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Envisioning 2030: US Strategy for the Coming Technology Revolution

A Report by the Strategic Foresight Initiative

Envisioning 2030: US Strategy for the Coming Technology Revolution

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Foreword

The world is on the cusp of another set of major technological transformations. Just as a teenager today has more computing power in the palm of her hand than NASA had when it launched Apollo 13 in 1969, the world of 2030 will feature surprises with benefits—and risks—we are only beginning to imagine.

This report builds on our report *Envisioning 2030: US Strategy for a Post-Western World,* issued at the beginning of the Obama Administration's second term. We may face a future of vast economic and political volatility, environmental catastrophe, and conflicting, inward-looking nationalisms. Alternatively, we could create a more cooperative, rules-based world of reduced poverty and human advancement. These diametrically opposed futures and any of the countless variations in between will all have technology as a driving force, ushering in a new level of cooperation or compounding existing problems and leading us down a much darker path.

This report examines three broad technology groups—energy, smart cities, and new manufacturing technologies such as 3D printing, biotech, and robotics that we term the "Third Industrial Revolution"—that appear to us as areas where emerging technologies play critical yet disruptive roles. These technologies, whose development exepmlifies the erratic patterns of innovation, are necessary for confronting many of the world's biggest challenges. All present opportunities for the United States in this globalized world.

The United States remains the world-class science and technology leader, but the field is increasingly more competitive, and the United States risks losing its edge. This comes at a time when innovation is more urgently required than ever before to address challenges that include managing climate change, natural resource constraints, galloping urbanization, data privacy, health care, education, and more generally the unprecedented speed of societal change.

Not only can technology be a source of economic recovery and societal rejuvenation, but it can connect what President Barack Obama has referred to as the much needed US "nation-building at home" with an expansion of US prestige and power overseas. **Technology presents a huge set of opportunities for the United States in developing a strategy for the post-Western world.**

After World War II, the United States won the hearts and minds of much of the rest of the world by linking US national interests with helping others overcome their challenges—whether it was helping Europe rebuild through the Marshall Plan or standing up to the Soviet threat with the creation of the NATO alliance. Today, leadership in many of the technologies described here can help the United States renew and forge an even stronger compact with our partners and friends.

As we tackle these generational challenges, we want to thank our partners, the governments of Sweden, Singapore, and the United Arab Emirates, for supporting much of the work that went into this study. Thanks as well to the remarkable braintrust of Atlantic Council senior fellows who have guided us through this project: Thomas Campbell, Peter Haynes, Paul Saffo, and Tom Fingar. Harvard University, Massachusetts Institute of Technology, Stanford University, and Singularity University also hosted us for several roundtables to discuss the intersection of technology and society.

Above all, thanks go out to the Strategic Foresight Initiative team who authored the report: Mathew Burrows, Peter Engelke, Banning Garrett, and Robert Manning.

Frederick Kempe
President and CEO, Atlantic Council

Executive Summary

The following paper is a companion to the Atlantic Council's Strategic Foresight Forum to be held on December 9-10, 2013, where outside experts and panelists will discuss these issues. The conference proceedings are on the record. Videos and a transcript will be available on the Atlantic Council website (http://www.atlanticcouncil.org) shortly after the event takes place.

This report has a simple message: We are not prepared for the negative consequences of many new technologies or as well-positioned as we should be to take full advantage of the benefits. Emerging technologies are likely to be more beneficial than detrimental, but the opposite could be true if we are not careful. This report examines emerging technologies in three broad areas—energy, smart cities, and manufacturing—that are playing critical yet disruptive roles: all present opportunities for the US and its partners, but also huge challenges and risks.

Manufacturing

Of the emerging technologies focused on here, synthetic biology is among the most promising, but also potentially the most dangerous. In this new synthetic biology age, we will be able to edit DNA like software in a computer. The bioengineered digital file could represent the DNA of an existing organism or an altered form of that organism. It could be an entirely new organism created from DNA building blocks called "BioBricks." BioBricks are DNA constructs of different functioning parts that can be assembled to create new life forms to perform specific functions. Genetically engineered organisms can be created for biofuels, water purifying, textiles, new medicines and vaccines, and food sources.

Perhaps even more astounding than the ability to digitize life is that digital life can be transmitted over the Internet and the organism recreated anywhere on the planet. Craig Venter, who led the private effort to map the human genome and created the first synthetic organism, has created "biological converters" to receive and print the files. This could be immensely beneficial: in a global pandemic, synthetic biology could greatly speed the time needed to develop a vaccine and could send the digitized vaccine sequence around the world to be bioprinted for immediate use. Synthetic biology and 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. It enhances our ability to fight disease and help ensure both longer life spans and better quality of life.

However, the ease associated with synthetic biology, including the low cost and wide availability of materials and capabilities, is also the source of its danger if it is used for the wrong purpose or is handled carelessly. With synthetic biology, we have the ability to alter viruses to become deadlier or to create wholly new lethal microorganisms.

On recent visits to the Massachusetts Institute of Technology (MIT) and Stanford University, scientists voiced concerns about a lack of a thorough-going national biological security strategy, but also worried about too heavy-handed an approach that could discourage innovation. Finding that fine line is one of the biggest challenges, but **a security strategy, which would have to be developed in partnership with other nations, is desperately needed if an accident or tragedy is to be avoided.**

Other emerging technologies also present challenges, but perhaps not of the same magnitude. Synthetic biology is part of a group of new manufacturing processes that is changing the way things are made, where and when they are produced, and how they are distributed. We and others have labeled all of these developments a Third Industrial Revolution. 3D/4D printing and robotics, in addition to synthetic biology, have now reached a takeoff point largely because of a convergence of several other technologies. In the 3D/4D case, the takeoff has been enabled by computer-aided design, big data and cloud computing, new materials, and reductions in the costs of printers.

4D is not as far along as 3D printing, but even more exciting. 4D printing is where material objects are programmed to change their form and function after they are produced. This will be useful in the case of buildings or infrastructures where the materials used can adapt to loads or weather. Even before the 4D future arrives, 3D printing is starting to be used in an enormous range of applications, from printing human organs and food to airplane wings. NASA recognizes 3D printing as a critical technology for space exploration.

3D printing could be especially transformative in places such as Africa that do not have significant manufacturing capability and relies on massive imports, including of basic consumer goods. The cost of establishing a basic 3D printing facility—a computer, printers, materials, and Internet access—would likely be significantly less than $10,000, far more affordable than a conventional factory.

The new robots are also the products of several rapidly improving technologies, including wireless communications technologies, artificial intelligence, and cheaper sensors. Developers are extending the capabilities of robots, crossing the boundary between industrial and non-industrial robots. In hospitals, for example, we are seeing them perform specialized functions such as surgical support including the "Da Vinci" device carrying out robotic surgery under the control of skilled surgeons. The military is expected to further increase the use of robots to reduce the risks for soldiers operating in dangerous environments. Robots like IBM's Watson are sifting through billions of data points to better answer, for example, urgent information queries in hospitals. Digital robots are replacing lawyers with "e-discovery" by scanning millions of legal documents at higher speed, lower cost, and with greater accuracy than humans.

The problem is that robots could replace too many workers before new jobs can be created, exacerbating wealth and income gaps. The skill sets required for jobs are changing dramatically, with many low-end skills gradually being eliminated, while many mid-level jobs are going too. A recent Organization for Economic Cooperation and Development (OECD) study blames new technology for four-fifths of the 4 percent global decline in the share of GDP going to labor in the labor-capital split. The few highly skilled and talented along with corporate managers and owners have been accruing an increasing percentage of the wealth. We worry about a growing backlash against the introduction of new technologies, turning the United States into an increasingly divided country between the technological "haves" and the "have-nots" who see themselves as losing out in the new knowledge economy.

Besides the potentially long-term, negative impact on jobs and compensation, there are other security downsides to the new manufacturing technologies. 3D printing of guns, high-capacity magazines for assault weapons, and improvised explosive devices (IEDs) will make control of lethal arms more difficult. Drone technology is increasingly cheap and globally available. Not only states but nonstate actors can build their own drones for lethal attacks and surveillance. Robotic weapons systems with the ability to autonomously make "kill decisions" are possible and could extend to robotic soldiers. Hacking of autonomous vehicles—from cars to drones—could also result in lethal destruction.

Energy

The payoff for the United States from the Shale Revolution has already been significant. In the few short years since 2008 when shale gas production really started to grow, the United States has gone from a net importer to what looks to be the world's largest producer of hydrocarbons. While the shale energy phenomenon, like the Internet, is now taken for granted, its rapid development is a useful reminder of both how protracted is the process of commercializing technology and how swiftly innovation can transform reality when it achieves a critical mass. Though shale gas and tight oil ramped up in 2007-08, the technology had existed for nearly a century. It was the combined public/private partnership of government-funded R&D from the 1970s and creative wildcatting entrepreneurs that developed the commercially viable fracking technology.

Strategically, the Shale Revolution has put the United States in a position to challenge the Organization of the Petroleum Exporting Countries (OPEC)'s control of oil markets and bolster its position in Asia where our allies—Japan, South Korea, and Taiwan—are major gas importers. Because shale is now so vital to US economic and security interests, it is important that we make sure production is safe and does not endanger the environment. Legitimate concerns over methane leaks, water pollution, and minor earthquakes are still being examined. Such concerns are inhibiting a number of states including New York, Colorado, and California, and a number of European allies from permitting fracking. If not addressed quickly by energy firms and regulation, this risk factor could undermine the Shale Revolution and, with it, major US security interests. **Because of the stakes involved, we recommend a bipartisan national commission comprised of scientists and engineers, energy companies, state regulators, and environmental groups be appointed to develop proposals for minimizing risks and harmonizing regulations.**

The problem now is that cheap and ample sources of energy may prove an obstacle for moving us beyond dependence on fossil fuels. Transitioning to a post-hydrocarbon world requires enormous changes in not only the sources of electricity, but the way it is used and distributed. The modernization of the US electricity grid, much of which is nearly a century old, into a smart grid is a critical part of the transformation. The building of a smart grid would require real investment capital. While the payoff would be big—up to $2 trillion in benefits—an industry study said utility companies would need to invest between $17-24 billion annually over the next two decades. **We believe the construction of a smart grid should be a national priority.**

Cities

Cities are growing rapidly, especially in Asia and Africa. Use of many of the emerging technologies in and by cities could make the difference between an urban nightmare world or one in which many of the big challenges regarding food, water, and energy security, poverty, and transport are largely solved. The "smart city" concept is critical to dramatically improving how cities function. Smart cities leverage information and communications technology (ICT) to maximize citizens' economic productivity, minimizing resource consumption and environmental degradation. A "virtual" dashboard that uses sensors to monitor in real time traffic patterns, electricity and water use among others can be used to increase efficiencies and manage complex and variable conditions during natural disasters.

"Green tech" is another set of technologies that complement the "virtual" dashboard and maximize its effectiveness. Architects and engineers involved in the green tech movement want to reduce the absolute amount of energy and water that buildings consume while maintaining or improving the services (light, heating, cooling, shelter, and aesthetics) they provide to inhabitants. A fascinating possibility is the use of a technology called protocell, which is a form of synthetic biology that enables designers to mimic the behavior of living organisms. While protocell applications are some years away, designers argue that protocell-based materials could be designed to filter and purify airborne pollutants, capture and retain excess rainwater until needed, or modulate sunlight, keeping building interiors at optimum temperatures and lighting conditions. **We could help accelerate adoption of these technologies by creating a national green building code with world-class energy and water efficiency performance standards.** The United States also has a huge opportunity to sell these urban technologies to the rapidly growing cities in the developing world.

There are real potential downsides to emerging urban technologies: enormous technical and organizational hurdles exist in coordinating, managing, and securing information coming from so many data sources. While networking data across millions of individual users and devices has many benefits, one major downside is increasing exposure to data security and privacy breaches. Such breaches could occur through deliberate and malevolent means or through unforeseen accidents, disasters, power outages, and other events.

Leadership for the Way Ahead

Finally, this review would not be complete without warning about the need to bolster US and European leadership in technology. One of the messages of the Atlantic Council's 2012 *US Strategy for a Post-Western World* report was that "the keystone of national power remains US economic strength and innovation." The lesson also applies to our transatlantic partners. There is no better argument for a renewed focus on technology.

US education in science, technology, engineering, and mathematics (STEM) continues to show little improvement. The United States ranks twenty-seventh among developed nations in the proportion of college students receiving undergraduate degrees in science or engineering. More foreign students study physical sciences in US graduate schools than Americans. And they are the same foreign students who once they graduate usually lose their visa to stay in the United States and give back. **We support calls for urgent reform of the immigration laws**

to enable US-trained scientists and engineers to be able to remain after they graduate.

Overall, the United States remains a leader in expenditure on R&D both in absolute terms and as a percentage of GDP, but the share of EU GDP spent on R&D is substantially below US and Japan. But US government spending on basic R&D has flatlined since about 2003 when adjusted for inflation and is expected to decline sharply as a percentage of GDP if sequestration budget cuts are fully implemented. Press reports indicate that the National Institutes of Health's budget could drop 7.6 percent in the next five years. Research programs in energy, agriculture and defense will decline by similar amounts. NASA's research budget could drop to its lowest level since 1988.

There has been a dramatic growth in Chinese R&D—now close to EU levels—indicative of Chinese efforts to become an innovation nation and position itself as a potential first mover in the biotech and green energy fields. On patent grants, the US and Europe have experienced a relative decline over the past decade as China increases both its absolute number and overall share. Obviously the value and significance of specific patents varies considerably, and there is controversy over the relative worth of many Chinese patents. But the underlying point is that the world is now much more competitive, and the United States and European countries risk losing their edge, which has negative national security implications. In the US government, the Defense Advanced Research Projects Agency (DARPA), the National Science Foundation (NSF), and the National Institutes of Health (NIH) have been among the most important engines of innovation in the past five decades, but they now face budget crunches. **US government R&D funding should be significantly increased to maintain US leadership in science and technology and to strengthen the foundation for US economic competitiveness and growth as well as to marshal science and technology to address global challenges.**

I. Technology’s Dynamic Role at a Tipping Point

“We are in for a fascinating few decades, but it definitely is not a time for the technologically faint-hearted.” —Paul Saffo, Silicon Valley futurist

You don’t have to be a believer in Ray Kurzweil’s “law of accelerating returns” to recognize the importance of technology in shaping tomorrow’s political, economic, and social trends. Whether innovation has kept pace with population growth—or not as some scholars contend—the technological changes have been mind-blowing all the same: doubling of computing power every eighteen months; a dramatic decline in costs of genetic sequencing from $3 billion when the first human genome was sequenced in 2003 to $1,000 today; the dramatic cost reductions in transmitting a trillion bits of information from $150,000 to just 12 cents over the last three decades; and a three-million-fold decrease in data storage costs since 1982, to name only a few. In the late 1980s when the human genome sequencing project began, it is well to remember that some critics thought it would take thousands of years to finish it.

The convergence and synergies of several broad technologies, particularly nano, bio, IT, 3D printing, artificial intelligence, new materials, and robotics is perhaps the most important driver of what we and others consider a Third Industrial Revolution with the potential to produce even more social, economic, and political disruption than we have ever seen before.

We would argue that technology is at a tipping point from changing the meaning of “work” to potentially solving the resource crunch to being the key for a better urban future and helping individuals and societies cope with aging.

Change within each domain is accelerating. Robots are turning up everywhere from software agents in cyberspace to robotic cars on our highways. Though still in their early stages, these robotic platforms are evolving at a rate similar to that plotted by Moore’s Law over the last four decades. The convergence of computers, communication, nanotechnology, and sensing into a single smart device has led to the sensor revolution. With the Internet of Things—more than fifteen billion sensors, cell phones, and other devices already connected to the Internet and each other—we will be able to monitor virtually everything from urban congestion to pollution in the environment to what plants need for growing and becoming better foodstuffs. With the proliferation of sensors, more and more systems can be self-regulating, not requiring human intervention, for them to operate at high efficiency, while at the same time uploading massive amounts of big data into the cloud. As has already happened in several fields, growing automation has huge implications for the workplace. At the same time, the new and growing number of megacities won’t be able to function without sensors to monitor the health of critical infrastructures such as transportation and power and water supplies.

Widespread diffusion of energy supplies and production was another unanticipated mega-change even five years ago. The debate over peak oil is legendary. But even for those who thought peak oil was a distant concern, there nonetheless was the worry that conventional oil and gas production was being increasingly concentrated in unstable areas like the Middle East, Russia, and West and Southern Africa. Unconventional energy—shale gas and light tight or shale oil—and non fossil fuels were dismissed as not likely to constitute a significant slice of the energy mix. In the case of shale gas and light tight oil, it was experimentation with the combined technologies of fracturing and horizontal drilling that led to the Shale Revolution.

Better energy storage could be an even bigger game changer if it increases the use of renewable or alternative energy, bringing reliable electric power to businesses and households in developing countries. Growth in market share of cost effective electric vehicles would be a boon in both developed and developing countries where car ownership is growing. Advanced energy storage would be particularly beneficial in remote areas in developing countries where infrastructure is lacking, but other forms of energy—particularly solar—are readily available.

Globalization: Both Cause and Effect

The accelerating rate of new technologies' absorption by developing countries is one of the most impressive features of the technological revolution and one underlying driver of globalization. Though there is a huge divide that is likely to remain for decades with more advanced countries, the diffusion of new technologies to the developing world is happening at a rapid pace. The 2013 UN Human Development Report on South-to-South ties attributed the spectacular increase in telephone connectivity in Africa over the past decade to the work of companies based in India, South Africa, and the United Arab Emirates (UAE). Mobile subscribers have been doubling every year since 2002 in Africa and increasingly with smartphones which enable Internet connectivity. Now Africa has twice as many cell phones as there are in the United States.

Many emerging technologies are helping to eliminate hurdles faced by developing countries in accelerating growth and development. The rapid spread of telephony in Africa is an example of mobile technology overcoming the lack of landline infrastructure to spur communication and connectivity. Similarly, the less developed are sprinting ahead in some technologically enabled areas such as mobile banking in part because the mortar and bricks institutions are less prevalent and mobile banking is filling in the gap. Indeed, with the possibilities so immense in the developing world, technology may actually prove more important for growth there than in the developed West. McKinsey's recent report on disruptive technologies, for example, pointed to the fact that while the productivity and GDP growth (from IT) 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 growth in developing economies.[1]

There is no one silver bullet that can dispel or derail all the negative disruptions from the juggernaut of oncoming emerging technologies. We will need to break down and understand the likely implications of each new technology. **Given the multiplicity of ways that the emerging technologies are likely to coalesce, merge, and then trigger new applications, there is no way of fully predicting all the ways they will impact the world. We must therefore build in resilience on top of foresight efforts. What is essential is that governments at all levels, businesses, think tanks, NGOs begin to think about the potential impact of new technologies and begin to devise ways of tempering the negative effects.** Disruption is inevitable and much is likely to be beneficial, but some of the disruption could be harmful, even posing existential threats if not controlled. This paper is focused on the intersection of those emerging technologies and the broader geopolitical, economic, and social trends. It looks at a number of critical areas where technologies form part of the solution, but also where the emerging technologies pose their own challenges.

1 James Manyika, et al., *Disruptive Technologies: Advances that Will Transform Life, Business, and the Global Economy* (San Francisco: McKinsey Global Institute, May 2013), http://www.mckinsey.com/insights/business_technology/disruptive_technologies%E2%80%8E.

II. The Energy Case: Promises, Promises

"The Stone Age did not end for lack of stone, and the Oil Age will end long before the world runs out of oil." —Sheikh Ahmed Zaki Yamani, former Saudi oil minister

Technological transformations seldom occur in linear fashion or according to anyone's plan or expectations. Rather, they tend to gestate over time and then occur in qualitative bursts. The historical pattern is that sometimes innovation is policy-driven, sometimes market driven, and sometimes driven by serendipity. Not infrequently, the resulting disruptive change reflects some combination of all of the above.

In the case of energy (not least, the Shale Revolution), there have been elements of all three factors. Energy is a critical enabler to the economy, to economic growth for the developing world, to addressing climate change and other environmental challenges, and not least, to shaping urban life and sustainability. The Shale Revolution is an interim step toward a new enabling capacity. Unlike the related challenges of food and water, the challenge of the first half of the twenty-first century is unlikely to be one of lack of adequate supply. Indeed, the world supply of proven oil reserves has increased from 683 billion barrels in 1980 to 1.69 trillion barrels by 2012, largely the result of technology innovation in deep sea oil drilling technology and the Shale Revolution.[2] This, despite a sixteen million barrels per day increase in production over that thirty-year period to the current eighty-nine million barrels per day level. The debate over the future of oil has moved from concern about "peak oil" and scarcity to speculation that we are reaching "peak demand," possibly by the end of this decade, as a Citigroup analysis has argued.[3] Projections for future global oil demand by 2030 range from 92 million barrels per day to 110 barrels per day or higher.

There is a serious problem of distribution. The International Energy Agency (IEA) estimates that 1.3 billion people still lack access to electricity, with the majority concentrated in ten countries in South Asia and Africa.[4] But the principal energy challenge is to move decisively toward a more resilient post-petroleum-centered energy system. This is made more poignant when one considers the demand growth for energy services with the global middle class growing to as much as four out of the eight billion people estimated to be on this planet by 2030.

The IEA projects overall global energy demand to increase by 35-46 percent from 2010-2035.[5] Whether the emerging middle class in China, India, and Southeast Asia are driving electric cars and getting electricity from sources other than coal will to a large degree determine the extent of global climate change.

The Shale Revolution

For all the vast changes in the energy landscape in the four decades since the 1973 Arab oil embargo and the vast array of R&D on new energy technologies, the Shale Revolution has been (after IT) one of the most dramatic innovations thus far in the twenty-first century. The combination of computer-aided horizontal drilling and hydraulic fracturing (known as "fracking") technology has enormously boosted both US production and reserves of oil and gas.

The US has already become the world's largest producer of hydrocarbons with vast potential to become a net oil exporter by 2030.[6] Oil production is now 7.32 million barrels per day (m/bd), the

2 British Petroleum, *BP Statistical Review of World Energy*, June 2013, http://www.bp.com/content/dam/bp/pdf/statistical-review/statistical_review_of_world_energy_2013.pdf.

3 "Yesterday's Fuel," *Economist*, August 3, 2013, http://www.economist.com/news/leaders/21582516-worlds-thirst-oil-could-be-nearing-peak-bad-news-producers-excellent; Ed Morse, Citigroup, *Energy Outlook 2013*.

4 International Energy Agency, *Energy for All: Financing Access for the Poor*, October 2011, http://www.iea.org/publications/freepublications/publication/weo2011_energy_for_all.pdf.

5 International Energy Agency, *World Energy Outlook 2012*, November 12, 2012, http://www.worldenergyoutlook.org/publications/weo-2012/.

6 Elizabeth Rosentahl, "US to Be World's Top Oil Producer in 5 Years, Report Says," *New York Times*, November 12, 2012, http://www.nytimes.com/2012/11/13/business/energy-environment/report-sees-us-as-top-oil-producer-in-5-years.html.

highest since 1994 and is projected to reach 8 m/bd in 2014.[7] Natural gas production is 72 billion cubic feet per day (b/cfd), 40 percent of which is from shale. There are currently ample natural gas reserves to meet US demand for a hundred years. While the shale gas phenomenon, like the Internet, is now taken for granted, the rapidity of its increase, since roughly 2008, is a useful reminder of both how protracted is the process of commercializing technology and how swiftly innovation can transform reality when it achieves critical mass. Though shale gas and tight oil ramped up in 2007-08, the technology had existed for nearly a century. It was the combined public/private partnership of government-funded R&D from the 1970s and creative wildcatting entrepreneurs aided by tax credits and oil prices in the $85-$100 per barrel range that developed the commercially viable fracking technology which has scaled up and took off.[8]

Moreover, estimates of recoverable shale gas and shale tight oil continue to be revised upwards: the EIA has increased its estimate of recoverable shale gas reserves from 6.2 trillion cubic feet (tcf) in 2011 to 7.3 tcf in 2013. It also raised its estimate of recoverable tight oil by 1,000 percent, from 32 billion barrels (bb) to 345 bb![9] It is worth noting that shale technology continues to improve, with recent developments cutting required amounts of water in half, improving knowledge of shale composition, and increasing the production of shale gas and tight oil.[10]

The multidimensional consequences of the Shale Revolution are still unfolding. But shale gas and tight oil have already reshaped global energy markets, altered the US energy mix, enhanced US global competitiveness, reduced greenhouse gas (GHG) emissions, and started to change the geopolitical balance. The center of gravity of world energy markets is shifting from the Persian Gulf to the Western Hemisphere (US, Canada, Mexico, Brazil). This shift has already reduced US dependency on oil imports from 60 percent in 2005 to 39 percent in 2013 with prospects for US self-sufficiency on the horizon.[11]

The falling price of US natural gas to roughly $4 b/cf has enticed both US firms and foreign investors to relocate energy-intensive industries (e.g., chemical, biochemical, cement, steel) catalyzing a revival of US industry. Average gas prices are about $10 b/cf in Europe and $16 b/cf in Japan. The cost competitiveness of US gas has driven a shift from coal-produced electricity to gas. Prior to the shale boom, coal accounted for 50 percent of US electricity production, but plants have increasingly shifted to gas. Depending on price fluctuations, coal accounts for roughly 39 percent of US electricity production and with gas growing to 32 percent. This shift, combined with the recent economic slowdown has led to a 12 percent drop in US greenhouse gas (GHG) emissions since 2007, a twenty-year low, achieving roughly 70 percent of Kyoto treaty goals, though the US has not ratified the treaty.[12]

Globally, the Shale Revolution has put the US in a position to challenge OPEC control of oil markets and to open the prospect of the United States becoming a major exporter of liquefied natural gas (LNG) in a burgeoning global LNG market over the coming decade. This prospect, now being debated in Congress would bolster the US position in Asia (Japan, South Korea and Taiwan are major gas importers), and, potentially, in Europe at the expense of Russia, Iran, and Qatar, the world's major gas producers up until now.

Strategically, it may bolster the US "rebalance" in Asia as well as spark a rethinking of US Middle East strategy.[13] Moreover, the diffusion of fracking

7 Ibid.

8 For a detailed analysis of the US government role in the Shale Revolution, see Alex Trembath et al., *Where the Shale Gas Revolution Came From* (Oakland, CA: Breakthrough Institute, May 2012), http://thebreakthrough.org/blog/Where_the_Shale_Gas_Revolution_Came_From.pdf.

9 US Energy Information Administration, *Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States* (Washington, DC: US Department of Energy, June 2013), http://www.eia.gov/analysis/studies/worldshalegas/pdf/fullreport.pdf?zscb=45945407.

10 Brian Westenhouse, "New Fracking Technology to Bring Huge Supplies of Oil and Gas to the Market," OilPrice.com, January 16, 2012, http://oilprice.com/Energy/Natural-Gas/New-Fracking-Technology-to-Bring-Huge-Supplies-of-Oil-and-Gas-to-the-Market.html.

11 US Energy Information Administration, "How Dependent are We on Foreign Oil?" May 10, 2013, http://www.eia.gov/energy_in_brief/article/foreign_oil_dependence.cfm.

12 See Andrea Thompson, "US Gas Emissions Drop 3.8% in 2012," Yahoo News, October 22, 2013, http://news.yahoo.com/us-carbon-dioxide-emissions-drop-3-8-percent-141555854.html; Julie M. Carey, "Surprise Side Effect of Shale Gas Boom: A Plunge in US Greenhouse Gas Emissions," *Forbes* online, December 7, 2012, http://www.forbes.com/sites/energysource/2012/12/07/surprise-side-effect-of-shale-gas-boom-a-plunge-in-u-s-greenhouse-gas-emissions/; US Energy-Related Carbon Dioxide Emissions (Washington, DC: US Energy Information Agency, October 2013), http://www.eia.gov/environment/emissions/carbon/.

13 For discussion of geoeconomic and geopolitical shifts driven by the shale boom, see Amy Myers Jaffe and Ed Morse, "The End of OPEC,"

technology globally to areas such as China, Australia, and Central Europe over the coming decade may further transform the energy landscape, significantly reducing CO2 emissions. China, for example, is dependent on coal for roughly 70 percent of its electricity. If China—which has even larger potential shale gas reserves than the US—substituted shale gas for coal to produce electricity, it would be a substantial step towards mitigating global warming.

Gas Still a Bridge Fuel, but a Long Bridge

However, the Shale Revolution it is not moving us beyond dependence on fossil fuels, and is very unlikely to do so by 2030. Gas should still be viewed as a bridging technology, albeit, a bridge for longer than many imagined. The US and global energy systems have yet to see a clear outline of the kind of qualitative transformation discernible in the IT-based Third Industrial Revolution (see Section IV on pp. 15) with new materials, 3D printing, artificial intelligence, robotics, nanotech and biotech all beginning to reshape a knowledge economy.

There remain questions about both the environmental impact and longevity of the shale boom. Legitimate concerns over methane leaks, water pollution and minor earthquakes are still being examined. Such concerns have discouraged several states including New York, Colorado, and California, along with a number of European countries from permitting fracking. If not addressed by energy firms and regulators, this risk factor could undermine the Shale Revolution. Recent studies suggest, however, that the adoption of best practices by companies engaged in fracking have the potential to ameliorate most concerns. In regard to the longevity of shale production, many experts foresee the possibility of rapidly declining shale production from 2030 or sooner.[14] **Because of the stakes involved for US strategic interests, we recommend a bipartisan national commission comprised of scientists and engineers, energy companies, state regulators, and environmental groups be appointed to develop proposals for minimizing risks and harmonizing regulations.**

Of course, a broad array of innovative energy technologies other than fracking has been percolating for several decades, with the potential to transform global energy systems in other ways. Continuing improvements in the efficiency and cost competitiveness of renewables such as wind and solar energy, qualitatively improved energy storage, new materials, biofuels, nuclear technology, and carbon sequestration (that could make coal a clean technology) are prominent in the portfolio of emerging technologies. It is, however, an open question to what extent the United States or other major consumers such as Europe, China, and India will transform their energy systems with such alternatives by 2030.

To grasp the challenge of transitioning to more sustainable and less carbon-based energy systems, disaggregating current energy use is a good starting point. At present, the breakdown of energy use in the United States and most major economies is roughly 28 percent for transportation, 31 percent for industry, and 41 percent for buildings. Transforming the current energy system to a post-hydrocarbon-centered system will require the electrification of transport, qualitatively improved energy storage capabilities, and a smart grid powered by clean energy (some combination of wind, solar, nuclear and/or nuclear fusion, hydro, geothermal and/or other renewable sources).

Prospects for the Electrification of the Transportation Sector

The probability of a complete transformation away from fossil fuels in the transportation sector by 2030 is small. But incremental progress toward such a transformation is already discernible and gaining momentum. In the realm of transport, high gasoline prices and increasingly demanding Corporate Average Fuel Economy (CAFE) standards are driving change. CAFE standards for 2013 average 29 miles per gallon (mpg), gradually increasing to 35.5 by 2016 and to 54.5 mpg for 2025 model automobiles, shaping the pace of change. In the near term, there is growing interest, particularly by commercial trucking interests and fleet vehicles (e.g., buses, taxis, government fleets) in converting to natural gas. This has begun to occur on a modest scale among truckers and local fleets. Efforts to develop competitively priced non-food based, or second generation biofuels such as cellulosic biomass (e.g., organic waste) or bioengineered algae have not yet proven able to scale up to compete with gasoline or natural gas.

Foreign Policy, October 16, 2013, http://www.foreignpolicy.com/articles/2013/10/16/the_end_of_opec_america_energy_oil.

14 "Scientists wary of shale oil and gas as US energy salvation," *Energy Daily* online, October 29, 2013, http://www.energydaily.com/reports/Scientists_wary_of_shale_oil_and_gas_as_US_energy_salvation_999.html.

Looking to 2030, the most likely path to transforming the transportation sector beyond hydrocarbons appears to be largely a question of the pace and scope of the electrification of transport. This process is already well underway, though still at a slow pace. The past decade has witnessed a tremendous shift from early adapters to mainstream consumers driving hybrid electric vehicles (HEV) with both an internal combustion engine and battery propulsion. Since Toyota introduced the Prius in the US market at the beginning of this century, there are now roughly three million hybrids in the US fleet, with all major Japanese and US automakers offering hybrid models. A variant of the post-hydrocarbon vehicle is the hydrogen fuel cell auto, which also has zero emissions, but which has yet to see commercial success.

More recently, several automakers (e.g., Toyota and Chevrolet) have introduced plug-in hybrid electric vehicles (PHEVs) like the Prius and the Volt, which are still at the early adopter stage, and several companies (e.g., Nissan and Tesla) have put full battery electric vehicles (BEVs) on the market. The challenge for gaining popular acceptance of both PHEVs and BEVs involves reducing the cost and size of the batteries, increasing their range and performance, and, perhaps most importantly, establishing an infrastructure for easily charging the vehicles. Putting in place a large number of easily accessible charging stations and the standardization of the costs and rules for use by electric vehicle (EV) owners are all looming issues that localities, state utilities, and the federal government are only beginning to sort out.[15] Some auto companies have begun renting or selling, but fuel cell vehicles are still at the very early adapter stage, and fuel cell cars have their own problems of infrastructure and hydrogen fuel commercial availability.

To reach price competitiveness with advanced internal combustion vehicles, a *McKinsey Quarterly* analysis argues that the price of a complete lithium battery pack would need to fall from its current \$500-\$600 level per kilowatt hour (kWh) to about \$200 kWh by 2020 and to about \$160 by 2025.[16] In addition, significant improvement in longer ranges for battery performance and an infrastructure convenient to consumers would almost certainly need to be part of a formula for all-electric vehicles to gain acceptance and reach a scale of use to displace current internal combustion engines and hybrids.

Only Incremental Progress on Energy Storage

Key to wider adaption of both electric vehicles and renewable energy such as wind and solar are breakthroughs in the efficiency, cost–effectiveness and capacity to store energy. Despite billions of dollars spent in both government and private sector R&D over more than two decades, to date only incremental progress has occurred. For example, the widely used rechargeable lithium ion batteries for autos or smaller devices such as laptops or cell phones have gotten cheaper and relatively more capable. There is a wide range of R&D on new materials and techniques for energy storage such as ultracapacitators to commercialize less expensive, more efficient storage technologies. Some are looking to new nano-manufactured materials such as graphene to replace lithium ion with faster, more efficient storage. The emerging area of synthetic biology is also considered a prospective source of new energy storage techniques. But energy storage has not yet seen the sort of breakthrough that will allow it to become qualitatively smaller, faster, cheaper by an order of magnitude to transform energy systems.

More broadly, to transform our energy system to a post-hydrocarbon world requires enormous changes not only in the sources of electricity, but also in the way it is used and distributed. The modernization of the US energy grid, much of which is nearly a century old, into a smart grid is a critical part of that transformation.

A smart grid is the digitization of utility electricity delivery systems, bringing them into the twenty-first century, using computer-based remote control and automation to provide real-time communication on supply and demand between the producers, the grid and consumers. These systems simply require the deployment of information technology that has become the lifeblood of the modern knowledge economy. Most of the devices utilities have used to provide electricity have to be monitored individually to check meters and voltage or fix equipment. Smart

15 For a detailed discussion of these issues, see the report on the MIT Energy Initiative Symposium on the Electrification of the Transportation System, April 8, 2010, http://mitei.mit.edu/system/files/electrification-transportation-system.pdf.

16 Russell Hensley, John Newman, and Matt Rogers, "Battery Technology Charges Ahead," *McKinsey Quarterly*, July 2012, http://www.mckinsey.com/insights/energy_resources_materials/battery_technology_charges_ahead.

A wind farm in Maui provides a glimpse into a post-hydrocarbon future. Photo Credit: Banning Garrett.

grids would all be automated and computerized. The grid is a network consisting of wires, substations, transformers, and switches that carry electricity from the plants where it is generated to consumers.

Smart grids are slowly beginning to take shape worldwide. In the US, progress varies from state to state. States like California with aggressive renewable standards (a target of 33 percent renewable energy by 2020) are further along than others. But renovating the US grid infrastructure is a long-term process requiring public/private sector collaboration between the federal government, states, and municipalities over a protracted period. The federal government invested $11 billion in the 2009 financial bailout legislation, but utilities will need to invest between $17-$24 billion annually over the next two decades. Such investment, a study by industry-backed Electric Power Research Institute (EPRI) suggests, would provide up to $2 trillion in benefits to utilities and consumers in increased efficiencies.[17]

A smart grid combined with improved storage would bring new efficiencies to both consumers and utilities. The provision of electricity could more easily be a two-way street. Wind and solar energy are intermittent technologies whose utility beyond the immediate generation of energy requires storage capacity. Similarly, electric and plug-in hybrid autos or even energy efficient "smart" office buildings could send energy back to a grid, charging at night when use is low and sending energy to the grid at other times. The most probable outcome by 2030 is a piecemeal smart grid, possibly complete in states and regions. But on a national scale, barring greatly stepped-up policy intervention and government funding, a full-fledged operational smart grid would still be a work in progress. **We believe the construction of a smart grid should be a national priority.**

Related to the smart grid is the smart building, which utilizes IT networks, data, and sensors to maximize efficiency of heating, cooling and lighting that can reduce energy use by 30 percent or more. Solar paneled buildings or homes, for example, achieve net zero energy use by selling energy to a smart grid. Given that home and office buildings consume 71 percent of electricity, smart buildings could reduce the cost of operating and reduce pollution, providing multiple benefits to urban areas. But as with the smart grid, public support for investments to transform energy systems can be an impediment. Consider that while light emitting diode (LED) light bulbs are forty times more efficient than traditional incandescent bulbs and six times more efficient than compact fluorescent bulbs, even as prices for LED bulbs have dropped precipitously, consumers have been slow to switch to LED.

17 "US Smart Grid to Cost Billions, Save Trillions," Reuters, May 24, 2011, http://www.reuters.com/article/2011/05/24/us-utilities-smartgrid-epri-idUSTRE74N7O420110524.

An Uphill Struggle for Clean Energy Sources

Despite rapid growth in deployment and steadily declining costs, solar and wind energy account for barely 1 percent of US energy use. Since 1980, radical improvements in photovoltaic technology such as thin-film solar have increased the conversion efficiency of solar power from 5 percent in 1980 to over 30 percent currently. Similarly, the cost of wind power installation has fallen by some 65 percent since 1980. Both are fast-growing sources of electricity, but from very low bases. The cost of coal and natural gas is in the 3-5 cents per kWh range, while wind is in the 6-8 cents range and solar energy 16-20 cents.

Wind technology has also seen steady improvements in efficiency. But while wind still requires subsidies to compete, it has grown substantially and currently provides nearly 5 percent of US electricity. According the Department of Energy, fifteen states have installed over 1,000 MW of wind capacity, nine states rely on wind for 12 percent of electricity, and a total of thirty-nine states now have installed at least some utility-scale wind power.

By 2030, wind and solar are likely to be more substantial portions of the US energy mix, but barring major breakthroughs ramping up efficiency and the deployment of a smart grid, these intermittent sources of energy will remain overshadowed by natural gas and nuclear energy, which currently supplies 20 percent of US electricity.

There are intriguing technologies in development that could alter the energy landscape. For example, carbon capture and sequestration (CCS) technology which prevents CO2 emissions from entering the atmosphere, in effect, turning coal into a clean energy source, exists today. If it were cost competitive, it could be a game changer not only for energy markets, but for combating climate change. However, analysts suggest that scaling up CCS to deploy for most US and international coal production is impeded by cost and a need to perfect and lower the cost of coal gasification. Most estimates project that commercial scale CCS is unlikely to become a real possibility much before the 2025-2030—if then. In the interim, the conversion of coal plants in the United States to natural gas casts a dark shadow over the future of coal production.

Similarly, there is a range of R&D in the realm of civil nuclear power, from smaller modular plants to a Department of Environment (DoE)-backed "Gen IV" new model nuclear reactor. DoE is organizing a coalition of partner countries to undertake the necessary R&D for these new nuclear reactor designs. Longer-term, there is the International Thermonuclear Experimental Reactor (ITER), an $18 billion multinational effort by the US, EU, Russia, China, South Korea, and Japan to create nuclear fusion technology. The standing joke for several decades has been: we are only thirty years away. Still more out-of-the-box, Bill Gates is a major investor in a firm called TerraPower which is trying to build a new type of reactor that would be fueled from nuclear waste, making it both proliferation-resistant and solving the still looming problem of disposing of that waste.[18] But none of these nuclear technologies is anticipated to be close to commercial viability by 2030.

No Near-term Breakthrough Likely

Many of the technologies discussed above will likely not redraw the energy landscape by 2030. But they are mentioned to provide a glimpse of the enormous ferment in the realm of new energy technology research. It is impossible to predict which of the numerous technologies may provide the strategic surprise and transform the energy world by 2030. But it is also difficult to believe, for example, that among the legions of researchers trying to create a breakthrough in energy storage, none will succeed.

In the 2030 timeframe the pace of change may accelerate and the internal combustion energy may be superseded by the full electrification of transport. Similarly, efforts to create smart grids in the United States and elsewhere may be accelerated. But for the foreseeable future, if there is a disruptive technology in the energy realm, it will continue to be the Shale Revolution.

18 Matthew L. Wald, "Atomic Goal: 800 Years of Power from Waste," *New York Times*, September 24, 2013, http://www.nytimes.com/2013/09/25/business/energy-environment/atomic-goal-800-years-of-power-from-waste.html.

III. The Urban Story: Smart Cities Leading the Way

"Technology and urban futures are now inextricably linked and will remain so if cities are to remain vital, sustainable and adaptable to changing societal needs." —Joseph N. Pelton, author of Future Cities

Cities are the key to every nation's future, from GDP growth to health, education, innovation, and national power. How urbanization processes are managed will determine whether the global war for sustainability and resiliency is won or lost. How cities are managed will go far in determining the shape of global governance and security, for effective management can turn cities into either sources of national and global governance success and security or sources of failure and instability. These are no idle claims, as more than half of all people on Earth now live in cities. Going forward, the world's urban population will continue to expand, to 60 percent of humankind by 2030 and 70 percent by 2050. If demographics is destiny, then cities must become central focal points for policymakers and other leaders who are trying to manage twenty-first century global challenges. These challenges range from the ecological (natural resource scarcities, climate change mitigation and adaptation) to the economic and technological (innovation and employment) to the political (effective governance).

Most of these challenges have important ties to urbanization, many related in one form or another to urban poverty and urban wealth. The world's slums, where more than a billion people now live, are sites of hunger and malnutrition, communicable diseases, energy poverty, social and political exclusion, and crime and physical insecurity. Over time, however, as the urban poor begin to enter the middle class, new types of problems arise. The rapidly growing global urban middle class is largely responsible for the world's high carbon emissions, air, water, and soil pollution, and most critically the side effects resulting from high consumption lifestyles. The rise of China's middle class over the past two decades is the quintessential example of this scaling problem. For the world going forward, the central dilemma is how to create cities that are sources of social and political stability and inclusive economic opportunity while being, at the same time, sources of constant ecological innovation.

While the world's urban problems are daunting, policymakers should understand that there is enormous opportunity in developing solutions to meet these problems. Cities concentrate people, buildings, infrastructure, and institutions into small physical spaces. Cities therefore are fiendishly complex. Yet this complexity is also a virtue, as the density of people, structures, and infrastructure presents opportunities for finding intersectoral solutions to social, political, economic, and ecological challenges. Viewing cities in this light enables problems to be recast in a different frame. Whereas certain types of global challenges appear to be both separate and intractable, viewing these same problems through an urban lens enables them to be seen as interconnected problems possessing interconnected solutions.

Solving the challenges presented by global urbanization will require the development and scaling of a wide range of emerging technologies. Urban systems frequently contain the latest in technical innovation, although to stay abreast of rapidly changing conditions and to prevent decay from overuse, these systems in turn need to be rebuilt and upgraded. To function optimally, however, urban systems also require paying close attention to how people living in cities actually use them. The most effective urban technical systems combine high-tech solutions with low-tech or even non-tech solutions that incorporate insights developed by people who are neither scientists nor engineers, including architects, urban planners and designers, activists, and ordinary citizens. Bike-sharing systems are a good example in that they marry a technology developed in the nineteenth century (the bicycle) with modern information and communication technologies (ICT) such as the smart phone and the Internet. When bike-sharing systems are designed properly (the bicycles are durable, the stations are attractively designed, etc.,), they produce a form of low-carbon urban transport that contributes to the health and well being of the city's residents.

Singapore's solar-powered super trees demonstrate the use of high tech in urban spaces. Photo Credit: Banning Garrett.

Cities therefore can be thought of as meta-systems, meaning that they contain overlapping human-technical systems—energy systems, water and sewage systems, communications systems, transport systems, and so on—that are in turn concentrated into small spaces. By definition, scientific and technological innovation is indispensable for improving conditions in cities and, by virtue of humankind's evolving demography, for the world as a whole. There is a nearly endless list of emerging technology applications for cities as illustrated in the box on the following page. Ongoing technical innovation is central to urban security and resiliency, governance, climate change and the food/water/energy nexus, urban transportation, public health, and a host of other domains. We see two areas, in particular, where emerging technologies will help solve both critical urban problems and larger global ones. On the local level, smart cities can significantly improve urban governance while help with climate change and the natural resource challenges on the broader level.

The Smart City Concept

Although the notion that cities can be made "smarter" through technological innovation is a fairly recent one, the "smart city" concept is now standard thinking. The central idea behind the smart city concept is that ICT can be harnessed to dramatically improve how cities work and function. While the "smart city" concept is now in use by many companies, cities, and institutions for their own purposes, the concept's simplest definition is of a city that leverages ICT to maximize citizens' economic productivity and quality of life while minimizing resource consumption and environmental degradation.

Smart cities improve governance by taking advantage of the enhanced data collection, information exchange, and automation that modern communication technologies enable. Local governments integrate advanced ICT capabilities into urban planning, resource management, physical and communications infrastructure, building design, transportation systems, security services, emergency services, and disaster response systems.

This enabling function is an important contribution to urban governance, for ICT can be used to enhance nearly every type of good or service. So-called "e-governance" systems are the most obvious and widely used applications of ICT to urban governance, wherein government functions are put online in order to streamline processing times while reducing costs. Many other applications marry ICT with physical systems in order to enhance performance or even to create new types of systems. A city's public transport system, for instance, benefits from ICT applications that can improve scheduling, notify

Urban Applications for Emerging Technologies

Security and Resilience

- Disaster resilience—e.g., flood control systems, earthquake resilience technologies, heat wave resistance technologies
- Protection of cyber infrastructure using advanced algorithms and other strategies
- Technologies for hard infrastructure protection
- Technologies and technical systems for integration into antiterror strategies – surveillance and monitoring, post-disaster communication and coordination response capabilities, etc.

Governance

- Innovations in information and communications technologies (ICT) for "Smart Cities" governance include Internet-based and cloud computing architecture, big data analysis, and development of urban "dashboards" for coordinated and real-time management
- Social media innovation for citizen participation in governance
- Sensor development (leading to an urban Internet of Things)

Climate Change and the Food-Water-Energy Nexus

- Low-carbon urban energy production—solar photovoltaic (PV), wind turbines, advanced nuclear power generation
- Distributed energy technologies—smart grids, distributed power generation
- Energy efficiency technologies—e.g., green building technologies
- Scaled urban food production—vertical farms, aquaponics, bio-printing of meat
- Fresh water conservation and management—e.g., lower-cost materials for piping infrastructure, green infrastructure innovation
- Desalination technologies
- Water reuse technologies
- Pollution control and waste management
- Multi-material recycling
- Solid waste and human effluent control and recycling
- Air and water pollution control technologies

Transport

- Smart roadways and other transport infrastructure
- Autonomous vehicles
- Emerging technologies for application to public transit, intercity rail transport, personal vehicles, human-powered transport, etc.

Public Health

- Technologies for basic healthcare delivery—sanitation, clean drinking water, indoor and outdoor air pollution control, innovative medicine delivery systems, etc.
- Emerging technologies for advanced healthcare—e.g., information technology applications, disease management technologies, robotics, and human augmentation technologies

Other

- Housing innovation—e.g., healthy and low-cost housing innovation for the urban poor
- Twenty-first-century education systems using ICT
- Advanced manufacturing systems for small-scale factory production

**Special thanks to Tom Campbell for his contributions on this box.*

Addis Ababa faces challenges of rapid urbanization. Photo Credit: Banning Garrett.

users of route changes and delays, and provide other logistics enhancements. The smart grid would have particular relevance for urban areas because of growing electricity demands in cities and necessity for providing adequate and continuous supply. The most far-reaching vision of the smart city integrates multiple urban systems into a single, coherent, and seamless operating environment to provide management tools for real-time decision-making. Under this vision, an army of sensors, whether embedded in a city's buildings and infrastructure or carried around by citizens (e.g., GPS signals sent from cell phones), would utilize digital networks to stream data for computer processing, display, and decision making. Algorithmic processing of real-time data can provide some automatic responses to the raw data inputs (smart grids, for instance, would monitor and manage energy flows throughout the network without direct human input), while integration of digital streams onto virtual "dashboards" would provide city leaders with the real-time information and visualization tools required to manage complex and variable conditions, such as occurs during natural disasters.

Solving Natural Resource Challenges

While ICT enables urban systems to operate more effectively and efficiently, ICT by itself will not be sufficient to solve the myriad challenges presented by global urbanization. Rather, other emerging technology breakthroughs are going to be required to effectively address these challenges posed by climate change and natural resource scarcities. We will have to develop and implement, at scale, a swathe of technological enhancements to cities' many overlapping systems in order to make cities more sustainable and resilient. Cities are where much of the climate change battle is going to be won or lost. On the mitigation side, cities produce most of the world's carbon dioxide; on the adaptation side, cities are where climate change's worst effects will be felt the most. Reliable access to food, water, and energy will be critical to the functioning of ever bigger and more complex cities.

Urban "greentech" illustrates the challenges but also the opportunities that are inherent in cities. For instance, buildings account for perhaps 41 percent of the world's energy demand and 71 percent of electricity use. Architects and engineers involved in the green building movement want to reduce the absolute amount of energy and water that the buildings themselves consume while maintaining or improving the services (light, heating, cooling, shelter, and aesthetics) that the buildings provide to inhabitants. In designing green buildings, architects and engineers merge high technology, low technology, and insights from ecology, architecture, and landscape architecture to produce designs that can reduce a building's energy consumption to zero. Some buildings can even produce more energy than they consume. The green building idea has become a global norm within a short period of time, and green building codes are now mainstream in the architectural profession.

In the coming decades, the green building field may benefit from emerging technologies to produce incredibly resource-efficient and resilient structures. One such technology is the protocell, which is a form of synthetic biology that enables designers to mimic the behavior of living organisms. While protocell applications are some years away, designers argue that protocell-based materials might enable building exteriors to interact with natural surroundings, similar to the function of skin in modulating between a person's insides and her immediate surroundings. These protocell-based building exteriors could be designed to filter and purify airborne pollutants, capture and retain excess rainwater until needed, or modulate sunlight so as to help keep building interiors at optimum temperature and lighting conditions. **We could help accelerate adoption of these technologies by creating a national green building code with world-class energy and water efficiency performance standards. The United States also has a huge opportunity to sell these urban technologies to the rapidly growing cities in the developing world.**

A similar story can be told for urban-based technologies overcoming natural resource constraints. As is true of green buildings, the scientists, engineers, technologists, and urban designers who are exploring solutions are marrying emerging technologies with designs that are appropriate for city spaces. The idea behind the vertical farm is to produce a lot of food on a very small parcel of real estate by stacking greenhouses one on top of the other. This simple idea makes larger-scale urban agriculture possible, but technologies such as genetically modified organisms (GMOs) could dramatically accelerate the amount and quality of food that vertical farms can produce going forward. GMOs, grown in perfect conditions (sterile and invariant conditions with exact lighting, for example), could produce extremely high yields all year round. Aquaponics—the marriage of fish farming (aquaculture) with plants grown in water (hydroponics)—is an analogous idea. Here, aquaponic farms located on rooftops and other urban spaces can produce high-quality food. As with vertical farms, the idea is a simple one that can benefit from emerging technologies in order to create high-volume and high-quality food production.

Farther afield is the idea of bioprinting of meat, which attempts to cultivate in-vitro meat from stem cells. While the technologies involved are highly complex, the underlying purpose is very simple: to eliminate the need to use an animal in meat production. If successful, meat bioprinting not only would eliminate animal suffering, but also reduce the energy, feedstock, and water inputs necessary to raise domesticated animals. The technology's advocates contend that these resource savings would be enormous—over 90 percent water and energy savings, for instance. As with vertical farms and aquaponics, meat bioprinting would enable food production to be brought into cities, where most food is consumed.

Technology's Risks and Opportunities in the Urban Setting

The biggest risk is that we will not identify, adapt, and scale the most promising technologies for use in the world's cities. If the world's rapidly growing megacities do not use technology to deal with the crush of ongoing problems or the new technologies are not deployed effectively, the unstoppable mass urbanization we are witnessing might turn into an urban nightmare. This logic also holds true for rich cities that are not growing rapidly, for these cities need to be redesigned and rebuilt using emerging technologies in order to make them more sustainable, resilient, inclusive, and prosperous. Cooperation and the sharing of best practices between cities could be a driving force for widespread innovation and adoption of new technologies and practices. An increasingly self-aware and assertive form of locally-based global leadership has developed, such as exists with "C40"—a global intercity institution dedicated to solving climate change problems through dialogue and transfer of best practices.

For cities built from scratch or needing to be rebuilt, the major difficulties will involve the enormous scale, complexity and costs of new technologies. Much of the challenge will not be scientific or technical in nature but political, economic, and cultural, wherein obstacles such as policy road blocks, poor financing mechanisms, a lack of awareness of emerging technologies, and cultural, social, and consumer resistance to new technologies form major impediments.

Yet there are real potential downsides to emerging urban technologies. One significant hurdle involves

Trams link Favelas to mainstream urban life in Rio de Janeiro. Photo Credit: Banning Garrett.

the rationalization of urban complexity. As meta-systems, cities are already exceptionally complex "systems of systems." To date, most cities have managed individual systems such as sewer and water or electrical grids in stovepiped fashion. In theory, the smart city paradigm overcomes this stovepiping through digital networking, but in practice, there are enormous technical and organizational hurdles involved in coordinating, managing, and securing information coming from so many data sources.

For example, consider the technical coordination challenges in just one arena, urban road transport. Here, the goal is to integrate in-vehicle and roadside ICT into a networked system that would facilitate traffic movement and safety. However, doing so effectively will require the integration of millions of individual ICT systems using different in-vehicle technical platforms, all moving at speed. Managing this system effectively while ensuring data security and integrity is not a given. Moreover, no technology can be implemented in a vacuum. Even the smartest of smart city applications must integrate raw data into analytic processing, communications, and decision making; these steps necessarily involve multiple, overlapping jurisdictions and institutions that involve human decision-makers.

A related and obvious problem involves creating or magnifying system vulnerabilities in pursuit of the seamlessly functioning smart city. While networking data across millions of individual users and devices (sensors, in-car applications, smart phones, etc.) has many benefits, one major downside is increasing exposure to data security and privacy breaches. Such breaches can occur through deliberate and malevolent means (hacking, spoofing, etc.) or through unforeseen accidents, disasters, power outages, and other events.

A final word of warning about urban technology—and about technology in general—concerns unintended consequences. The modern history of cities includes examples of emerging technologies that have been created and scaled to meet and overcome one set of problems, only to create another set of challenges. During the first half of the twentieth century, for instance, the automobile came to be seen as a means for addressing some of industrialization's major headaches, including the congestion and public health problems existing in densely-packed industrial cities. Many believed that motorization would enable people to lead healthy lives in far-flung suburbs while speeding rapidly between destinations. They did not foresee the chronic traffic jams, high resource consumption, and pollution problems that this solution would create later in the century. Such second- and third-order effects are an omnipresent byproduct of technological innovation, and while such effects likely cannot be avoided, they should at least be considered in advance.

IV. The Third Industrial Revolution

"The digitisation of manufacturing will transform the way goods are made—and change the politics of jobs too." —The Economist*, April 21, 2012*

A Third Industrial Revolution (TIR) is emerging that will transform not just production but society itself. The first industrial revolution was the application of steam power to production processes in the eighteenth century; the second was the invention of the modern assembly line at the beginning of the twentieth century.[19] Like its predecessors, TIR is changing the way things are made, where and when they are produced, and how they are distributed. It is reducing the energy and raw materials consumed and the carbon footprint of manufacturing. It is changing social relations, creating but also destroying jobs, and altering the relationship of people to production. It is moving the world from mass production of standardized items to bespoke products to meet the requirements of individual needs. It is also transforming the global economy, providing new opportunities for the developing as well as developed world, and costs if nations don't adapt.

The TIR is as much about the combination of and synergy among technologies as it is about the products or machines themselves. It has been enabled by the innovative application of decades of developments in ICT and artificial intelligence, as well as by big data and algorithms, the emerging Internet of Things, and new materials development through nanotechnology.

The TIR involves not just a different way of using raw materials—steel, aluminum, plastic, and other materials—and fashioning them into different material objects. Rather, it also includes the materialization of digital information. A computer-created design or a scanned physical object can be converted from digital bits to material atoms. And this can be done remotely, with the digital file for the 3D object sent over the Internet and rematerialized anywhere in the world, like we have all experienced with a PDF file sent to us that we have printed out in three dimensions.

The TIR is also raising the age-old question of whether new advances in technology will eventually create a myriad of new jobs and more widely distributed wealth, as has been the case in the past, or will new technologies lead to long-term structural unemployment, exacerbating already high levels of inequality and potentially sparking social instability. Alternatively, by mid-century, will the increased productivity of the global economy create abundance with fewer workers enabling a transformation of global society in which poverty is virtually eliminated and social goods production is well rewarded, decoupling income from traditional market dynamics?

From Mass Production to Bespoke Customization

The Economist has hailed 3D printing as the foundation of the TIR.[20] The basic 3D printing technology was invented some three decades ago, but it has reached a take-off point as other technologies have combined to enhance the capability and reduce the cost of 3D printing, which is a seemingly simple process of layering to make things ("additive manufacturing," the more formal term for 3D printing) rather than carving them out of pieces of material (or "subtractive manufacturing").[21] This takeoff has been enabled by computer-aided design, big data and cloud computing, new materials, and reductions in the costs of many of these capabilities as well as of the printers themselves.

The 3D printing revolution is happening from both the "top down" and the "bottom up." Leading

19 There are different views on stages of the Industrial Revolution. Peter Marsh of the *Financial Times* maintains that we are now entering the fifth industrial revolution. See Marsh, *The New Industrial Revolution: Consumers, Globalization and the End of Mass Production* (New Haven and London: Yale University Press, 2012), chapter I.

20 "Special Report: Manufacturing and Innovation," *Economist*, April 21, 2012, http://www.economist.com/node/21552901.

21 For more background on how 3D printing works, see Thomas Campbell, et. al., *Could 3D Printing Change the World? Technologies, Potential and Implications of Additive Manufacturing* (Washington, DC: Atlantic Council, October 2011).

global manufacturers such as EADS, GE, Boeing, and Ford are using high-end 3D printing machines to transition from rapid prototyping to producing critical parts for airplanes, automobiles, wind turbines, and a myriad of other machines. From the bottom up, the 3D printing revolution has been driven by the "do it yourself" (DIY) movement with tens of thousands of early adopters buying personal 3D printers for experimentation or starting their own mini-manufacturing enterprises. And increasingly, small- and medium-sized businesses are using 3D printing machines as well.

There is a reason so much attention has been focused on 3D printing, although other advanced manufacturing capabilities are also contributing to the TIR. 3D printing is a transformative technology that offers extraordinary structural benefits over traditional manufacturing.[22] In traditional manufacturing, the more complicated a product, the more expensive it is to manufacture—if it is even possible to make it at all. By contrast, 3D printing is a "single tool" process—no matter the desired geometry, there is no need to change any aspect of the process.

Since 3D printing one-of-a-kind products is no more costly than mass-producing the same object, 3D printing technology enables the design and efficient manufacture of personalized products. This unique capability of 3D printing is driving a transition from mass production to mass customization. Initially, 3D printing was referred to as "rapid prototyping," and was primarily used to quickly fabricate conceptual models of new products for form and fit evaluation. But the application of 3D printing technologies has evolved from solely creating prototypes to fabricating parts for functional testing, to creating tooling for injection molding and sand casting, and finally, to directly producing end-use parts.

3D printing is a "platform technology" that is likely to be used in an enormous range of applications, from printing human organs and food to printing airplane wings and large structures, including houses, large buildings, and even bases on the moon and Mars. NASA recognizes 3D printing as a critical technology for space exploration. The space agency has already commissioned the development of 3D printers for the International Space Station (ISS). While the first ISS 3D printers will be used for printing spare parts,[23] NASA has also commissioned development of 3D printers for food and for building structures on the Moon,[24] and is exploring concepts for using 3D printers to fabricate large-scale structures in space with minimal amounts of materials.

3D printing could be especially transformative in the developing world. Many emerging market countries, especially in Africa, do not have significant manufacturing capabilities and rather rely on massive imports, including of basic consumer goods. They also have large numbers of unemployed, many with sufficient education and entrepreneurial drive to build new businesses around 3D printing. The cost of establishing a basic 3D printing facility—a computer, printers, materials and Internet access—is significantly less than $10,000, while building a conventional factory might require millions of dollars of investment. Unlike a traditional factory, the 3D printing facility could produce an unlimited number of products without retooling, while in some cases using recycled materials, making products on demand for the local market, and requiring far less sophisticated and expensive infrastructures than those which serve factories in China. For some developing countries, 3D printing might be as economically transformative in the material world as the cell phone has been in the digital world, bringing them many of the benefits of advanced manufacturing. 3D printing could thus help countries leapfrog some manufacturing sectors and obviate the need for large manufacturing facilities in the developing world.

3D printing is likely to have a number of significant second-order effects on society, including moving designs, not products, around the world: The Internet first eliminated distance as a factor in moving information instantly across space. Now sending digital files over the Internet instead of making and shipping physical products has the potential to transform the distribution of material things much as MP3 technology has changed the distribution of music.

3D printing could reduce and even eliminate supply chains and assembly lines for many products. Manufacturing could shift from large-scale assembly

22 Hod Lipson and Melba Kurman, *Fabricated: The New World of 3D Printing* (Indianapolis, IN: John Wiley & Sons, 2013), pp. 20-24.

23 Made in Space, a Singularity University startup, has built printers that have passed all NASA tests for certification, and its first 3D printer is scheduled to be launched to the ISS in 2014.

24 Dina Spector, "In the Future, Astronauts Could Print Out Their Moon Bases," *Business Insider*, February 4, 2013, http://www.businessinsider.com/3D-printed-moon-base-2013-2.

Coming Soon: 4D Printing

On the horizon is 4D printing or "programmable matter," in which the fourth dimension is time. This will be a world in which 3D printing produces material objects that are programmed to change their form (shape) and function (capabilities) after they are produced and can even be commanded to disassemble into microscopic, "intelligent" particles or "voxels," and then reprogrammed to become entirely different material objects. The potential of voxels can be understood by analogy to biological life, which is composed of twenty-two building blocks[1]—amino acids that are directed by DNA to assemble themselves in widely differing permutations to create different proteins and eventually life forms. A relatively small number of types of voxels could assemble and disassemble themselves into objects in the non-biological material world, based on software that performed a programming function similar to DNA. "Just as amino acids are the low-level common denominator that enables nature to recycle materials perfectly, if all products would be made of a few dozen basic voxel types, products could be 'printed,' then decomposed, and reprinted into other products," according to Hod Lipson, Cornell professor of engineering, and Melba Kurman, a veteran technology writer.[2] While voxels do not yet exist outside of the laboratory, Lipson and Kurman foresee that eventually everyday objects might be made of billions of voxels.

Potential applications of programmable matter might include airplane wings that change shape in flight; buildings that transform as desired for different functions, conserving space, cost and the environment; infrastructural systems that adapt to loads or weather; furniture that is packaged flat but self-assembles after purchase; shoes, clothes and sportswear that adapts to the user's performance or environment; and objects that disassemble for protection of private information, recyclability, or self-repair.[3] Envisioning the effects of such technology on society is only just beginning. The emerging outlines of 4D printing's potential suggest a wide range of implications for security and the military as well as potentially transformative impacts on the economy and society.

1 Lipson and Kurman, p. 276.
2 Ibid, pp. 277-8.
3 Thomas A. Campbell, Skylar Tibbits, and Banning Garrett, "Beyond 3D Printing: Programming the Material World," forthcoming policy paper; Lipson and Kurman, pp. 275-281.

of thousands of parts produced by subcontractors into millions of final products by tens of thousands of workers at a few massive factory complexes, for example, to the on-demand printing of small numbers of those same products in thousands of locations near consumers around the world by a handful of workers at each local production facility.

3D printing is likely to play a significant role in economic and environmental sustainability by dramatically increasing the efficiency of resource use and in lowering overall carbon emissions, from the process of manufacturing to delivering products to the end user. Walmart estimates that 80 percent of its corporate carbon emissions are generated by its vast global network of suppliers, many of which also have their own supply chains. A huge increase in global resource productivity is also possible as only the material needed for the final part is used, reducing waste in the production process by 90 percent or more. 3D printing can also reduce or eliminate the use of toxic chemicals often used in conventional manufacturing processes.

The pace of development and implementation of 3D printing is, of course, uncertain, and is likely to vary widely for different types of manufactured products. Many consumer products will continue to be cheaper to mass produce by traditional methods and shipped to points of consumption, especially simple products produced in huge numbers—the result of decades of investment in that existing production and supply-chain infrastructure. Nevertheless, there will be tipping points in various fields of production, triggering manufacturers to adopt to the new process or lose their competitive edge. It will be an uneven process and will take many years longer in some sectors than in others.

3D Printing Life: The Synbio Revolution

Synthetic biology ("synbio") and bioengineering are an emerging factor in the TIR, building on the convergence of a wide-range of technologies leading to development of new, previously unimaginable technological capabilities. While there are a huge number of potentially beneficial products of the synbio revolution, there are also growing concerns about the potential for the bioengineering of deadly viruses by error or design.

In the new synthetic biology age, you will be able to edit DNA like software in a computer. Craig Venter, who led the private effort to map the human genome and created the first synthetic organism, has termed this "digital life."[25] The bioengineered digital file could represent the DNA of an existing organism or an altered form of that organism. It could also be an entirely new organism created from DNA building blocks such as BioBricks. BioBricks are DNA constructs of different functioning parts that can be assembled to create new life forms to perform specific functions.[26] Venter suggests such genetically engineered organisms can be created for biofuels, water purifying, textiles, food sources, and bioremediation.

A recent National Research Council (NRC) and National Academy of Engineering (NAE) report on synbio explained how this works.[27] According to the report, "synthetic biologists have the ability to design genetic code to elicit a specific function, pre-test the code for functionality using computer modeling, order the relevant genetic material from a commercial or open-source gene synthesis facility, and insert the material into a cell body in order to test real world functionality."

Perhaps even more astounding than the ability to digitize life is that this digital life can be transmitted over the Internet and the organism recreated anywhere on the planet. Or, Venter adds, digital life can be used to recreate organisms found on Mars by digitizing their DNA and transmitting the file back to Earth. And perhaps it might even be possible to send digital files of life-saving drugs to a future generation of human colonists on the Red Planet. Venter has created "biological converters" to receive and print the files. This process is like 4D but using organic rather than inorganic matter. The 4D process permits the printed organism not only to change form and function over time but in some cases to self-replicate. In a global pandemic, synbio could both greatly reduce the time required to develop a vaccine and then send the digitized vaccine sequence around the world to be bioprinted for immediate use.

There will be no need to build a new organism from scratch. The 3D/4D printing process allow the designer of a synbio product to work with pre-existing modules of the product. Synthetic biologists can work, for example, with BioBricks that can be bought and downloaded, each with a specific functionality. The building-block devised design can be sent to a bioprinter that will assemble the genetic material (like the plastics, metals, etc., in a conventional 3D printer) to create the new life form. The creator of the organism will not have to be knowledgeable about how each of the BioBricks works, just as the designer of a 3D printed object does not have to be a software engineer but only trained to use computer-aided design software to design the object and send it to the printer.

Synbio may have a massively transformative impact on the world, like the Internet and, soon, 3D/4D printing. Combined, these technologies will change what we can make, how we make it, where we make it, and what materials we use to make it. There is huge potential for sustainability (e.g., recycling amino acids). The word "organic" will have an entirely new meaning as structures will not only look more "organic" but also be made of organic materials. Drew Endy, a bioengineering professor at Stanford University, calculates that genetic engineering and synthetic biology already contribute about 2 percent to US GDP and predicts a near-term synbio-generated technological and economic boom comparable to the impact of the Internet earlier in this century.[28]

The ease associated with bioengineering—and the low cost and wide availability of materials and capabilities—is increasing concern about potential dangers posed by synbio, especially the ability to alter viruses to become more deadly or to create wholly new lethal microorganisms. Laurie Garrett, global health expert at the Council on Foreign

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25 Craig Venter, "J Craig Venter Sequenced the Human Genome. Now He Wants to Convert DNA into a Digital Signal," *Wired*, November 7, 2013, http://www.wired.co.uk/magazine/archive/2013/11/features/j-craig-venter-interview. Venter addresses this in greater detail in his new book, *Life at the Speed of Light: From the Double Helix to the Dawn of Digital Life* (New York: Viking, 2013).

26 The BioBricks Foundation (http://biobricks.org/) maintains a registry of a growing collection of genetic parts that can be mixed and matched to build synthetic biology devices and systems. BioBrick standard biological parts are DNA sequences of defined structure and function that share a common interface and are designed to be incorporated into living cells such as E. coli to construct new biological systems. Many of these parts are created through the International Genetic Engineered Machine Competition (iGEM) of young scientists and engineers.

27 National Research Council, *Positioning Synthetic Biology to Meet the Challenges of the 21st Century* (Washington, DC: The National Academies Press, 2013), 10.

28 Cited by Laurie Garrett, "Biology's Brave New World—Be Happy—And Worry," *Foreign Affairs*, November/December 2013, 36.

An Organovo bioprinter used for printing human liver tissue for toxicity testing. Photo Credit: Banning Garrett.

Relations, notes that "the world of biosynthesis is hooking up with 3D printing." Scientists in one city designing a genetic sequence on a computer can send the code to a printer somewhere else. The code might be the creation of a life-saving medicine or vaccine. "Or it might be information that turns the tiny phi X174 virus….into something that kills human cells, or makes nasty bacteria resistant to antibiotics, or creates some entirely new viral strain."[29] **A security strategy is needed that minimizes the dangers posed by dual use of synbio without undermining development of the field.**

Advances in synthetic biology, like those in 3D printing, robotics and so many other technologies, have been enabled by a wide range of other emerging technologies combining together. The National Research Council/National Academy of Engineering report stated that "while synthetic biology arises from a century's work in biology and related fields…its practice would not be possible without breakthroughs in such diverse fields as engineering, computer science, and information technology."[30] The report especially noted that "progress in computer and Internet technology revolutionized the ability to process and transfer data and provided ideas and methods for how to manage complexity when engineering multi-component integrated systems. Calculations that only a decade ago would have taken weeks on a mainframe computer now take minutes: a gene sequence may be processed on a laptop."[31]

Robots Head Out of the Factory and into Our Lives

While 3D printing is changing when, where, and how things are made, what we term "the new robotics" is enhancing productivity and changing the role of humans in the production process and the overall economy. The development of a new generation of robots that are easier to program and are safer and easier for humans to interact with is making it possible for people and robots to work alongside each other. It has also become possible

29 Garrett, 38.

30 National Research Council, *Positioning Synthetic Biology to Meet the Challenges of the 21st Century*.

31 Ibid, 9-10.

to substitute robots for human labor in more manufacturing and service jobs.[32] The new robotics extends far beyond traditional roles and forms of robots. Not only are vehicles from cars to drones to submarines becoming robotic, but digital robots are taking on tasks that only humans were previously able to perform.

The new robots, both physical and digital, are powered by a set of emerging or rapidly improving technologies, including wireless communications technologies, artificial intelligence, the Internet of Things, advanced and cheap sensors, big data, advanced algorithms, cloud computing and storage, and the global positioning system (GPS).[33] These robotic platforms have evolved at a rate over the last four decades similar to that plotted by Moore's Law for microchips. The future is one of ever smarter, more capable, and dramatically less expensive robots insinuating themselves into every corner of our lives, well beyond manufacturing and the overall economy.

Autonomous vehicles, including the iconic Google self-driving cars, may be on the road commercially well before 2020. The long-term impact on society of self-driving cars and other autonomous vehicles (their development spurred by a DARPA challenge) could be a radical change in how humans use cars, design transportation infrastructure, and utilize land in cities. There could be a sharp reduction in driving accidents and fatalities, some 80 percent of which are due to human error. The percentage of land in cities now dedicated to cars, about 60 percent, could be substantially reduced by cars being available on demand, summoned by apps, and in constant use, drastically reducing the need for parking spaces as well as the overall number of cars, which, as personal vehicles, are idle 90 percent of the time. At the same time, such personal-use vehicles may be more efficient than most public transport, taking people directly between desired starting and end points. The self-driving car could thus lead to a redesign of cities and a transformation of urban life styles. Such a shift to robotic vehicles, especially if accompanied by a change in patterns of ownership and use, would be highly disruptive to the global economy, especially the auto industry. Some auto manufacturers could benefit (or new majors could emerge), but the entire notion of what an automobile represents could change as people view autos more as a utility and less as a symbol of status or of driving pleasure. Over the next decade, autonomous vehicles may also play an increasingly important role in the commercial sphere. Autonomous cargo carriers may include trucks on the highways and unmanned cargo planes as well as survey and delivery drones in the skies.

Developers are extending the capabilities of robots, crossing the boundary between industrial robots and nonindustrial robots. Although much development is still required to improve robots' cognitive abilities, many of the building blocks for futuristic and highly disruptive systems will be in place in the next couple decades. Such robotics could eliminate the need for human labor entirely in some manufacturing environments with total automation becoming more cost-effective than outsourcing manufacturing to developing economies. Even in developing countries, robots might supplant some local manual labor in sectors such as electronics, potentially holding down local wages.

Digital robots are powering the TIR, in many cases taking on tasks of highly-skilled knowledge workers. We have already seen the extraordinary power of search engines, such as Google Search, Microsoft Bing, and others, based on powerful "ranking" algorithms that far exceed any human capability, almost instantly sifting through billions of data points to answer human information queries. Other powerful algorithms are replacing lawyers with "e-discovery" by scanning millions of legal documents at higher speed, lower cost, and with greater accuracy than humans. Similarly, medical x-rays can now often be read more quickly and more accurately by computers than radiologists. Some digital robots, like IBM's Watson, can help diagnose cancer and will soon provide expert advice across a wide range of medical and other disciplines. Google Translate is constantly improving through massive data mining and advanced algorithms. In short, a large number of jobs and even job categories are or will be

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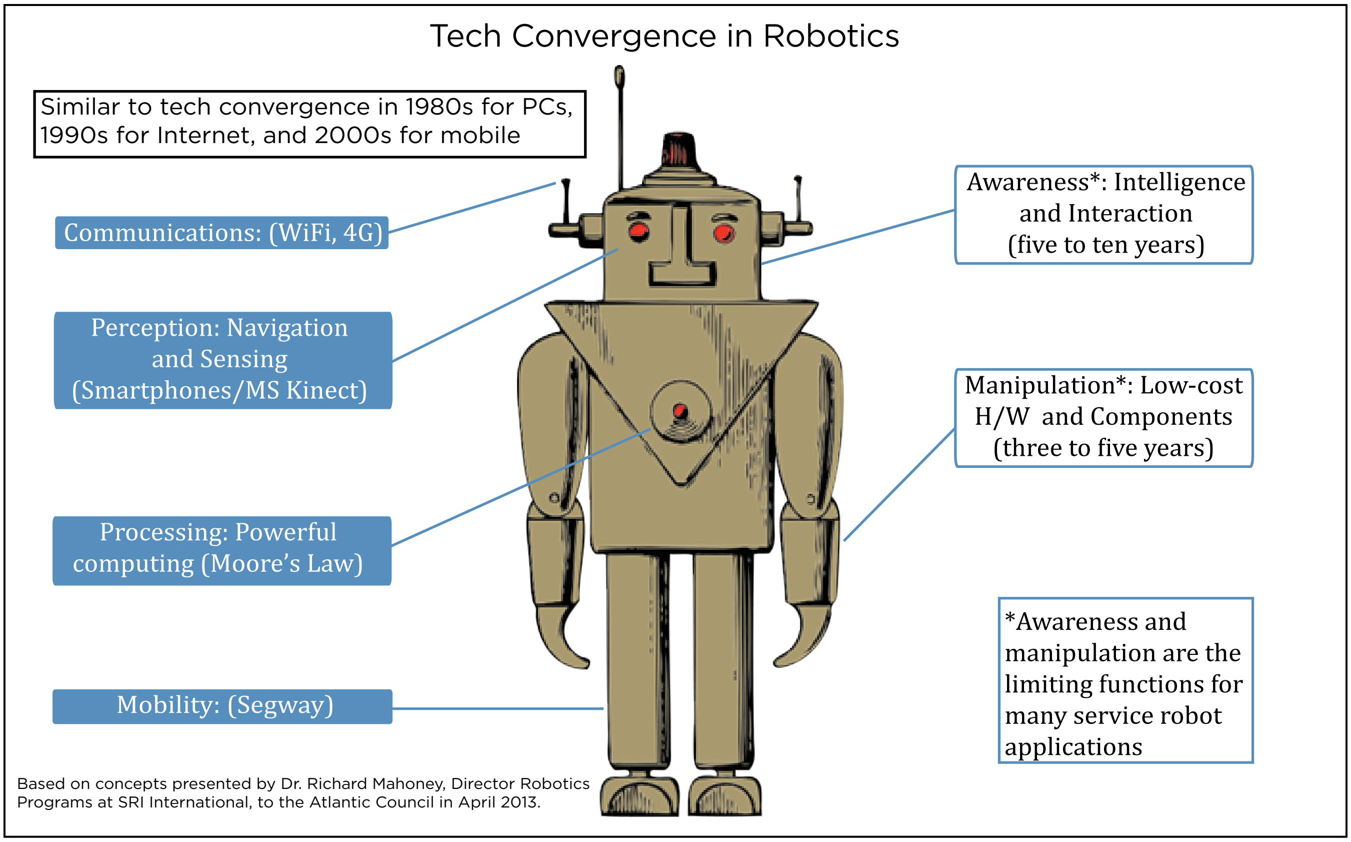
32 For example, "Baxter" represents a new generation of cheaper, more capable, and uncaged robots that can work alongside humans and be easily programmed and reprogrammed by humans. Baxter was developed by a small US startup, Rethink Robotics, headed by Rodney Brooks, and is driving down prices from the $200,000-$300,000 range to $22,000 or less. For background, see Bernadette Johnson, "How Baxter the Robot Works," HowStuffWorks, http://science.howstuffworks.com/baxter-robot1.htm. See also Robert A. Manning, *Rising Robotics and the Third Industrial Revolution* (Washington, DC: Atlantic Council, June 2013), http://www.atlanticcouncil.org/images/publications/rising_robotics_third_industrial_revolution.pdf.

33 The new open-source Robotic Operating System (ROS) even relies on computer and data processing in the cloud to operate sensors and actuators in the robot, reducing the cost and size of the robot.



eliminated by digital robots.

Robots are likely to play an increasing role in labor-intensive industries like healthcare, eldercare, and militaries. In hospitals, we are already seeing them perform specialized functions such as surgical support, including the "Da Vinci" robotic device carrying out robotic surgery under the control of skilled surgeons. Japan and South Korea are investing heavily in the development of robots able to assist with daily living in an effort to deal with the onset of aging for much of their population. The military is expected to increase its use of robots to reduce human exposure in high-risk situations and environments as well as the number of troops necessary for certain operations. The ability to deploy such robots rapidly, for particular tasks, could help military planners address wider resource issues.

These digital robots are increasingly part of what has been called a digital "second economy" of computers and networks that can perform services independent of most human activity—as in swiping a credit card, buying an online product or service, or getting an airline boarding pass online.[34]

Computers, the Internet, and networks combined with increasingly sophisticated robotics have begun to transform the workplace.

Will More Jobs Be Created than Lost?

3D printing will likely eliminate many routine, assembly-line jobs and replace them with fewer, but better, jobs that could be widely distributed in micro as well as small- and medium-sized enterprises (SMEs). Industrial robots have already replaced many factory jobs, and ever-more capable robots are set to do even more, including those that have moved out of their cages to work alongside humans. Increasingly powerful and ubiquitous digital robots are also eliminating countless jobs and possibly entire professions while yielding dramatic productivity gains.

This trend could continue indefinitely, exacerbating other technological trends of the TIR. A recent McKinsey report asserted that "advances in artificial intelligence, machine learning and natural user interfaces are making it possible to automate many knowledge worker tasks that have long been regarded as impossible or impractical for machines to perform." Certainly the skill sets required for jobs are changing dramatically, with many low-end skills gradually being eliminated, while many mid-level

34 W. Brian Arthur, "The Second Economy," *McKinsey Quarterly*, October 2011, http://www.mckinsey.com/insights/strategy/the_second_economy.

jobs have already been eliminated by information and communications technology in the past two decades.

Will this trend also further exacerbate the wealth gap? The impact of new technology on incomes over the last twenty years is blamed for some 80 percent of the 4 percent global decline in the share of GDP going to labor in the labor-capital split.[35] A small number of highly-skilled and talented workers, especially those critical to the TIR, along with corporate managers and owners, have been accruing an increasing percentage of the wealth, while the middle class has seen its relative income drop.[36] Will new technologies reverse this trend and spawn large numbers of new, high-paying jobs, and return the middle class to income growth? While the trends are not encouraging, nor are they set in stone. New technologies will create new industries, and government policies could significantly affect income distribution to cushion the effects of the secular shift in the economy produced by the TIR.

Disruption Has Its Dangers

Besides a potentially long-term, negative impact on jobs and compensation, the TIR is spawning other "downsides." 3DP has recently attracted the attention of the US Congress and the public with reports that people have printed guns and high-capacity magazines for assault weapons.[37] No doubt other worrisome products such as IEDs will be printable, making control of lethal items more difficult. Drones have already proved highly controversial with their ability to be used as weapons of selective destruction to target terrorists. The United States may have developed and first deployed drones for such purposes, but the technology is increasingly cheap and globally available. Not only states but nonstate actors have access to the technology to build and deploy their own drones for lethal attacks and surveillance. Robotic weapons systems with the ability to autonomously make "kill decisions" are possible and could be extended to robotic soldiers. The "stuxnet" virus, reportedly developed and deployed by the United States and Israel to destroy Iranian centrifuges, has likely set a precedent for development of other autonomous "kinetic" algorithm weapons that can be deployed to seek out and destroy physical objects.

Hacking of autonomous vehicles from cars to drones could also result in lethal destruction. In addition, 4D printing could enable the creation of objects that could change form and function, potentially including harmless objects that can be transformed by an external signal or hacked to become lethal, such as morphable wings on an airplane commanded by a hacker to change shape to destroy the aircraft in flight and cause it to crash.

The United States is not only the overall leader in the development and deployment of the new technologies and innovations of the TIR, but it also has a number of other advantages. These include cheap and available energy resulting from the unconventional gas revolution in the United States that is providing a competitive edge for US manufacturers and is attracting foreign corporations, especially in petrochemical and other high-energy consuming industries, to relocate to the United States.

The United States also has an unmatched foundation of scientific discovery and technological development built on a long history of government investment in R&D. This technology leadership is being challenged, however, by rising technological capabilities and science and technology (S&T) spending in other countries and, more critically, by continued cuts to US government funding of basic research.

Other advantages include high productivity in US manufacturing requiring fewer labor inputs, thus reducing the advantages from outsourcing, while 3DP, robotics and other technologies create new advantages for "in-sourcing." Top research universities have been educating scientists and engineers essential to the Third Industrial Revolution. A do-it-yourself culture has been a plus in advancing innovation from the bottom up and incubating new ideas and companies based on 3DP and robotics as well as ICT and bioengineering. Finally, the United States has a favorable investment environment compared with many overseas competitors due to the effective rule of law (including intellectual property rights protection).

35 "Labour Pains," *Economist*, November 2, 2013, http://www.economist.com/node/21588900/comments. The Economist cites a new OECD study reporting that since the 1990s, labor's share of GDP globally has dropped to 62 percent from over 66 percent, with 80 percent of the drop due to technology.

36 The OECD study shows that the share income earned by the top 1 percent of workers has actually increased since the 1990s. This differential applies especially to employees of companies such as Google, Apple, Facebook, and Microsoft who are highly compensated in wages and stock options.

37 Michael S. Rosenwald, "Weapons Made with 3D Printers Could Test Gun-Control Efforts," *Washington Post*, February 20, 2013, http://www.washingtonpost.com/local/weapons-made-with-3=d-printers-could-test-gun-control-efforts/2013/02/18/9ad8b45e-779b-11e2-95e4-614e45d7adb_story.html.

V. A Call to Action

All of the technologies described here will serve up a risky measure of surprise, but the biggest surprises will not come from any single technology. Rather, the greatest changes will come from the cross-symbiotic impact of many emerging technologies interacting with each other. This is a familiar pattern found in earlier periods of expansion. In the 1980s, microprocessor advances intersected with laser-based bandwidth expansion and network protocols to set the stage for the emergence of the World Wide Web.

Similar transformations are lurking in our near future. Fully autonomous vehicles will arrive well within the next decade or so, and their arrival will overturn current assumptions about how we think about personal vehicles and mass transportation. Ever more capable robots will yield dramatic productivity gains that will wipe out countless jobs and possibly entire professions. The great social issue before mid-century could be what will replace the notion of work and a job as the central activity that gives us income, health care, and ultimately meaning. And algorithms will yield the greatest surprises of all. We certainly will have to change our notions of privacy, but that is only the tip of a much larger iceberg. We are in for a fascinating few decades, but it definitely is not a time for the technologically faint-hearted.

If the United States can marshal its advantages—a big "if"—the various technologies analyzed here should be especially promising. The Shale Revolution has demonstrated US dexterity in pulling a rabbit out of the hat, combining two pre-existing technologies to upend worldwide energy markets. But, lest we forget, the US government played a critical role in its development. As described, government-funded R&D from the 1970s was behind the fracking innovation, and wildcat entrepreneurs were aided by tax credits.

This is the case for other transformative innovations. In a recent book by Mariana Mazzucato, an economics professor at the University of Sussex, considers the roles played by "bold entrepreneurs" and "the much-maligned state" only to find the latter being the critical innovator for many of our biggest technological breakthroughs.[38] As she notes, "the US National Science Foundation funded the algorithm that drove Google's search engine." All the technologies that make the iPhone "smart" were state-funded—the Internet, wireless networks, the global positioning system, microelectronics, touchscreen displays and the latest voice-activated SIRI personal assistant.

The state's role is all the more important because as Mazzucato's research has shown, it is the one entity that can bear the risks of spending money on R&D when the commercial uses are not yet evident. In the US government, DARPA, the NSF and NIH have been the most important engines of innovation in the past five decades, but they do not get the credit they deserve for their achievements.

	Gross Domestic Expenditure on R&D (Current prices and PPPs; millions USD)			Gross Domestic Expenditure on R&D (as percentage of GDP)		
	2000	2006	2011	2000	2006	2011
European Union	184,153	253,885	320,456	1.74	1.76	1.94
United States	268,121	353,328	415,193	2.71	2.65	2.77
China	27,216	86,619	208,172	0.90	1.39	1.84
Russia	10,495	22,857	35,045	1.05	1.07	1.09
Japan	98,667	138,339	146,537	3.00	3.41	3.39

38 Mariana Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths* (London and New York: Anthem Press, 2013).

US R&D Spending by Funding Source, 1960-2010

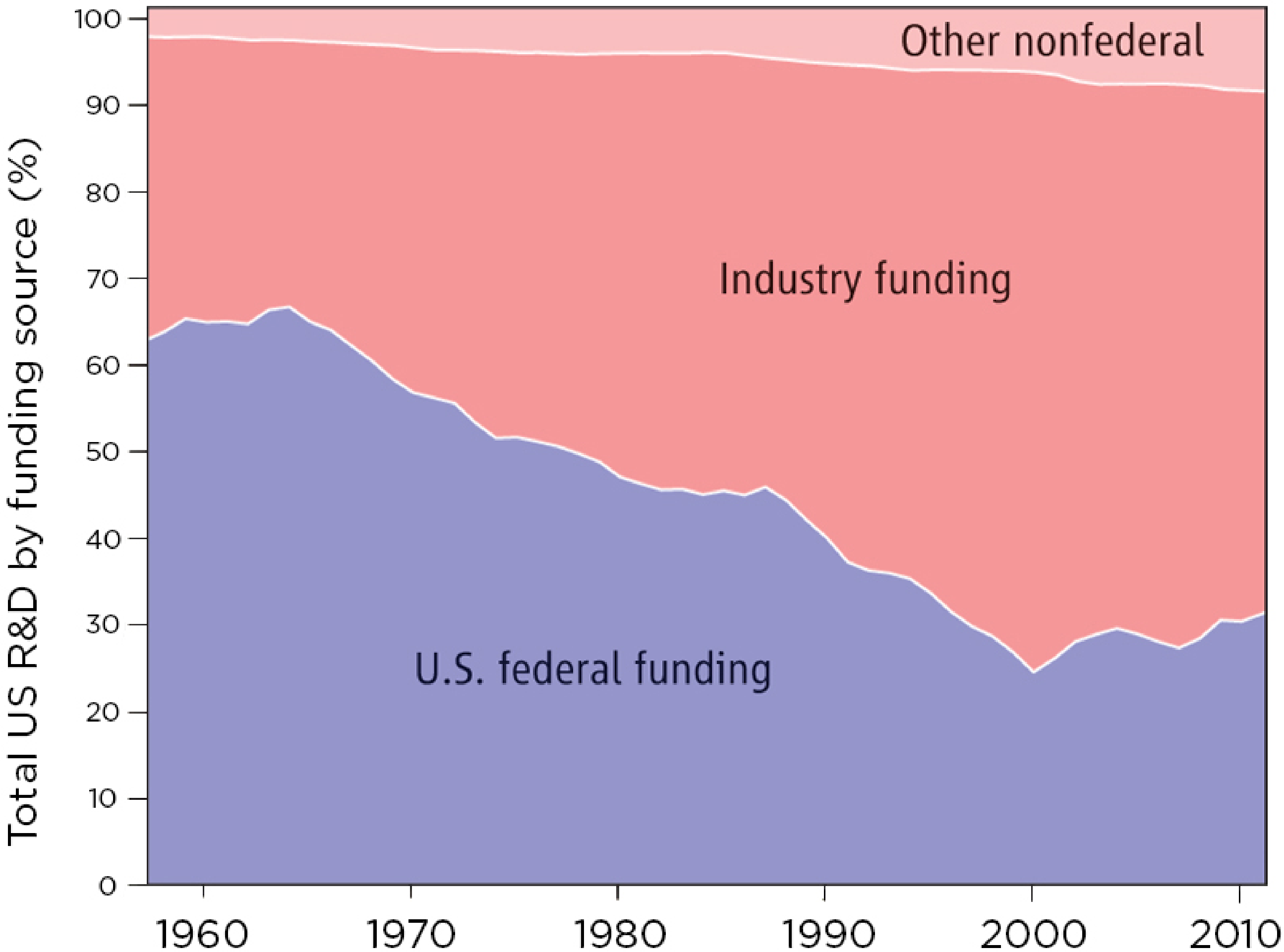
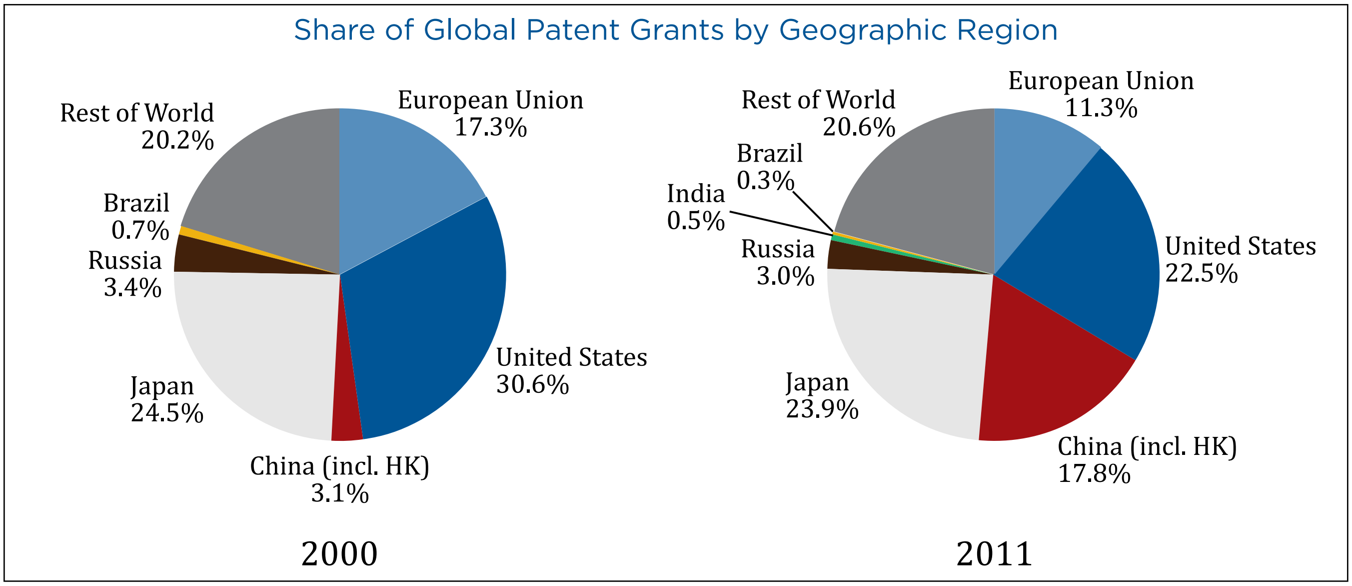


Image from Science, *http://www.sciencemag.org/content/342/6160/817.full.*

Overall, the United States remains a leader in expenditure on R&D in absolute terms; the share of EU GDP spent on R&D is substantially below that of the United States and Japan. But US government spending on basic R&D has flatlined since about 2003 when adjusted for inflation and is expected to decline sharply as a percentage of GDP if sequestration budget cuts are fully implemented. Press reports indicate that the National Institutes of Health's budget could drop 7.6 percent in the next five years. Research programs in energy, agriculture and defense will decline by similar amounts. NASA's research budget could drop to its lowest level since 1988.

In contrast, there has been a dramatic growth in Chinese R&D—now close to EU levels in share of GDP—indicative of their efforts to become an innovation nation and position themselves as a potential first mover in the biotech and green energy fields. On patent grants (see table on following page), the United States and Europe have experienced a relative decline over the past decade as China increases both its absolute number and overall share. Obviously the value and significance of specific patents varies considerably, and there is controversy over the relative worth of many Chinese patents. But the underlying point is that the world is now much more competitive and the United States and Europe risk losing their edge. **US government R&D funding should be significantly increased to maintain US leadership in science and technology and to strengthen the foundation for US economic competitiveness and growth as well as to marshal science and technology to address global challenges.**

US education in STEM continues to show little improvement. The United States ranks twenty-seventh among developed nations in the proportion of college students receiving undergraduate degrees in science or engineering. There are more foreign



students studying physical sciences in US graduate schools than Americans. **We support calls for urgent reform of the immigration laws to enable US-trained scientists and engineers to be able to remain after they graduate.** Ensuring continued US leadership on S&T means remaining the magnet for the world's talent.

All the technologies featured here show the incredible uses to which they can be put, particularly in confronting the major global challenges of climate change, resource constraints, and galloping urbanization, among others. If nothing else, technology presents a huge set of opportunities for the United States in developing a strategy for the post-Western world. In December 2013, the Atlantic Council launched a long-term strategy for the US—*Envisioning 2030: US Strategy for a Post-Western World*. A key message in that work was that "the keystone of national power remains US economic strength and innovation." There is no better argument for why a focus on technology is so vitally important. Not only can technology be a source of economic recovery and rejuvenation, but it can connect the much needed nation-building at home with an expansion of US prestige and power overseas. Opinion poll after opinion poll has shown that the US is admired and envied for its proverbial science and technology achievements and prowess even in regions like the Middle East where US popularity is low.

After the Second World War, the US won the hearts and minds of much of the rest of the world by linking US national interests with helping Europe rebuild through the Marshall Plan and standing up to the Soviet threat with the creation of the NATO Alliance. The US also supported the developing world's aspirations for independence from colonial rule. Today, US leadership in so many of the technologies that the rest of the world needs to confront its challenges can help the US renew and forge an even stronger compact with others, sealing a pivotal position for the US in tomorrow's post-Western world.

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