and estimate it to remain within 15 to 18 percent in 2025.

167 The phenomenon in which electrically charged particles are released from or within a material when it absorbs electromagnetic radiation, often defined as the ejection of electrons from a metal plate when light falls on it.

Box 13. Other potential sources of renewable energy

We have chosen to focus on solar photovoltaics and wind (both onshore and offshore) power for this report due to their potential for disruptive impact by 2025. But these are not the only important sources of renewable energy. Other technologies with significant potential include:

- **Biofuels.** Biofuels, which are made from organic materials such as corn, are currently not efficient sources of power and require a great deal of energy to harvest, transport, and process. The share of global energy supply from biomass is currently 2 percent and is projected to reach 4 percent in 2025. However, coupled with next-generation gene sequencing (see Chapter 7, “Next-generation genomics”), there is significant potential for increased power generation from biofuels. For example, research is under way to use photosynthesis from synthetically sequenced cyanobacteria, a blue-green algae, to convert atmospheric CO₂ into fuel.
- **Concentrated solar power (CSP).** This technology uses giant lenses or mirrors to focus the sun’s energy on a small area, converting light into heat energy to drive a steam turbine to produce electricity. CSP’s share of global electricity production is negligible, and investment in CSP has suffered as the price of photovoltaic cells has fallen.
- **Ocean thermal energy conversion.** The world’s oceans are a huge untapped source of energy. Ocean thermal energy conversion (OTEC) uses the difference in temperature between deep and shallow ocean water to generate electricity. There is immense energy in the world’s oceans; however, the technology to capture it is currently immature and produces only a very small amount of power.
- **Geothermal power.** The temperature difference between the earth’s surface and its core can be used to drive a heat engine or steam turbine to produce electricity. Commercially viable extraction is currently limited to only a few locations situated at tectonic plate boundaries (Iceland, for example) and is currently less than 1 percent of global power production.
- **Next-generation nuclear power.** Nuclear power already supplies nearly 15 percent of the world’s electricity. However, the technology faces significant social, political, economic, and environmental challenges. Following the 2011 Fukushima nuclear disaster in Japan, many countries have slowed, postponed, or canceled their nuclear programs. The question of nuclear waste storage is also a deterrent to adoption. However, next-generation nuclear technology taps into energy contained in current nuclear waste products to create a closed and sustainable system.

Solar and wind are intermittent sources of energy, which complicates their use in utility grids. While solar energy is quite predictable, wind is much less reliable, causing difficulties in planning for maximum utilization and off-take. Both technologies are limited to certain locations: solar power generation requires abundant and unobstructed sunlight, while wind farms require large areas of land in locations where wind blows regularly. Current technologies for both require frequent—and often challenging—maintenance. For example, solar panels need to be cleared of dust and debris regularly, especially in deserts. Wind turbines often require maintenance of rotor components, which are hard to reach without specialized equipment due to the great height at which they are located. Solar energy peaks during the day and vanishes during the night, matching the typical demand cycle for power. Wind energy is continuous throughout the day, though intermittent, and in some areas wind speeds are higher at night. It is therefore possible to combine solar and wind power to build a stronger combined portfolio by allowing the variability of one source to partially offset that of the other.

POTENTIAL FOR ACCELERATION

The adoption of renewable sources of energy such as solar and wind power could be driven by two main factors: the need for greater amounts of energy to keep up with rising demand caused by economic growth and the need to mitigate environmental degradation and climate change. The world's economic machinery requires a huge amount of energy, which could become more difficult to supply because of the nonrenewable nature of fossil fuels and the increasing costs of exploring new deposits. Even the unconventional oil and gas deposits that we discuss in Chapter 11, which could have significant impact on supplies in some nations, are exhaustible. Governments are increasingly aware of the need to ensure abundant energy supplies far into the future, which could potentially raise the demand for renewables.

The environmental costs of reliance on fossil fuels are becoming more apparent every day. A recent study commissioned by China's Ministry of Environmental Protection pegs the annual cost of damage to the ecosystem at \$230 billion per year, or more than 3 percent of China's GDP.¹⁶⁸ In 2007 the United Nations Intergovernmental Panel on Climate Change (IPCC) projected that there will be more cycles of extreme weather, that sea ice could shrink in both the Arctic and Antarctic, and that 20 to 30 percent of animal species studied could be at risk of extinction. Major economies such as the United States and China have agreed to target a maximum global temperature increase of two degrees Celsius by 2050 to limit these changes.¹⁶⁹ As part of that effort, the United States has drawn plans to double its use of renewable energies by 2020, while the Chinese government has planned to meet at least 20 percent of the country's energy demand with renewables by 2020.¹⁷⁰

168 Edward Wong, "Cost of environmental damage in China growing rapidly amid industrialization," *The New York Times*, March 29, 2013.

169 The two-degree Celsius limit was agreed to by the United States and the BASIC nations (Brazil, South Africa, India, and China) as part of the Copenhagen Accord in 2009.

170 Evan Lehmann and Nathanael Massey, "Obama warns Congress to act on climate change, or he will," *Scientific American*, February 2013; Jack Perkowski, "China leads the world in renewable energy investment," *Forbes*, July 2012.

Technological advances that reduce the costs of renewable energy generation will be important enablers of adoption. During the past two decades, the efficiency of solar panels (the percentage of solar energy converted into electricity) has risen to 15 percent; in laboratory tests, panels have achieved as much as 44 percent efficiency.¹⁷¹ The cost of solar cells has already dropped from nearly \$8 per watt of capacity in 1990 to less than 80 cents.¹⁷² Wind technology is also progressing. Between 2000 and 2010, the average capacity of wind turbines in the United States doubled to 1.8 MW, as wind towers grew larger: hub height increased by a third to 260 feet and rotor diameter rose by two-thirds to more than 280 feet. The LCOE for wind power has fallen from nearly \$80 per MW to \$70 per MW, and wind generation costs now approach parity with coal and gas.¹⁷³

Further advances in solar and wind power technologies are under way. Thin film cells, which are made from compounds like cadmium telluride, copper indium gallium arsenide (CIGS), or amorphous silicon (A-Si), are being developed for PV use. These advances reduce the amount of material used in creating solar cells and can be “printed” on flexible surfaces, potentially reducing cost and increasing ease of application. Researchers are also working with nanomaterials, including polymer films that are less than 100 nanometers thick that could replace silicon cells and nanomaterial-based coatings that repel water and that prevent dust and debris from sticking to panels. Research is focused on turbine and blade design, such as the Japanese “Windlens,” which uses a curving ring around the perimeter of the blades to double or triple airflow through the blades. New vertical axis wind turbine designs place the main components—the generator, gearbox, and brake assembly—near the ground, making them more easily accessible for repair and maintenance.

POTENTIAL ECONOMIC IMPACT BY 2025

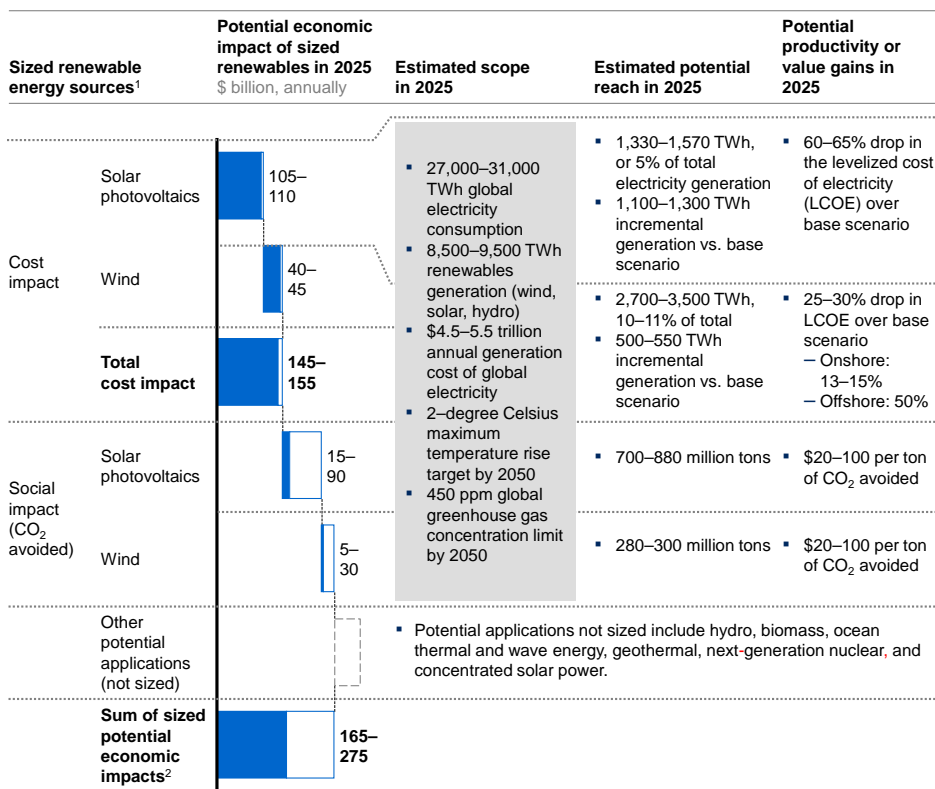
As noted, we have estimated the potential economic impact of solar and wind power by comparing one scenario, which assumes significant technological breakthroughs by 2025, with a base scenario in which technology remains frozen at current levels; estimated impacts include the social value of CO₂ emission avoidance. In this way, the incremental impact of solar and wind technology, after netting the cost of government subsidies, could potentially be \$165 billion to \$275 billion a year in 2025 (Exhibit 16). The larger part of this impact could be in the form of direct value added to the economy from the power generated by the additional capacity created by solar and wind sources, as well as the value added by the technological improvements that raise efficiency above current levels for these power sources. The remaining would be value to society from CO₂ emission avoidance. Only about 15 percent of the overall direct impact may come in North America, but more than 30 percent could come in China. (North America, meanwhile, currently stands to realize the most value from unconventional oil and gas.)

171 “Award-winning PV cell pushes efficiency higher,” National Renewable Energy Laboratory (NREL), www.nrel.gov/news/features/feature_detail.cfm/feature_id=2055.

172 Geoffrey Carr, “Sunny uplands,” *The Economist*, November 2012.

173 Mark Bolinger and Ryan Wiser, *Understanding trends in wind turbine prices over the past decade*, Lawrence Berkeley National Laboratory for US Department of Energy, October 2011.

Exhibit 16
Sized applications of renewable energy could have economic impact of \$165 billion to \$275 billion per year in 2025



¹ Value calculated for a set of regions representing approximately 90% of the total market.
² Only direct value added—indirect and induced impact not sized.
 NOTE: Potential economic impact not comprehensive; includes potential impact of sized applications only. Numbers may not sum due to rounding.
 SOURCE: McKinsey Global Energy Perspective; US Environmental Protection Agency; McKinsey Global Institute analysis

Since subsidies are such an important factor in adoption of renewable energy sources, we tested two sets of assumptions about subsidies in the next decade. In one, subsidies increase moderately from current levels, with many countries offering no subsidies at all, even in 2025.¹⁷⁴ The alternate scenario estimates the level of government subsidies that would induce enough use of renewables to meet climate change targets. These benefits are partially offset by the cost of providing subsidies to energy producers. We estimate the incremental production in 2025 due to technology improvements (the difference between our technology-improvement scenario and our base scenario) and use national electricity prices and standard multiplier tables to translate impact into incremental value added.

¹⁷⁴ Market prices for CO₂ credits (or equivalent subsidies) are projected to rise in most markets where they are already in place, according to the International Energy Agency’s *World energy outlook 2012*; the “low” end of our range of subsidies assumes regions with no subsidies (e.g. India, the Arab Gulf) will continue to have no subsidies in 2025.

To estimate the benefit from avoided emissions, we have estimated a social cost of carbon.¹⁷⁵ For our estimates, we have used a range of \$20 to \$100 per ton in 2025, based on a survey of estimates and roughly in line with third-party estimates.¹⁷⁶ Current market prices are much lower (the European Union Emissions Trading Scheme price has dropped from \$20 in 2008 to less than \$5 in March 2013), and, we believe, do not reflect the cost of CO₂ emissions to society. We use the market price of CO₂ as an input in the LCOE computations for renewables but have not used it as the basis for our social cost estimate.

Wind power capacity could be twice as much as solar power by 2025, but solar power could have greater economic impact. This is because of the greater potential for improvement in solar energy technology: in our technology-improvement scenario, the LCOE of solar power could fall by 50 percent or more by 2025, compared with the base scenario. Improvements in wind power technology could drive a reduction of up to 30 percent in the cost of wind power compared with the base scenario, with offshore wind, which is currently costly to install and maintain, following a steeper cost-reduction curve.

Solar power

The LCOE of solar power dropped from more than \$400 per MWh in 2000 to \$150 per MWh in 2010. We see potential for this rate of improvement to continue through 2025. The PV cell module and inverter, typically 60 percent of the capital costs in these technologies, could follow a semiconductor-like improvement in price performance, while panel installation, usually a fifth of the cost, can be made quicker and cheaper through GPS-guided power tools and robots. Overall, technology improvements could reduce solar LCOE by 65 percent by 2025. This drop could potentially accelerate adoption, raising total global solar capacity from 28 TWh in 2010 to between 1,330 and 1,570 TWh in 2025, or about 5 percent of global electricity production. Taking the incremental production over the base scenario (250 TWh) in 2025, the direct value added from solar power could be more than \$100 billion a year, with an additional \$15 billion to \$90 billion in social impact through eliminated emissions.

As described below (see Box 14, “Distributed solar power”), solar power could also yield large benefits through distributed generation (use by consumers and businesses), especially in cost savings from deferred investments in new transmission and distribution infrastructure. However, because of the intermittent nature of solar power, as well as the need to accommodate bidirectionality (in which excess power generated during the day flows into the grid from end-points such as homes and other buildings), utilities may have to make some up-front investments to realize these medium- and long-term benefits.

¹⁷⁵ The social cost of carbon is a metric that estimates “the monetized damages associated with an incremental increase in carbon emissions”; Michael Greenstone, Elizabeth Kopits, and Ann Wolverton, “Estimating the social cost of carbon for use in US federal rulemakings: A summary and interpretation,” *Review of Environmental Economics and Policy*, May 2011; Laurie T. Johnson and Chris Hope, “The social cost of carbon in US regulatory impact analyses: An introduction and critique,” *Journal of Environmental Studies and Sciences*, volume 2, number 3, August 2012; and Joanna M. Foster, “The social cost of carbon: How to do the math?” *The New York Times*, September 18, 2012.

¹⁷⁶ *Social cost of carbon for regulatory impact analysis under executive order 12866*, US Environmental Protection Agency, February 2010; William D. Nordhaus, *Estimates of the social cost of carbon: Background and results from the RICE-2011 model*, National Bureau of Economic Research working paper number 17540, October 2011.

Box 14. Distributed solar power

In our estimates of impact, we have looked at only large-scale implementation of solar and wind power—wind and solar “farms” with hundreds or thousands of PV units or wind turbines that connect to power grids. However, distributed generation, principally solar panels used to power individual households or supply part of a building’s energy requirements, may drive significant benefits in the coming years.

Distributed generation enjoys a large share of overall solar power production in some countries, such as the United Kingdom and the Netherlands, where more than half of renewable generation is residential (mostly rooftop solar). The impact on national energy systems can be significant. A recent report by the California Solar Initiative estimated that 1 to 1.6 GW per year of solar power generated by consumers would supply the equivalent capacity of adding a new 500kV transmission line, estimated to cost nearly \$1.8 billion in capital costs.¹ Distributed generation could also provide other benefits, such as lower line losses due to shorter distances transmitted, productive use of unutilized real estate (rooftops), and environmental benefits. It could be particularly relevant for heavily congested areas where adding new infrastructure is impractical. Distributed generation can also make the grid more resilient, since it would continue to function when central infrastructure is out of commission.

If renewable generation costs continue to fall and energy storage capabilities grow rapidly (see Chapter 8, “Energy storage”), we can imagine entire neighborhoods or factory complexes being served through distributed solar power. This could make remote housing and manufacturing plants more viable by reducing the transmission capacity required from the grid or even eliminating the need to access the grid altogether. Developing economies could benefit from electrifying “dark” villages or areas without incurring high costs in building infrastructure.

1 Joseph F. Wiedman, Erica M. Schroeder, and R. Thomas Beach, *12,000 MW of renewable distributed generation by 2020: Benefits, costs and policy implications*, Interstate Renewable Energy Council, July 2012; *California Solar Initiative 2009 impact evaluation*, California Public Utilities Commission, June 2010.

Wind power

Given the relatively mature state of onshore wind power technology, we have focused on likely improvements in construction costs (potentially 20 percent) and operating expenses (potentially 25 percent). Offshore wind technology, which is much less evolved, could see a drop of more than 50 percent in capital expenditure requirements and operating expenses. For both onshore and offshore wind power, we base our estimates on improvements in the iron and steel materials used for turbine blades and advances in engineering design that enable longer and stronger blades, yielding greater output in slow wind, as well as reduced development costs achieved by increasing the scale of wind farms. For both onshore and offshore wind, we use the same social cost of CO₂ as for computation of the impact of solar power. The net effect of these factors, combined with an increase in the market value of CO₂ credits, could potentially reduce the LCOE of onshore wind by 15 percent and offshore wind by 50 percent compared with the base case. While the estimated drop for onshore wind is small, it is significant given how close onshore wind already is to parity with fossil fuel plants. The direct value added for wind could be \$40 billion to \$45 billion per year, with an additional impact of \$5 billion to \$30 billion from CO₂ emission avoidance.

Power generation through onshore as well as offshore wind could grow significantly by 2025, from 330 TWh to 2,300–2,840 TWh for onshore and from six TWh to 400–650 TWh for offshore wind. Wind energy capacity could be distributed similarly to solar energy, with China, a major investor in wind power, accounting for nearly 30 percent of onshore wind production and advanced economies 40 percent. Together, wind generation could potentially account for 10 to 11 percent of the world's electricity production by 2025.

BARRIERS AND ENABLERS

As noted, advances in other technologies are an important factor in the economics and adoption of renewable energy sources. While we are not assuming any significant advances in battery storage capabilities in our impact estimates, if storage technology does advance rapidly, it could make adoption of renewables, particularly distributed and off-grid solar and wind power, more economical. This could help bring electricity to remote or sparsely populated locations to which it is too difficult or expensive to extend transmission and distribution infrastructure. Battery storage also has the potential to make it more economical to generate power at scale in remote areas, for example through offshore wind or solar panel farms in deserts.

Another factor for renewables, at least in places such as North America, could be the impact of unconventional oil and gas sources. An increase in the supply of gas and oil could drive down prices, as well as reduce emissions, by substituting natural gas for coal, thereby reducing the economic and social rationale for adoption of renewables.¹⁷⁷ At the same time, some studies conclude that greater availability of shale gas could lead to greater adoption of solar and wind power since the replacement of coal-fired “baseload” plants (that cannot easily adjust their output) with gas-fired “peaker” plants (which can easily cycle up and down)

¹⁷⁷ Shale gas and light tight oil are fossil fuels found in source rock such as shale or which are adsorbed in nearby organic material, typically three to five kilometers under the surface, and are extracted using horizontal drilling and hydraulic fracturing technologies.

could add the flexibility required for the grid to accommodate intermittent sources of energy like solar and wind power.¹⁷⁸

As always with renewables, there is the question of subsidies. Despite technological advances and falling LCOEs, for most of the coming decade governments could need to subsidize solar and wind power to make them cost competitive with conventional fossil fuels such as coal and gas. While governments acknowledge the importance of continuing to push adoption in order to meet environmental goals, fiscal realities could make subsidies vulnerable to budget cuts. Germany, for example, reduced its solar feed-in tariffs (long-term purchase contracts based on the cost of generation, even when it is higher than market prices) by 15 percent in January 2012 and again by more than 20 percent in March 2012. Similar cuts in subsidies across Europe caused some companies to go out of business.¹⁷⁹

Moreover, intergovernmental cooperation is required. Countries have sought to share the cost of combating climate change through mutual agreement, so that participating nations would shoulder the impact of subsidies and other costs of controlling global warming together. A lack of commitment from any of the major parties carries the danger of causing the rest to reduce their commitments. Conversely, coordinated action—for example, through an overhauled CO₂ pricing mechanism that reflects the true economic and social value of reducing emissions—could significantly accelerate adoption of renewables.

IMPLICATIONS

The prospect of renewables such as solar and wind taking on a much larger share of global energy generation has significant implications for energy players and related industries, for governments, and for citizens. Increasing demand for renewable power, especially solar and wind, could generate opportunities for suppliers of renewable power across the world, as well as suppliers and other businesses connected to the value chain. As adoption spreads, so will the competition among global players. The Chinese solar and wind industries, which have made significant investments in the past decade, are well positioned to grab a large share of the global market. But they could be challenged by companies from other nations that are able to develop and commercialize next-generation designs and materials, as well as improved operating and maintenance capabilities, more effectively.

To accommodate the rising share of solar and wind power in grids, utilities could need to invest in infrastructure improvements to manage increased intermittency and bidirectionality (caused by feeds from distributed solar power) on their grids. These investments may seem costly, but utilities can better justify them if they take a portfolio view of their clean energy investments, which could include both solar and wind power (which are intermittent) and hydro-electric power (which is not). In addition, the two intermittent sources are complementary: in many places, wind power is stronger at night when solar is unavailable. Utilities could consider planning for greater renewables adoption by combining solar, wind, and hydro-electric power sources in a single portfolio and by investing in

178 Jason Channell, Timothy Lam, and Shahriar Pourreza, *Shale & renewables: A symbiotic relationship*, Citi Research, September 2012.

179 Mark Scott, "In Europe, green energy takes a hit from debt crisis," *The New York Times*, November 2012.

advanced battery storage technologies to help accommodate renewables on the grid. This approach could not only make utilities cleaner, but also better able to meet peak demand. In many places, utilities can take advantage of solar power's production pattern matching demand (during the day), driven by air-conditioning requirements. Distributed generation could even help defer infrastructure investments, reduce line losses, and add resiliency against centralized failures.

Suppliers of fossil fuels may be adversely affected by the growth of renewables, which could curb demand for their products. They could also face government sanctions (carbon taxes, for example) that would add to their costs. Renewable energy sources could represent an opportunity for industries or companies that are heavy users of energy to undertake more environmentally sustainable operations to address the concerns of shareholders and other stakeholders.

Consumers may not realize direct economic benefits from renewable energy since solar and wind power used by their utility providers may not cut their electric bills. But they stand to gain in other ways. If renewables are adopted at the potential rates we describe and goals for reducing planetary warming can be achieved, the effects of climate change may be reduced and air and water quality could improve in many parts of the world. Reducing fossil fuel emissions could also have direct health effects, reducing the incidence of respiratory diseases and improving overall health through cleaner air, a need that is increasingly pressing in many rapidly developing nations.

Governments will have to weigh the benefits of adopting more solar and wind power against the costs of maintaining subsidies. To meet the global target of a less than two-degree rise in temperature by 2050, it is estimated that total carbon emissions cannot exceed 880 gigatons, of which 380 gigatons have already been used. At the current rate of emission growth, the 880-gigaton limit will be reached in 2025.¹⁸⁰ Policy makers may have to consider creating more aggressive policies related to greenhouse gas emissions and make more concessions toward developing international consensus on more environmentally sustainable uses of energy.

180 Malte Meinshausen et al., "Greenhouse-gas emission targets for limiting global warming to 2° C," *Nature*, volume 458, April 30, 2009; James Leaton, "Unburnable carbon—Are the world's financial markets carrying a carbon bubble?" Carbon Tracker Initiative (www.carbontracker.org), 2009.

Conclusion

By the time the technologies that we describe are exerting their influence on the economy in 2025, it will be too late for businesses, policy makers, and citizens to plan their responses. Nobody, especially business leaders, can afford to be the last person using videocassettes in a DVD world. Business leaders, policy makers, and stakeholders should look ahead, identify the technologies that could affect them, and determine how to shape markets and policies in ways that will serve their interests. While the appropriate response will vary by stakeholder and technology, we find that there are some useful guiding principles that can help define responses.

BUSINESS LEADERS

The technologies we have focused on in this report could fuel a decade of rapid innovation in products, services, business processes, and go-to-market strategies. Companies will have new ways of developing and producing products, organizing their businesses, and reaching consumers and business-to-business customers. Business leaders will need to determine when, how, and whether to take advantage of new technologies—and be prepared to move quickly when others use emerging technologies to mount challenges.

In the 21st century, all business leaders must understand technology. More than ever, leaders must develop their own well-informed views of what developments like cloud computing could do for their enterprises and work to separate hype from reality. Leaders should think carefully about how specific technologies could drive economic impact and disruption in ways that could affect their businesses. Leaders should make sure to invest in their own technology knowledge; they don't have to become programmers or compulsive Facebook posters, but they should keep abreast of technology trends and pay attention to what their most tech-savvy customers are doing and saying. A teenage customer halfway around the world may offer a better perspective on technology than a panel of experts in a conference room.

Time is the enemy: the world is changing at Internet speed, and technology is continually evolving. Strategies can quickly fall behind, so the rhythm of planning has to keep pace. When technologies have disruptive potential, the stakes are even higher and the range of strategic implications is wider. Management thinker Clayton Christensen warns companies against focusing too much on their largest, most established markets and related value propositions. In doing so, companies can miss the ways in which disruptive technologies can jump industry or market boundaries and change the rules of the game. The first MP3 files had inferior audio quality and were easily dismissed; they went on to make music CDs all but obsolete.

When necessary, leaders must be prepared to disrupt their own businesses and make the investments to effect change: as the past two decades have shown, successful companies repeatedly reinvent themselves to keep up. This

will require experimentation and investment. Early investment will probably dilute the profitability of a company's portfolio in the near term, but ultimately it is tomorrow's sources of growth that ensure the enterprise's future. In our experience, companies that reallocate resources early to capture trends often have higher returns and are more likely to survive long term. Failing to reinvent and focusing only on existing markets open the door for disruptors, particularly at the bottom end of the market.

Everywhere, the democratization of technology is advancing, reducing barriers to entry and allowing entrepreneurs and other new competitors to disrupt established markets and industries. Cloud services make it easier for new companies with little capital to obtain operating infrastructure and access to markets that it has taken global companies decades to build. 3D printing goes a step further; it not only opens up markets to competition from entrepreneurs, but it also has the potential to shift value directly to consumers as they learn how to make things that they used to buy. To compete in this environment, companies need deep sources of value or competitive advantage. The prospect of more than two billion new Internet users in developing economies promises both access to new consumers and the threat that those consumers will go into business against you. To survive, companies will need to learn the tricks of the Internet trade; multi-sided business models (such as online advertising or monetizing exhaust data) need not be reserved for Google and Facebook.

Some of the biggest opportunities and challenges for business leaders will arise from new tools that could transform how work is done. With technologies like advanced robotics and automated knowledge work, companies could have unique opportunities to realize rapid improvements in productivity. These tools could redefine jobs as tasks are augmented by, or transferred to, machines, requiring new skills for workforces. Knowledge workers are the foundation of future success—in all sectors of the economy; by 2025 some manufacturers could be hiring more designers and robotics experts than assemblers. Companies that use technology to make knowledge employees more productive will gain large business model advantages and attract the best talent. More than ever, companies will need to have the right people, along with the training systems to keep these workers' skills current.

Adopting disruptive technologies entails risks, and managing these risks will be critically important. Internally, organizational effectiveness and cohesion could suffer as some jobs are transformed—or eliminated—by technology. By working with employees and redesigning jobs to focus on higher-value skills—and by investing in workforce development—companies can minimize these risks. External risks include reputational risk and consumer resistance, as well as safety and regulatory issues. For example, new materials may have unforeseen health effects and may pose environmental risks. Autonomous vehicles might not deliver the potential impact we estimate unless the safety of driverless vehicles can be established, consumers accept the idea, and regulators come up with the necessary rules and standards to put these cars and trucks on the road. Business leaders need to strike a careful balance as they adopt new technologies; they must be thoughtful about risk, but they should also manage these risks without stifling potential.

POLICY MAKERS

Since the Industrial Revolution, governments have played an increasingly important role in bringing disruptive technologies to life. This ranges from the support for basic research that helped bring about the microelectronics and Internet revolutions to mobilizing coordinated efforts like the Human Genome Project. Equally important, governments help set standards and facilitate the emergence of new markets, for example by setting the rules for the use of electromagnetic spectrum for things like mobile Internet devices or the Internet of Things.

Governments also have the power to limit the adoption or progress of technology. The people who set policy have multiple responsibilities that are often in conflict when disruptive technologies emerge: the rising productivity that automation of knowledge work could help drive productivity growth, but the potential impact on employment might create social and economic strain. At the same time, those who benefit from the established ways of doing things, imperiled by disruptive technologies, often find ways to influence policy. Given the scale of impact of the technologies we consider, the job of reconciling these conflicts and balancing the needs of today's citizens with those of future generations will place unprecedented demands on policy makers.

Government leaders may need to update their approaches to facilitating adoption of new technologies while managing the attendant risks. Governments often provide initial funding and incentives for technology development and even act as early buyers to speed progress and adoption. In the past, government efforts often involved huge, decades-long projects. These large-scale programs could remain important going forward, but as technology grows ever more complex and competition between nations to be at the forefront of innovation intensifies, policy makers should consider models for smaller, more frequent experimentation in the development of specific technologies, while continuing to invest in basic research. At the same time, encouraging early adoption before technologies are completely understood raises some big challenges. For example, government support has been critical to the advance of nanomaterials and hydraulic fracturing and both carry potential health and environmental risks, which government also has the responsibility to address.

In addition to creating incentives for the development and adoption of technologies, governments can play an important role in facilitating the creation of networks that can speed up innovation. By sponsoring collaborative efforts at a national or international level, governments can help bring world-class expertise to bear and foster relationships that extend beyond the research phase to help ensure successful commercialization.

Standards-setting efforts could be very helpful to many of the disruptive technologies we describe, and governments can be influential in these processes. For example, the Internet of Things will require a high level of inter-operability among different types of sensors and actuators across public and private networks. In addition, interfaces will need to be secure to ensure that hackers and viruses do not interfere. This will require international standard setting. Across technologies, governments will need to cooperate on matters of international law, regarding intellectual property, liability, and other issues that span borders.

The biggest challenges for policy makers could involve the effects of technologies that have potentially large effects on employment. By 2025, technologies that raise productivity by automating jobs that are not practical to automate today could be on their way to widespread adoption. Historically, when labor-saving technologies were introduced, new and higher value-adding jobs were created. This usually happens over the long term. However, productivity without the innovation that leads to the creation of higher value-added jobs results in unemployment and economic problems, and some new technologies such as the automation of knowledge work could significantly raise the bar on the skills that workers will need to bring to bear in order to be competitive.

Given the large numbers of jobs that could be affected by technologies such as advanced robotics and automated knowledge work, policy makers should consider the potential consequences of increasing divergence between the fates of highly skilled workers and those with fewer skills. The existing problem of creating a labor force that fits the demands of a high-tech economy will only grow with time. Advanced economies are already facing a shortage of high-skill workers, particularly in technical fields. Secondary and tertiary curricula need to be aligned with those needs. Critically, policy makers—as well as employers—can no longer focus only on building the skills of young people entering the labor force. They will need to support the whole workforce, including through retraining.

Policy makers also will have opportunities to employ emerging technologies to address the challenges of 2025. The mobile Internet and advances in the automation of knowledge work, for example, could make it possible to bring customized, interactive training to students and workers anywhere. Emerging technologies can also be used by government to deliver services more effectively and responsively. They can help societies address grand challenges such as poverty and climate change.

Finally, policy makers can take a step back and look at how they address technology issues. Technology continues to advance on many fronts, and many developments bring new challenges for society and government. Governments cannot afford to be passive or reactive. If policy makers wait until bioterrorists show what they can do with a low-cost gene-sequencing machine, it will be too late. Policy makers should also have well-thought-out, structured methods for assessing technologies, to add rigor to their analyses. Also, they can look for better metrics to understand the value of emerging technologies. As we have discussed in this report, the value of technology often lies in its benefits to users—including in consumer surplus that is not captured by GDP measures. Measures of economic activity such as GDP are important and expedient, but better efforts can be made to measure aggregate societal and economic welfare comprehensively. Metrics can influence policy decisions, so policy makers should select them carefully.

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