

Industrial Internet: Pushing the Boundaries of Minds and Machines

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imagination at work

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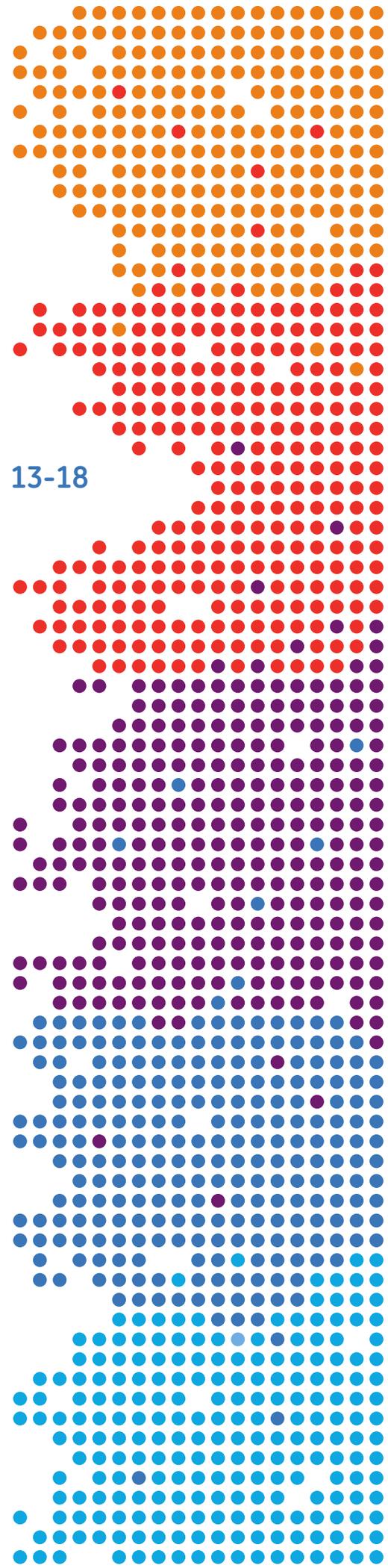
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I. Executive Summary

The world is on the threshold of a new era of innovation and change with the rise of the Industrial Internet. It is taking place through the convergence of the global industrial system with the power of advanced computing, analytics, low-cost sensing and new levels of connectivity permitted by the Internet. The deeper meshing of the digital world with the world of machines holds the potential to bring about profound transformation to global industry, and in turn to many aspects of daily life, including the way many of us do our jobs. These innovations promise to bring greater speed and efficiency to industries as diverse as aviation, rail transportation, power generation, oil and gas development, and health care delivery. It holds the promise of stronger economic growth, better and more jobs and rising living standards, whether in the US or in China, in a megacity in Africa or in a rural area in Kazakhstan.

With better health outcomes at lower cost, substantial savings in fuel and energy, and better performing and longer-lived physical assets, the Industrial Internet will deliver new efficiency gains, accelerating productivity growth the way that the Industrial Revolution and the Internet Revolution did. And increased productivity means faster improvement in income and living standards. In the US, if the Industrial Internet could boost annual productivity growth by 1-1.5 percentage points, bringing it back to its Internet Revolution peaks, then over the next twenty years through the power of compounding it could raise average incomes by an impressive 25-40 percent of today's level over and above the current trend. And as innovation spreads globally, if the rest of the world could secure half of the US productivity gains, the Industrial Internet could add a sizable \$10-15 trillion to global GDP – the size of today's U.S. economy – over the same horizon. In today's challenging economic environment, securing even part of these productivity gains could bring great benefits at both the individual and economy-wide level.

The Next Wave

How will this be possible? The Industrial Internet brings together the advances of two transformative revolutions: the myriad machines, facilities, fleets and networks that arose from the Industrial

Revolution, and the more recent powerful advances in computing, information and communication systems brought to the fore by the Internet Revolution.

Together these developments bring together three elements, which embody the essence of the Industrial Internet:

INTELLIGENT MACHINES: New ways of connecting the world's myriad of machines, facilities, fleets and networks with advanced sensors, controls and software applications.

ADVANCED ANALYTICS: Harnessing the power of physics-based analytics, predictive algorithms, automation and deep domain expertise in material science, electrical engineering and other key disciplines required to understand how machines and larger systems operate.

PEOPLE AT WORK: connecting people, whether they be at work in industrial facilities, offices, hospitals or on the move, at any time to support more intelligent design, operations, maintenance as well as higher quality service and safety.

Connecting and combining these elements offers new opportunities across firms and economies. For example, traditional statistical approaches use historical data gathering techniques where often there is more separation between the data, the analysis, and decision making. As system monitoring has advanced and the cost of information technology has fallen, the ability to work with larger and larger volumes of real-time data has been expanding. High

frequency real-time data brings a whole new level of insight on system operations. Machine-based analytics offers yet another dimension to the analytic process. The combination of physics-based approaches, deep sector specific domain expertise, more automation of information flows, and predictive capabilities can join with the existing suite of "big data" tools. The result is the Industrial Internet encompasses traditional approaches with newer hybrid approaches that can leverage the power of both historic and real-time data with industry specific advanced analytics.

Building Blocks and "Things that Spin"

The Industrial Internet starts with embedding sensors and other advanced instrumentation in an array of machines from the simple to the highly complex. This allows the collection and analysis of an enormous amount of data, which can be used to improve machine performance, and inevitably the efficiency of the systems and networks that link them. Even the data itself can become "intelligent," instantly knowing which users it needs to reach.

In the aviation industry alone, the potential is tremendous. There are approximately 20,000 commercial aircraft operating with 43,000 commercial jet engines in service. Each jet engine, in turn, contains three major pieces of rotating equipment which could be instrumented and monitored separately. Imagine the efficiencies in engine maintenance, fuel consumption, crew allocation, and scheduling when

Figure 1. Key Elements of the Industrial Internet

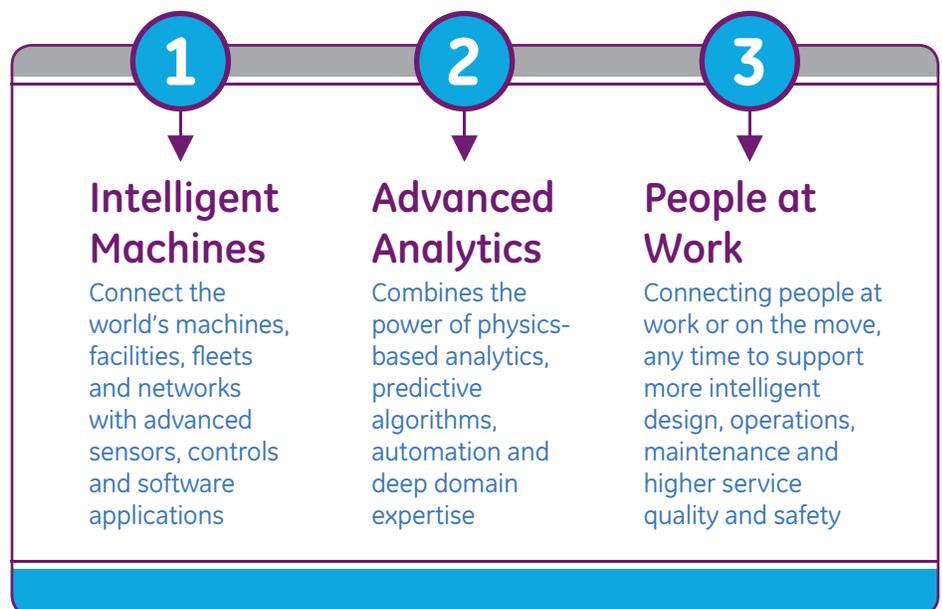


Table 1: Industrial Internet: The Power of 1 Percent

What if... Potential Performance Gains in Key Sectors			
Industry	Segment	Type of Savings	Estimated Value Over 15 Years (Billion nominal US dollars)
Aviation	Commercial	1% Fuel Savings	\$30B
Power	Gas-fired Generation	1% Fuel Savings	\$66B
Healthcare	System-wide	1% Reduction in System Inefficiency	\$63B
Rail	Freight	1% Reduction in System Inefficiency	\$27B
Oil & Gas	Exploration & Development	1% Reduction in Capital Expenditures	\$90B

Note: Illustrative examples based on potential one percent savings applied across specific global industry sectors. Source: GE estimates

‘intelligent aircraft’ can communicate with operators. That is just today. In the next 15 years, another 30,000 jet engines will likely go into service as the global demand for air service continues to expand.

Similar instrumentation opportunities exist in locomotives, in combined-cycle power plants, energy processing plants, industrial facilities and other critical assets. Overall, there are over 3 million major “things that spin” in today’s global industrial asset base—and those are just a subset of the devices where the Industrial Internet can take hold.

Power of just one percent

The benefits from this marriage of machines and analytics are multiple and significant. We estimate that the technical innovations of the Industrial Internet could find direct application in sectors accounting for more than \$32.3 trillion in economic activity. As the global economy grows, the potential application of the Industrial Internet will expand as well. By 2025 it could be applicable to \$82 trillion of output or approximately one half of the global economy.

A conservative look at the benefit to specific industries is instructive. If the Industrial Internet achieves just a one percent efficiency improvement then the results are substantial. For example, in the commercial aviation industry alone, a one percent

improvement in fuel savings would yield a savings of \$30 billion over 15 years. Likewise, a one percent efficiency improvement in the global gas-fired power plant fleet could yield a \$66 billion savings in fuel consumption. The global health care industry will also benefit from the Industrial Internet, through a reduction in process inefficiencies: a one percent efficiency gain globally could yield more than \$63 billion in health care savings. Freight moved across the world rail networks, if improved by one percent could yield another gain of \$27 billion in fuel savings. Finally, a one percent improvement in capital utilization upstream oil and gas exploration and development could total \$90 billion in avoided or deferred capital expenditures. These are but a few examples of what can be potentially achieved.

Broad Global Benefits

As an early mover and source of key innovation, the US is at the forefront of the Industrial Internet. Given increasingly deeper global integration and ever more rapid technology transfer, the benefits will be worldwide. In fact, with emerging markets investing heavily in infrastructure, early and rapid adoption of Industrial Internet technologies could act as a powerful multiplier. There may be opportunities to avoid the same phases of development that developed economies went through. For example, the use of cables and wires may be avoided by going straight to wireless technology. Or the

availability of private, semi-public, or public cloud-based systems may displace the need for isolated systems. The result could be a more rapid closing of the productivity gap between advanced and emerging nations. And in the process, the Industrial Internet would ease resource and financial constraints, making robust global growth more sustainable.

Enablers and Catalysts

The Industrial Internet will require putting in place a set of key enablers and catalysts:

- A sustained effort in technological innovation is needed, along with investment to deploy the necessary sensors, instrumentation and user interface systems. Investment will be a fundamental condition to rapidly transfer new technologies into capital stock. The pace of Industrial Internet growth will ultimately be driven by how cost effective and beneficial they can be relative to current practice. The costs of deploying the Industrial Internet will likely be sector and region specific, but the assumption is that the costs of deployment will be providing a positive return for technology dollars invested.
- A robust cyber security system and approaches to manage vulnerabilities and protect sensitive information and intellectual property.
- Development of a strong talent pool including new cross-cutting roles that combine mechanical and industrial engineering into new “digital-mechanical engineers,” data scientists to create the analytics platforms and algorithms, and software and cyber security specialists. Endowing workers with these skills will help ensure that, once again, innovation will result in more jobs as well as higher productivity.

It will take resources and effort, but the Industrial Internet can transform our industries and lives— pushing the boundaries of minds and machines.



II. Innovation and Productivity: What's Next?

For much of human history, productivity growth was barely perceptible, and living standards improved extremely slowly. Then approximately 200 years ago, a step change in innovation occurred: the Industrial Revolution, in which muscle power, from both humans and animals, was replaced by mechanical power. The Industrial Revolution unfolded in waves, bringing us the steam engine, the internal combustion engine, and then the telegraph, telephone and electricity. Productivity and economic growth accelerated sharply. Per capita income levels in western economies had taken eight hundred years to double by the early 1800's; in the following 150 years they rose thirteen-fold. But in the 1970's, productivity growth in the US, then at the "frontier" of productivity, fizzled out.

The second step change in innovation followed more recently with the rise of computing and the global internet which rested on breakthroughs in information storage, computing and communication technology. Its impact on productivity was even stronger, but seemed to lose momentum after just ten years, around 2005.

Some now argue that this is where the story ends. They acknowledge that businesses and economies have benefited significantly from past waves of innovation but are pessimistic about the potential for future growth in productivity. They argue that the transformations brought about by the Industrial Revolution were of a one-off nature, and their gains have already been realized; that the Internet Revolution has already played out, its innovations being nowhere near as disruptive and productivity-enhancing as those of the Industrial Revolution.

We challenge this view. In this paper we examine the potential for a new wave of productivity gains. Specifically, we point to how the fruits of the Industrial Revolution and the machines, fleets and physical networks that it brought forth are now converging with the more recent fruits of the Internet Revolution: intelligent devices, intelligent networks and intelligent

decisioning. We call this convergence the Industrial Internet. We highlight evidence which suggests that a wide range of new innovations can yield significant benefits to business and to the global economy. We believe the skeptics have been too quick to draw conclusions that close the book on productivity gains. Much like the Industrial Revolution, the Internet Revolution is unfolding in dynamic ways—and we are now at a turning point.

A number of forces are at work to explain why the Industrial Internet is happening today. The capabilities of machines are not being fully realized. The inefficiencies that persist are now much greater at the system level, rather than at the individual physical machine level. Complexity has outstripped the ability of human operators to identify and reduce these inefficiencies. While these factors are making it harder to achieve improvements through traditional means, they are creating incentives to apply new solutions arising from Internet-based innovations. Computing, information, and telecommunication systems can now support widespread instrumentation, monitoring, and analytics. The cost of instrumentation has declined dramatically, making it possible to equip and monitor industrial machines on a widening scale. Processing gains continue unabated and have reached the point where it is possible to augment physical machines with digital intelligence. Remote data storage, big data sets and more advanced analytic tools that can process massive amounts of information are maturing and becoming more widely available. Together these changes are creating exciting new opportunities when applied to machines, fleets and networks.

The rapid decline in the cost of instrumentation is matched by the impact of cloud computing, which allows us to gather and analyze much larger amounts of data, and at lower cost, than was ever possible. This creates a cost-deflation trend

Processing gains continue unabated and have reached the point where it is possible to augment physical machines with digital intelligence.



comparable to that which spurred rapid adoption of information and communication technology (ICT) equipment in the second half of the 1990's—and which will this time accelerate the development of the Industrial Internet. The mobile revolution will also accelerate this deflation trend, making it more affordable to efficiently share information and leading to decentralized optimization and personalized optimization. Remote monitoring and control of industrial facilities, distributed power, and personalized and portable medicine are just some of the most powerful examples.

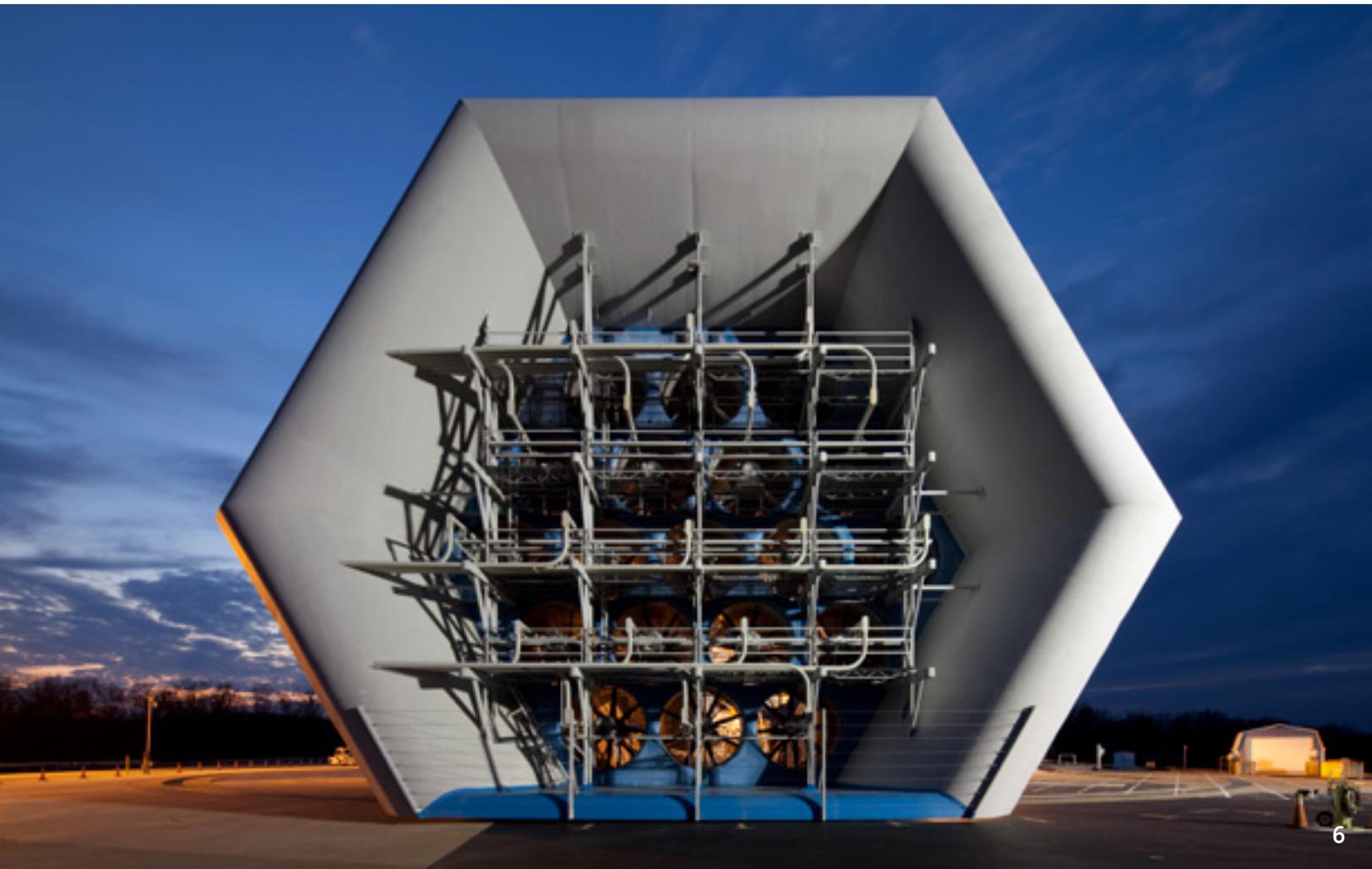
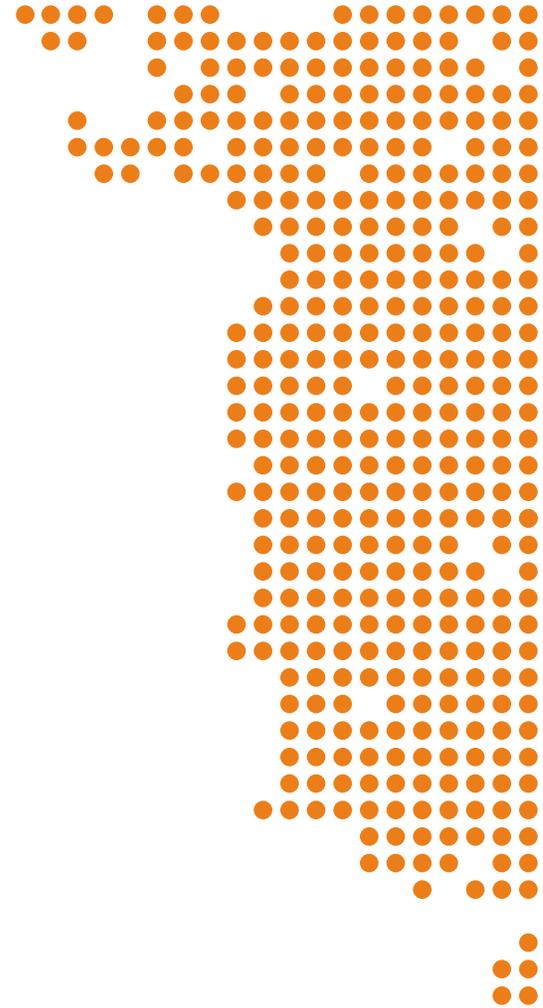
To fully appreciate the potential, it is important to consider how large the global industrial system has become. There are now millions of machines across the world, ranging from simple electric motors to highly advanced computed tomography (CT) scanners used in the delivery of health care. There are tens of thousands of fleets, ranging from power plants that produce electricity to the aircraft which move people and cargo around the world. There are thousands of complex networks ranging from power grids to railroad systems, which tie machines and fleets together.

The Industrial Internet will help make each of these levels of the industrial system perform better. It will enable enhanced asset reliability by optimizing inspection, maintenance and repair processes. It will improve operational efficiency at the level of fleets as well as larger networks.

The conditions are ripe and early evidence suggests that this new wave of innovation is already upon us. In the following pages we present a framework for thinking about how the Industrial Internet will unfold, and examples of benefits it holds for businesses and more broadly for economies around the world.



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III. Waves of Innovation and Change

Over the last 200 years, the world has experienced several waves of innovation. Successful companies learned to navigate these waves and adapt to the changing environment. Today we are at the cusp of another wave of innovation that promises to change the way we do business and interact with the world of industrial machines. To fully understand what is taking place today, it is useful to review how we got here and how past innovations have set the stage for the next wave we are calling the "Industrial Internet."

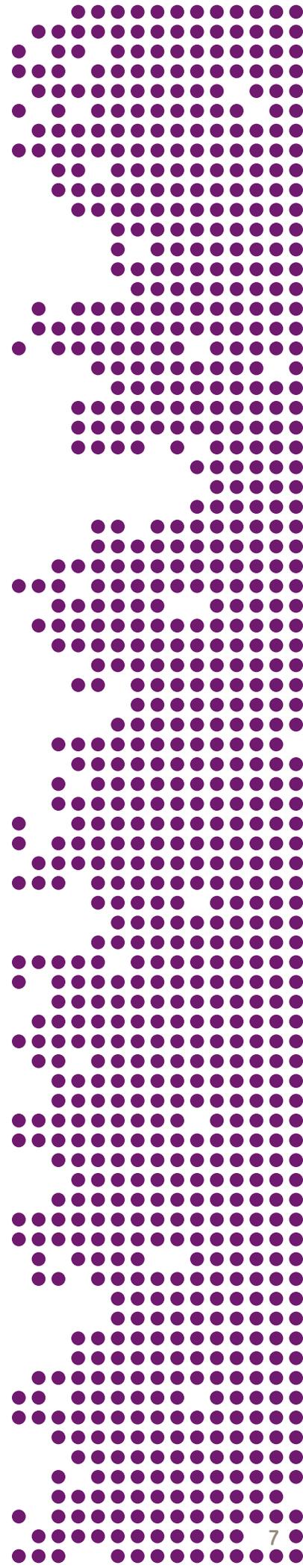
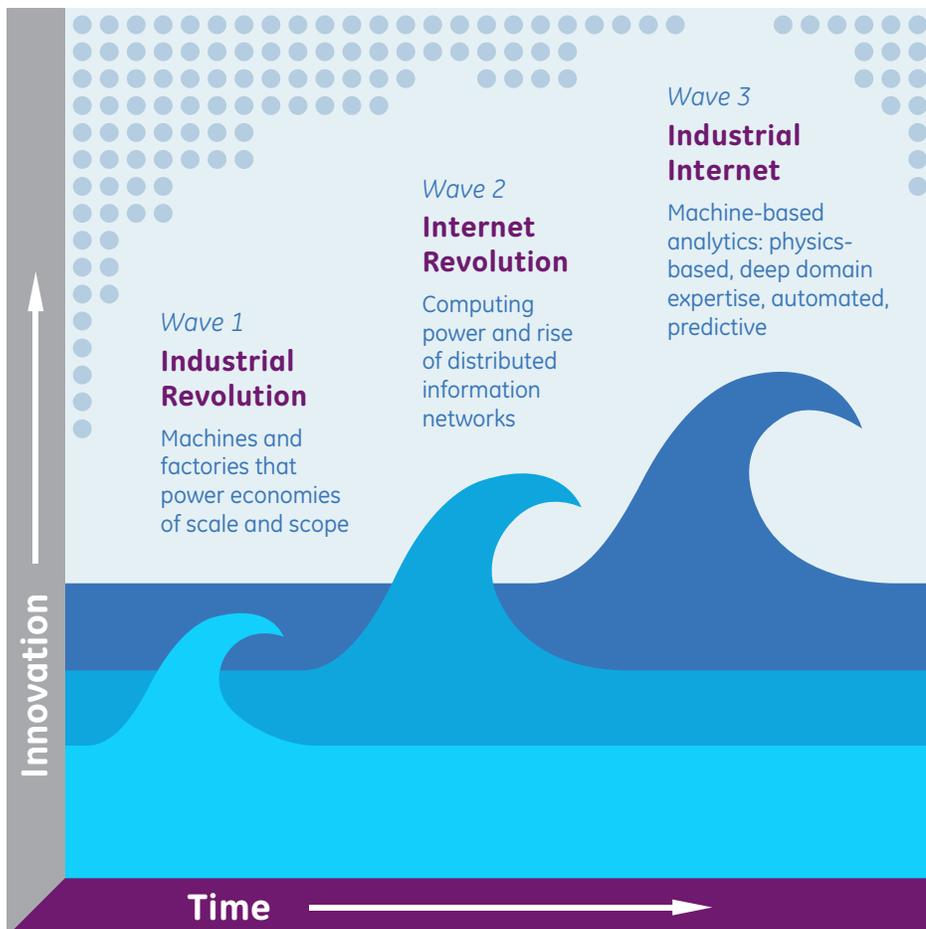
The First Wave: The Industrial Revolution

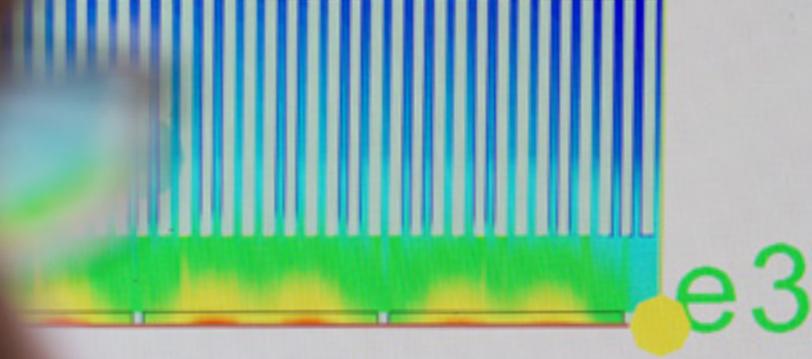
The Industrial Revolution had a profound impact on society, the economy and culture of the world. It was a long process of innovation that spanned a period of 150 years between 1750 and 1900. During this

period, innovations in technology applied to manufacturing, energy production, transportation and agriculture ushered in a period of economic growth and transformation. The first stage started in the mid-eighteenth century with the commercialization of the steam engine. The Industrial Revolution started in Northern Europe, which at the time was the most productive economy, and spread to the United States, where railways played a crucial role in accelerating economic development.¹ The second surge came later, in 1870, but was even more powerful, bringing us the internal combustion engine, electricity and a host of other useful machines.

The Industrial Revolution changed the way we lived: it brought about a profound transformation in transportation (from the horse-carriage and the sailboat to the railways, steamboats and trucks); in communication (telephone and telegraph); in urban centers (electricity, running water, sanitation and medicine). It dramatically transformed living standards and health conditions.²

Figure 2. Rise of the Industrial Internet





Several key features characterized this period.³ It was marked by the rise of the large industrial enterprise spanning new industries from textiles to steel to power production. It created significant economies of scale and corresponding reduction in costs as machines and fleets got larger and production volumes increased. It harnessed the efficiencies of hierarchical structures, with centralization of control. The global capital stock of dedicated plant and equipment grew dramatically. Innovation began to be thought of in a systematic way, with the rise of central laboratories and centers for research and development (R&D). Enterprises, both large and small, worked to harness new inventions in order to create and profit from new markets.

Despite the enormous gains reaped by the economy and society, the Industrial Revolution also had a downside. The global economic system became more highly resource-intensive and had a more significant impact on the external environment as a result of both resource extraction and industrial waste streams. In addition, working conditions during this era needed vast improvement. Much of the incremental innovation that has occurred since the Industrial Revolution has been focused on improving efficiency, reducing waste and enhancing the working environment.

The Second Wave: The Internet Revolution

At the end of the twentieth century, the Internet Revolution changed the world yet again. The timeframe in which it unfolded was much shorter, taking place over about 50 years instead of 150; but like the Industrial Revolution, the Internet Revolution unfolded in stages. The first stage started in the 1950's with large main frame computers, software and the invention of "information-packets" which permitted computers to communicate with one another. The first stage consisted of experimentation with government-sponsored computer networks.

In the 1970's, these closed government and private networks gave way to open networks and what we now call the World Wide Web. In contrast to the homogenous closed networks used during the first stage of the Internet, the open networks were heterogeneous. A key feature was that standards and protocols were explicitly designed to permit incompatible machines in diverse locations owned by different groups to connect and exchange information.

Openness and flexibility of the network were key elements that created the basis for its explosive growth. The speed of growth was breathtaking. In August 1981 there were less than 300 computers connected to the Internet. Fifteen years later the number had climbed to 19 million.⁴ Today the number is in the billions. Speed and volume of information transmitted grew dramatically. In 1985 the very best modems were only capable of speeds of 9.6 kilobits per second (Kbps). The first generation of iPhone, by contrast, was 400 times faster, capable of transmitting information at 3.6 megabits per second (Mbps).⁵

The combination of speed and volume created powerful new platforms for commerce and social exchange by driving down the cost of commercial transactions and social interactions. Companies went from selling nothing over the internet to creating large new efficient markets for exchange. In some cases this involved existing companies shifting to new digital platforms; however, the vast majority of the innovation and ferment centered on the creation of brand new companies and capabilities. When eBay began in 1995, it closed the year with 41,000 users trading \$7.2 million worth of goods. By 2006, it had 22 million users trading \$52.5 billion worth of goods. Social networking had a similar trajectory. Facebook was launched in February 2004 and in less than a year reached 1 million active users. By August

2008, Facebook had 100 million active users. Facebook now has over one billion users. In eight years, Facebook enabled more than 140 billion friend connections to be made, 265 billion photos were uploaded, and more than 62 million songs were played 22 billion times.⁶

The qualities of the Internet Revolution were very different from the Industrial Revolution. The Internet, computing and the ability to transmit and receive large amounts of data, have been built on the creation and value of networks, horizontal structures and distributed intelligence. It changed thinking about production systems by permitting deeper integration and more flexible operations. Also, rather than an ordered linear approach to research and development, the Internet has enabled concurrent innovation. The ability to exchange information rapidly and decentralize decision-making has spawned more collaborative work environments that are unconstrained by geography. As a consequence, older models of centralized internal innovation have ceded ground to start-ups and more open innovation models that harness an environment of more abundant knowledge. Thus, rather than resource-intensive, the Internet Revolution has been information and knowledge-intensive. It has highlighted the value of networks and the creation of platforms. It has opened up new avenues to reduce environmental footprints and support more eco-friendly products and services.



The Third Wave: The Industrial Internet

Today, in the twenty-first century, the Industrial Internet promises to transform our world yet again. The melding of the global industrial system that was made possible as a result of the Industrial Revolution, with the open computing and communication systems developed as part of the Internet Revolution, opens up new frontiers to accelerate productivity, reduce inefficiency and waste, and enhance the human work experience.

Indeed, the Industrial Internet Revolution is already underway. Companies have been applying Internet-based technologies to industrial applications as they have become available over the last decade. However, we currently stand far below the possibility frontier: the full potential of Internet-based digital technology has yet to be fully realized across the global industry system. Intelligent devices, intelligent systems, and intelligent decisioning represent the primary ways in which the physical world of machines, facilities, fleets and networks can more

deeply merge with the connectivity, big data and analytics of the digital world.

INTELLIGENT DEVICES

Providing digital instrumentation to industrial machines is the first step in the Industrial Internet Revolution. Several factors have aligned to make the widespread instrumentation of industrial machines not only possible, but economically viable. Widespread instrumentation is a necessary condition for the rise of the Industrial Internet. Several forces are at work to make machines and collections of machines more intelligent.

- **Costs of deployment:** Instrumentation costs have declined dramatically, making it possible to equip and monitor industrial machines in a more economical manner than in the past.
- **Computing power:** Continued improvements in microprocessor chips have reached a point that now makes it possible to augment physical machines with digital intelligence.

- **Advanced Analytics:** Advances in “big data” software tools and analytic techniques provide the means to understand the massive quantities of data that are generated by intelligent devices.

Together, these forces are changing the cost and value of collecting, analyzing and acting on data that has existed in theory but has not been fully harnessed in practice.

Making sense of the rivers of data that can be generated by intelligent devices is one of the key components of the Industrial Internet. As illustrated in Figure 3, the Industrial Internet can be thought of in terms of the flow and interaction of data, hardware, software and intelligence. Data is harvested from intelligent devices and networks. The data is stored, analyzed and visualized using big data and analytics tools. The resultant “intelligent information” can then be acted upon by decision makers, in real-time if necessary, or as part of broader industrial assets optimization or strategic decision processes across widely diverse industrial systems.

Figure 3. Applications of the Industrial Internet

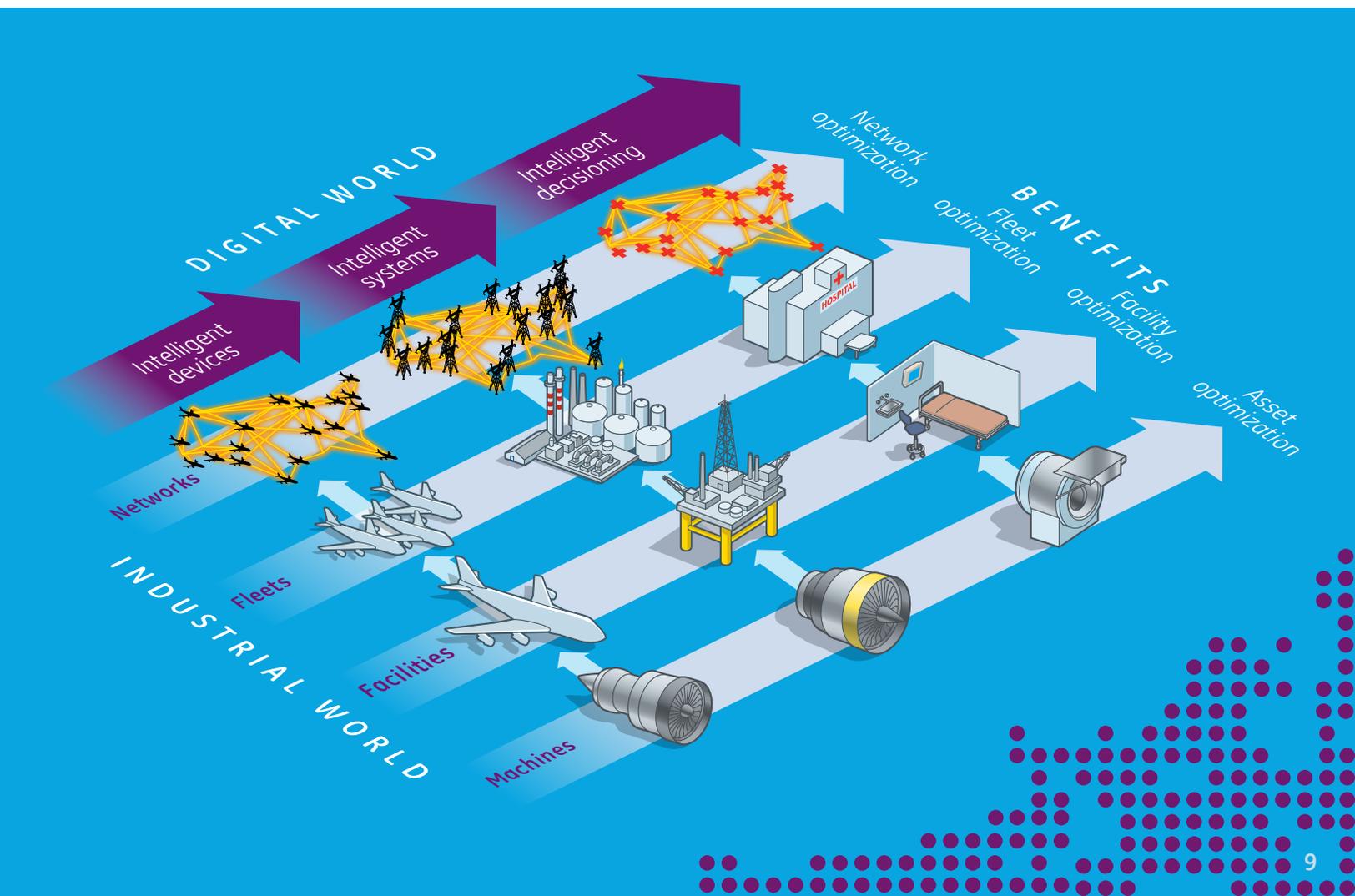
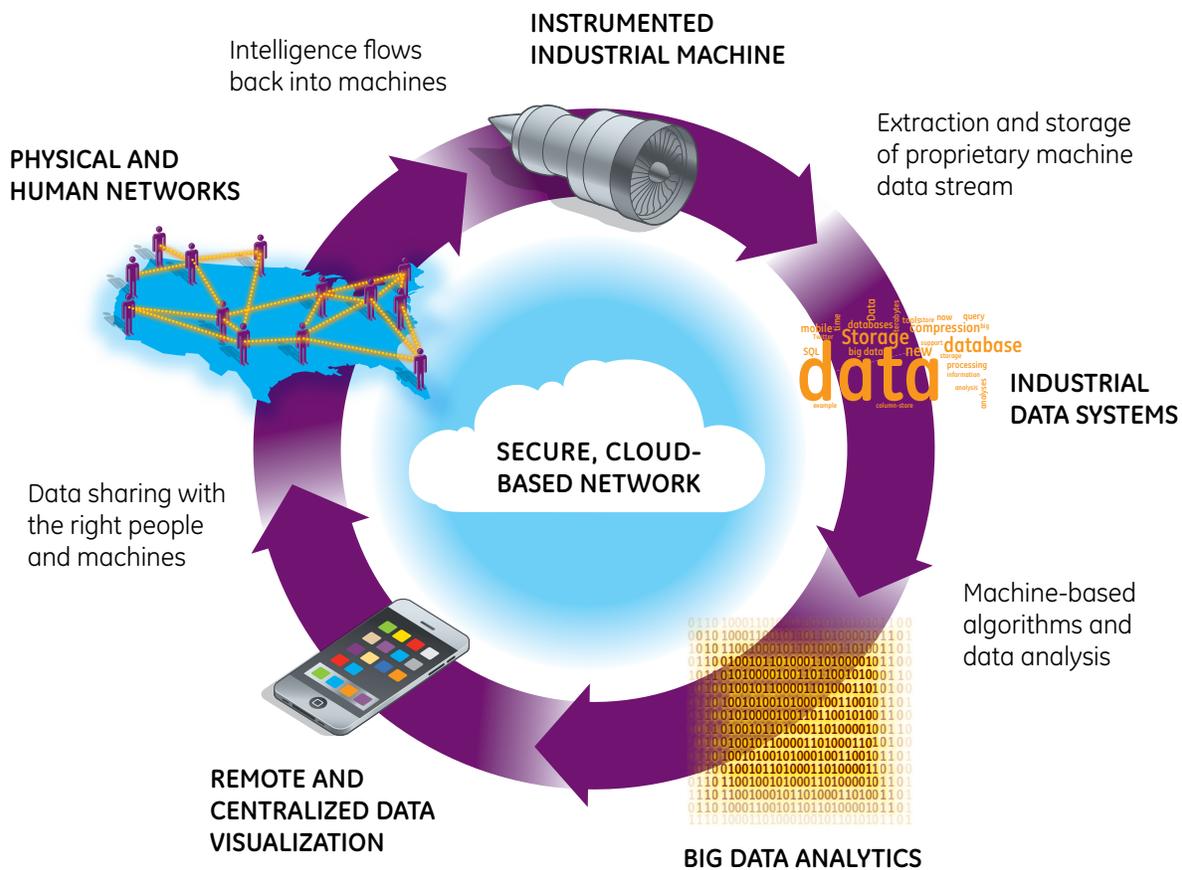


Figure 4. Industrial Internet Data Loop



Intelligent information can also be shared across machines, networks, individuals or groups to facilitate intelligent collaboration and better decision making. This enables a broader group of stakeholders to engage in asset maintenance, management and optimization. It also ensures that local and remote individuals that have machine-specific expertise are brought into the fold at the right time. Intelligent information can also be fed back to the originating machine. This not only includes data that was produced by the originating machine, but also external data that can enhance the operation or maintenance of machines, fleets and larger systems. This data feedback loop enables the machine to “learn” from its history and behave more intelligently through on-board control systems.

Each instrumented device will produce large quantities of data that can be transferred via the Industrial Internet network to remote machines and users. An important part of the implementation of the Industrial Internet will involve determining which data remains resident on devices and which data is

transferred to remote locations for analysis and storage. Determining the degree of local data residency is one of the keys to ensuring the security of the Industrial Internet and the many and diverse companies who will benefit from being a part of it. The important point here is that new innovations are permitting sensitive data generated by an instrumented machine to remain on-board, where it belongs. Other data streams will be transferred remotely so that they can be visualized, analyzed, augmented and acted upon, as appropriate, by people at work or on the move.

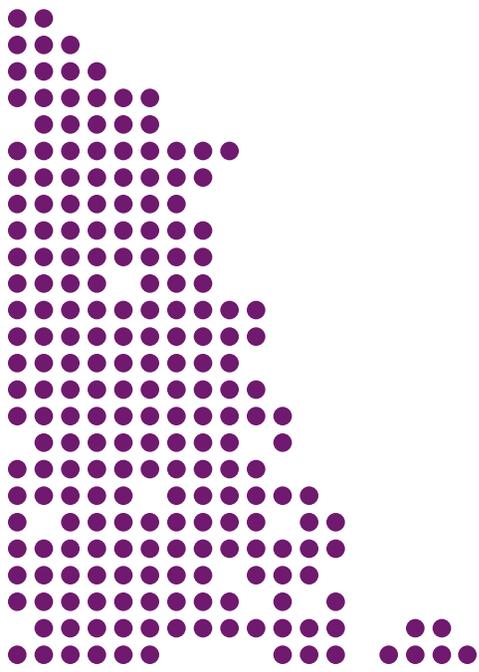
Over time, these data flows provide a history of operations and performance that enables operators to better understand the condition of the critical components of the plant. Operators can understand how many hours a particular component has been operating and under what conditions. Analytic tools can then compare this information to the operating histories of similar components in other plants to provide reliable estimates of the likelihood and timing of component failure. In this manner, operating data and

predictive analytics can be combined to avoid unplanned outages and minimize maintenance costs.

All of these benefits come from machine instrumentation using existing information technologies and doing so in ways that enable people to do their jobs more effectively. This is what makes the widespread deployment of intelligent devices so potentially powerful. In an era when it is increasingly challenging to squeeze more productivity from high-performance machines such as highly-engineered aircraft engines, the broad deployment of intelligent devices holds the potential to unlock additional performance and operational efficiencies.



Each machine can be aggregated into a single information system that accelerates learning across the machine portfolio.



INTELLIGENT SYSTEMS

The potential benefits of intelligent systems are vast. Intelligent systems include a variety of traditional networked systems, but the definition is broader to encompass the combination of widespread machine instrumentation with software as deployed across fleets and networks. As an increasing number of machines and devices join the Industrial Internet, the synergistic effects of widespread machine instrumentation can be realized across fleets and networks.

Intelligent systems come in a number of different forms:

Network Optimization: The operation of interconnected machines within a system can be coordinated to achieve operational efficiencies at the network level. For example, in health care, assets can be linked to help doctors and nurses route patients to the correct device more quickly. Information can then be seamlessly transmitted to care providers and patients resulting in shorter wait times, higher equipment utilization, and better quality care. Intelligent systems are also well suited for route optimization within transportation networks. Interconnected vehicles will know their own location and destination, but also can be alerted to the location and destination of other vehicles in the system—allowing optimization of routing to find the most efficient system-level solution.

Maintenance Optimization: Optimal, low-cost, machine maintenance across fleets can also be facilitated by intelligent systems. An aggregate view across machines, components and individual parts provides a line of sight on the status of these devices and enables the optimal number of parts to be delivered at the right time to the correct location. This minimizes parts inventory requirements and maintenance costs, and provides higher levels of machine reliability. Intelligent system maintenance optimization can be combined with network learning and predictive analytics to allow engineers to implement preventive maintenance programs that have the potential to lift machine reliability rates to unprecedented levels.

System Recovery: Establishing broad system-wide intelligence can also assist in more rapidly and efficiently restoring systems after major shocks. For example, in

the event of major storms, earthquakes or other natural hazards, a network of smart meters, sensors, and other intelligent devices and systems can be used to quickly detect and isolate the biggest problems so that they do not cascade and cause a blackout. Geographic and operational information can be combined to support utility recovery efforts.

Learning: Network learning effects are another benefit of machine interconnection with a system. The operational experiences of each machine can be aggregated into a single information system that accelerates learning across the machine portfolio in a way that is not possible with a single machine. For example, data collected from airplanes coupled with information about location and flight history can provide a wealth of information about airplane performance in a variety of environments. The insights derived from this data are actionable and can be used to make the entire system smarter, thereby driving a continuous process of knowledge accumulation and insight implementation.

Building out intelligent systems harnesses the benefits of widely deploying intelligent devices. Once an increasing number of machines are connected within a system, the result is a continuously expanding, self-learning system that grows smarter over time.

INTELLIGENT DECISIONING

The full power of the Industrial Internet will be realized with a third element—Intelligent Decisioning. Intelligent Decisioning occurs when enough information has been gathered from intelligent devices and systems to facilitate data-driven learning, which in turn enables a subset of machine and network-level operational functions to be transferred from operators to secure digital systems. This element of the Industrial Internet is essential to grapple with the increasing complexity of interconnected machines, facilities, fleets and networks.

Consider fully instrumented networks of facilities or fleets across wide geographic locations. Operators need to quickly make thousands of decisions to maintain optimal system performance. The challenges of this complexity can be overcome by enabling the system to perform select operations with human consent. The burden of complexity is transferred to the digital system. For example, within an intelligent system, signals to increase the output of a dispatchable power plant will not have to be sent to the operators of individual plants. Instead, intelligent automation will be used to directly co-dispatch flexible plants in response to variable resources like wind and solar power, changes in electricity demand, and the availability of other plants. These capabilities will facilitate the ability of people and organizations to do their jobs more effectively.

Intelligent Decisioning is the long-term vision of the Industrial Internet. It is the culmination of the knowledge gathered as the elements of the Industrial Internet are assembled device-by-device and system-by-system. It is a bold vision that, if realized, can unlock productivity gains and reduce operating costs on a scale comparable to the Industrial and Internet Revolutions.

INTEGRATING THE ELEMENTS

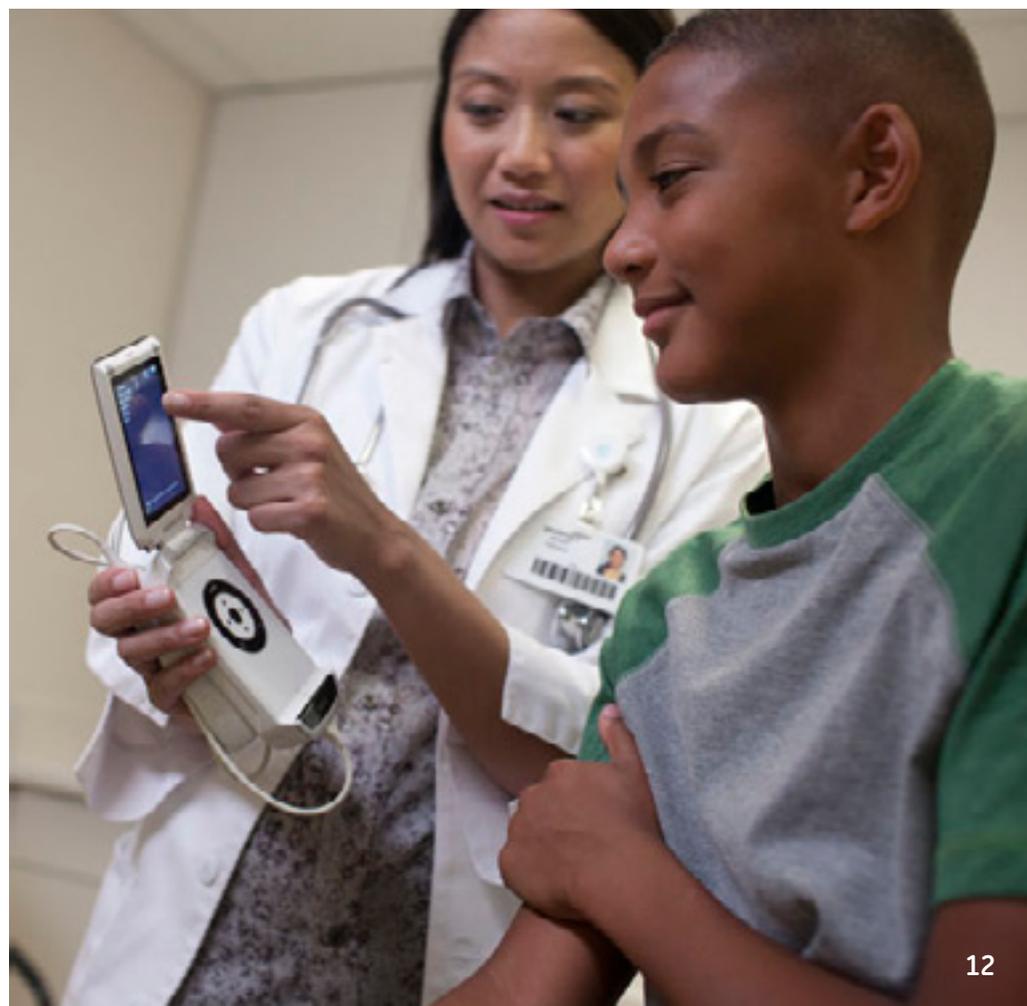
As the intelligent pieces are brought together, the Industrial Internet brings the power of “big data” together with machine-based analytics. Traditional statistical approaches use historical data gathering techniques where often there is more separation between the data, the analysis, and decision making. As system monitoring has advanced and the cost of information technology has fallen, the ability to work with real-time data has been expanding. Greater capability to manage

and analyze high frequency real-time data brings a new level of insight on system operations. Machine-based analytics offer yet another dimension to the analytic process. Using a combination of physics-based methodologies, deep sector-specific domain expertise, increased automation of information flows, and predictive techniques, advanced analytics can be joined with the existing suite of “big data” tools. The result is the Industrial Internet encompasses traditional approaches with newer hybrid approaches that can leverage the power of both historic and real-time data with industry-specific advanced analytics.

The full potential of the Industrial Internet will be felt when the three primary digital elements—intelligent devices, intelligent systems and intelligent decision-making—fully merge with physical machines, facilities, fleets and networks. When this occurs, the benefits of enhanced productivity, lower costs and reduced waste will propagate through the entire industrial economy.



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IV. How Big is the Opportunity? Three Perspectives

To appreciate the scale of the opportunity of the Industrial Internet it is useful to first scale the global industrial system. How big is this system? The simple answer is very big. However, there is no single simple measure. We therefore suggest three different perspectives: economic share, energy requirements, and physical assets in terms of machines, facilities, fleets and networks. While not exhaustive, these measures when taken together provide a useful perspective on the vast potential scale and scope of the Industrial Internet.

Economic Perspective

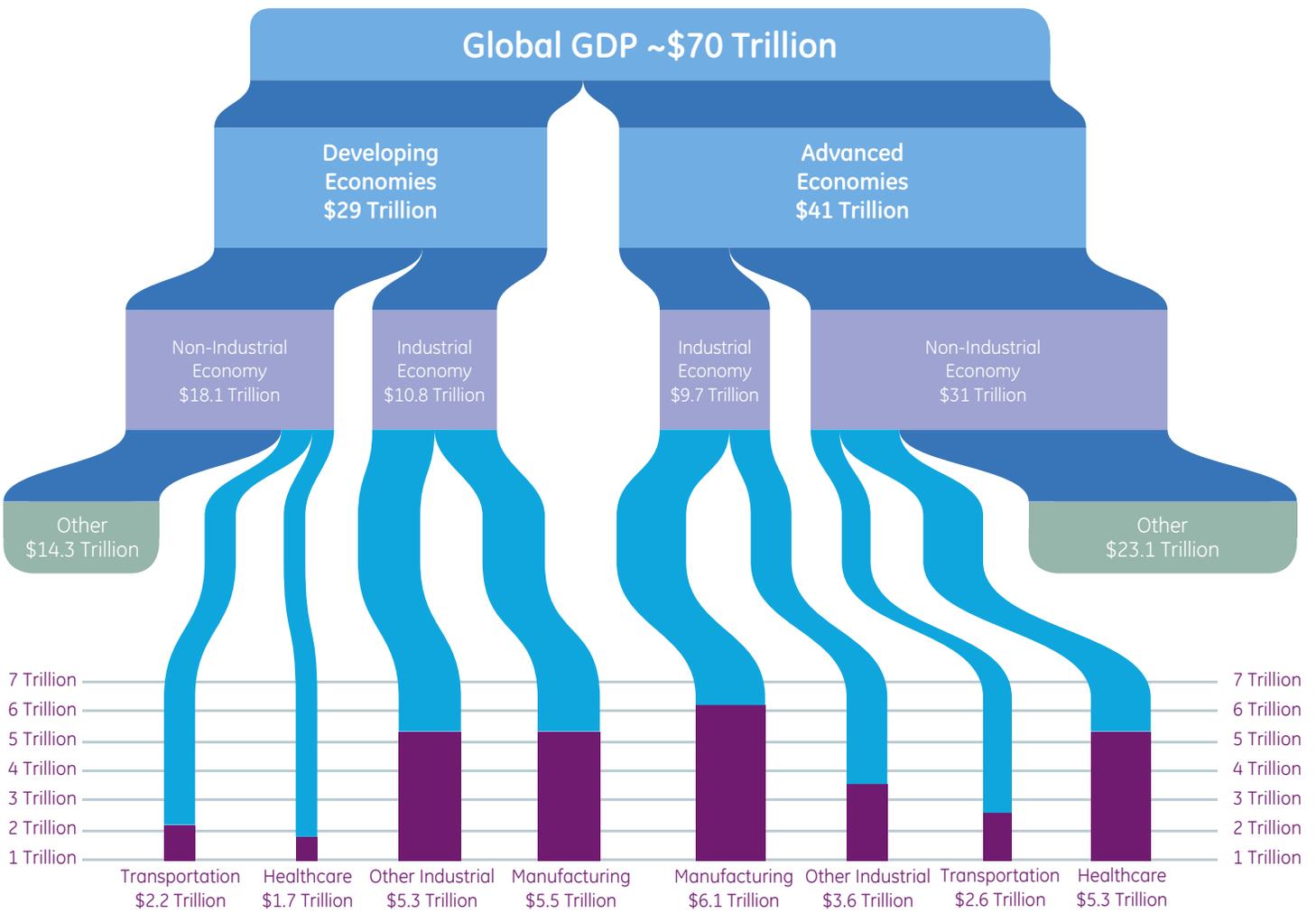
Traditional economic definitions of global industry include manufacturing, natural resource extraction, construction, and utilities sectors.⁷ Based on these categories, in 2011, global industry represented about 30 percent or \$21 trillion of the \$70 trillion dollar world economy.⁸ Of that, manufacturing of goods represented 17 percent of output, while other industries including resource extraction and construction contributed about 13 percent of global output. At a regional level, there is considerable variation depending on the economic structure and resource endowment of any particular country.

Within the developed economies, industry represents roughly 24 percent of output,

while in developing economies industrial sectors represent about 37 percent of GDP output. Within this industrial total, manufacturing activities represent 15 percent and 20 percent of advanced and developing country economic output, respectively. Thus, by traditional economic accounting measures, industrial activity represents roughly one-third of all economic activity, with country-by-country variation.

While one-third of the global economy is extremely large, it does not capture the full expanse of the Industrial Internet's potential. The Industrial Internet will encompass a broader array of sectors than captured by conventional economic categories. For example, it will also engage large swaths of the transport sector including:

Figure 5. Industrial Internet Potential GDP Share



Industrial Internet opportunity (\$32.3 Trillion) 46% share of global economy today

Source: World Bank, 2011 and General Electric

industrial transport fleets and large-scale logistical operations such as aviation, rail, and marine transport.⁹ In 2011, the global transportation services sector including land, air, marine, pipelines, telecommunications and supporting logistics services, represented about 7 percent of global economic activity. Transportation fleets are critical links in the supply and distribution chains associated with manufacturing and energy production. Here the Industrial Internet helps by optimizing timing and flow of goods within heavy industries. In commercial transport services like passenger aircraft, there are further opportunities for optimizing operations and assets while improving service and safety.

Other commercial and government services sectors will also benefit. For example, in health care, finding the critical commonalities and analogs in high-volume secure data can literally be a matter of life or death. The health care industry, including public and private spending, is estimated to comprise 10 percent of the global economy or \$7.1 trillion in 2011—a giant sector of the global economy by itself. Here the focus of the Industrial Internet shifts from optimizing the flow of goods to the flow of information and workflows of individuals—getting the right information, to the right person, at the right time.

When traditional industry is combined with the transportation and health services sectors, about 46 percent of the global economy or \$32.3 trillion in global output can benefit from the Industrial Internet. As the global economy grows and industry grows, this number will grow as well. By 2025, we estimate that the share of the industrial sector (defined here broadly) will grow to approximately 50 percent of the global economy or \$82 trillion of future global output in nominal dollars.¹⁰

The technologies of the Industrial Internet will not be instantly applied to the entire asset base corresponding to the 50 percent of the world economy described above. Introducing them will require investment, and the pace of the investment may in turn depend on the speed at which the enabling infrastructures are developed. To this extent, what we have described represents an upper limit, the available envelope. On the other hand, it also limits this envelope to those sectors where the Industrial Internet can find direct application. But the benefits of the

Industrial Internet will be felt beyond those sectors. For example, the positive impact on the health sector will result in better health outcomes, which in turn will result in fewer workdays lost because of sickness across the rest of the economy. Similarly, improvements in transportation and logistics will benefit all economic activities which rely on shipping of goods and on the reliability and efficiency of supply chains.

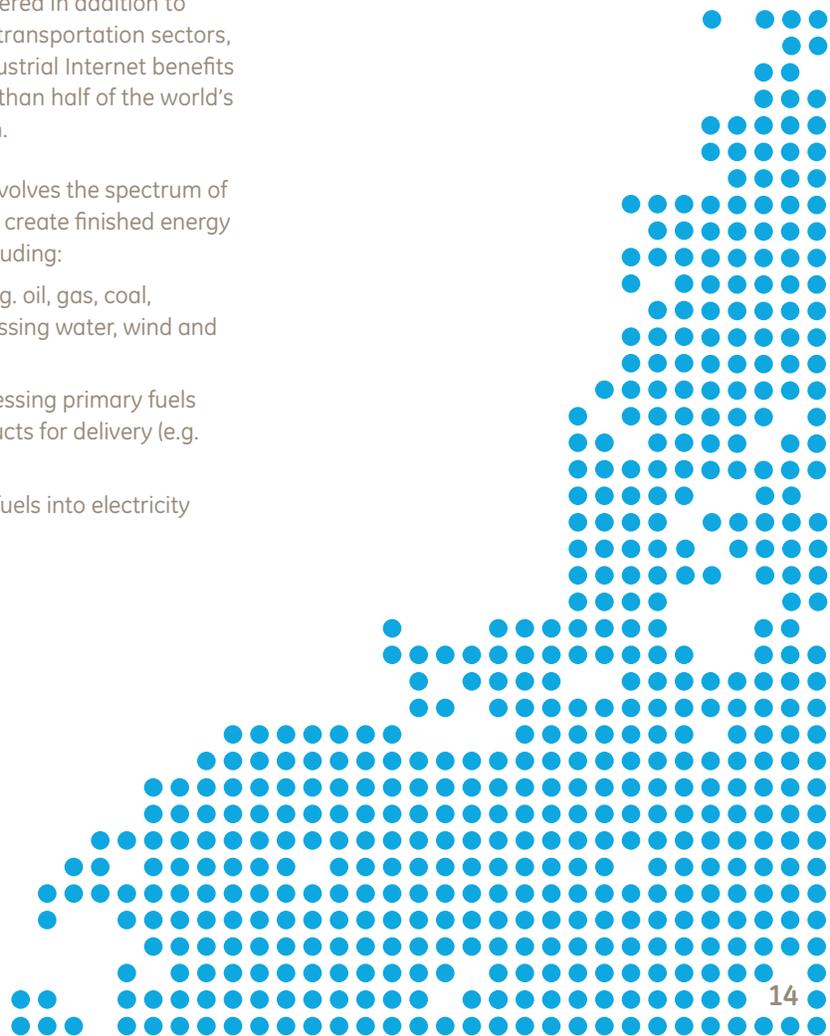
Energy Consumption Perspective

One of the key benefits of the integration of smarter technologies and robust networks is the ability to create energy saving efficiencies and reduce costs. Constraints on the energy system are intensifying. Scarcity of resources, need for better environmental sustainability, and lack of infrastructure are issues across the world. It might even be argued that the rise of the Industrial Internet is a direct response to increasing resource constraints and scarcity. Therefore, another perspective on the scale of the Industrial Internet comes from understanding the energy footprint associated with the global industrial system. Huge volumes of energy resources are required to create the goods and services the world needs. If energy production and conversion is considered in addition to manufacturing and transportation sectors, the scope of the Industrial Internet benefits encompasses more than half of the world's energy consumption.

The energy sector involves the spectrum of activities required to create finished energy for consumption including:

- Extracting fuels (e.g. oil, gas, coal, uranium) or harnessing water, wind and solar energies
- Refining and processing primary fuels into finished products for delivery (e.g. gasoline, LNG)
- Converting those fuels into electricity

About 46 percent of the global economy or \$32.3 trillion in global output can benefit from the Industrial Internet.



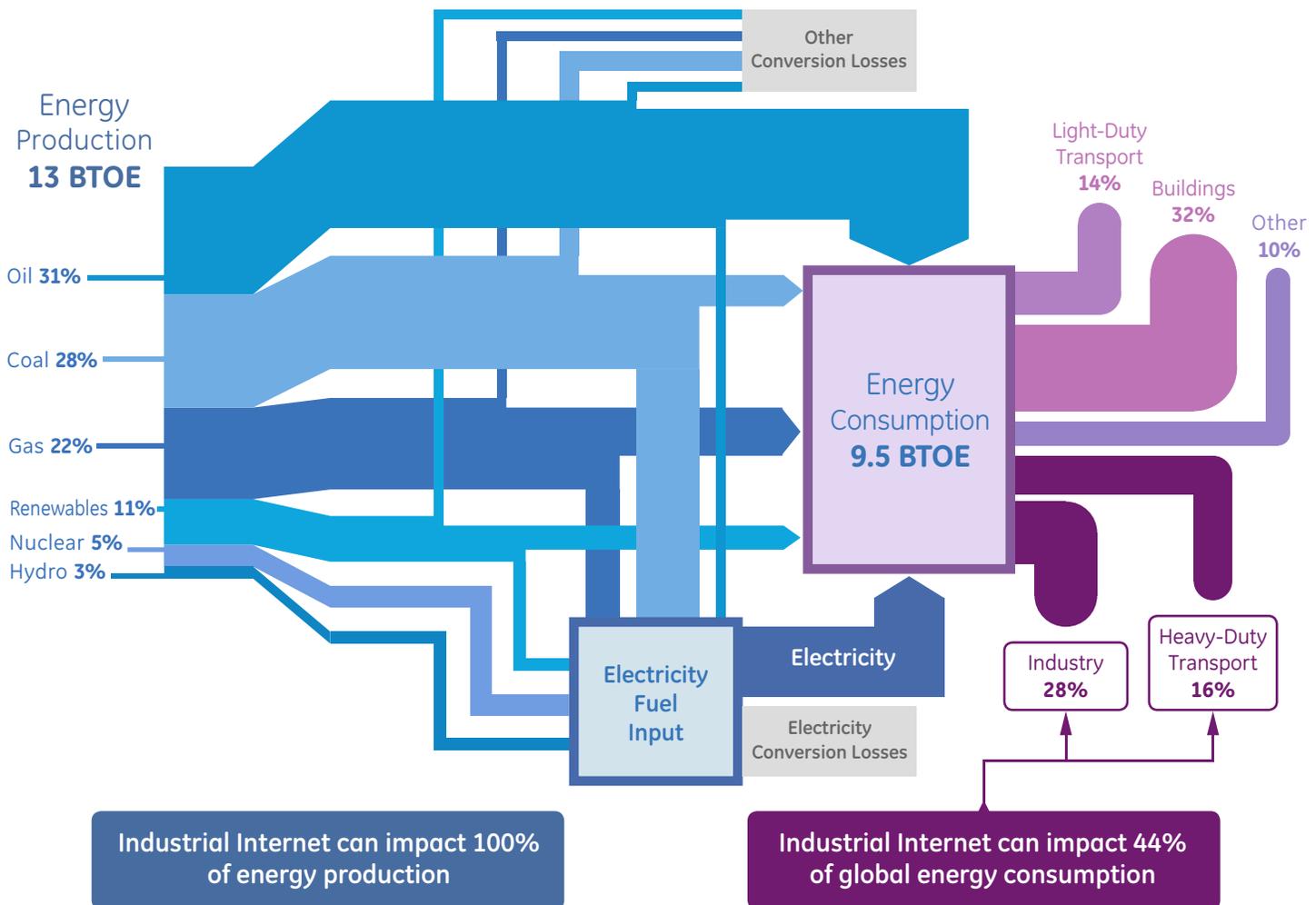
In 2011, the world produced more than 13.0 billion metric tons of energy, when converted to an oil equivalent basis (Btoe) for comparative purposes.¹¹ To help put this in perspective, all the cars and light vehicles in the United States, which now total about 240 million, consumed less than one half of one Btoe. Of this 13.0 Btoe of global primary energy production, 4.9 Btoe was converted to electricity at a conversion efficiency of about 40 percent and the other 8.1 Btoe was refined, processed for impurities, washed (in the case of coal) or converted in preparation for transport and delivery to energy consumers. It's important to recognize there are immense costs associated with energy production. To maintain and grow energy supply, the global energy industry including coal, gas, oil, and power, on average, will require about \$1.9 trillion dollars (about 3 percent of global GDP) in new capital spending each year. The large volume and cost creates tremendous scope for continued deployment of Industrial Internet technologies.

Shifting to the consumption side of the energy balance, the world's primary energy sources were converted into 9.5 Btoe of useful energy products including 1.9 Btoe of electricity and 7.1 Btoe of other finished fuels. Industrial end-users consumed 36 percent in the form of electricity, diesel fuel, metallurgical coal, natural gas, and chemical feedstocks. This roughly aligns with the manufacturing sector described in the economic perspective above. Within the industrial sector, the heaviest energy consumers are the steel and metals industries and the petrochemical industry. Together, these heavy industries represent about 50 percent of the industrial energy consumed. Recent studies indicated that if best practice technologies are deployed, heavy industry energy consumption could be reduced by 15 to 20 percent.¹² The continued and expanded Industrial Internet deployment can support this effort through process integration, life-cycle optimization, and more efficient utilization and maintenance of motors and rotating equipment.

The transportation sector is another large consumer of energy comprising 27 percent of global energy demand—primarily oil products. Within the transportation sector, approximately half (48 percent) of the fuel consumed is in heavy fleets including trucks, buses, aircraft, marine vessels, and rail locomotives. The other half of transport sector energy (52 percent) is used in light duty vehicles. Using information technology and networked devices and systems to optimize transport appears to be one of the most exciting opportunities from the Industrial Internet. Assuming most of the large fleets and a portion of the light duty vehicle fleets can benefit, perhaps 14 percent of global transportation fuel demand can be impacted by Industrial Internet technologies.

There are clearly many dimensions and challenges in achieving real changes in global energy consumption. Each system and sub-system needs to be evaluated

Figure 6: 2011 Global Energy Flows



Source: GE, Global Strategy & Planning Estimates, 2011

in terms of how it performs within the system and how it interacts with the larger energy networks. Advances over the last two decades in process management and automation appear to have been largely successful. While some parts of the energy system are being optimized, new efforts are underway. All of the many machines, facilities, fleets, and networks involved in energy production and conversion have inefficiencies that can be improved through the growth of the Industrial Internet.

Physical Asset Perspective... Things That Spin

A third perspective on opportunities to expand the Industrial Internet is to look at specific physical assets involved in various parts of the industrial system. The industrial system is comprised of huge numbers of

machines and critical systems. There are now millions of machines across the world, ranging from simple electric motors to highly advanced computed cosmography (CT scanners) used in the delivery of health care. All of these pieces of equipment are associated with information (temperature, pressure, vibration and other key indicators) and are valuable to understanding performance of the unit itself and in relation to other machines and systems.

One area of particular interest concerns critical rotating machinery. While it is probably impossible to know precisely how many machines and devices, fleets, and networks exist within the world's ever expanding industrial system, it is possible to look at some specific segments to get a feel for the scale of the industrial system.

Table 2 provides an illustrative list of major pieces of rotating machinery in key industry categories. Within this list, there are currently over 3 million types of major rotating equipment. These numbers are based on a basic review of major system processes in these machines and plants. The high degree of customization within the industrial system makes comparisons difficult. However, a general assessment can be made based on the typical sets of rotating equipment and key devices that are targets for monitoring and control. The result is an estimate of "things that spin" in parts of the industrial system. All of these assets are subject to temperature, pressure, vibration and other key metrics, which are already being, or can be, monitored, modeled, and manipulated remotely to provide safety, enhanced productivity, and operational savings.

Table 2. Things that Spin: Illustrative List of Rotating Machines

Sector	Rotating Machinery	# of Global Assets & Plants	"Big" things that spin
Transportation			
Rail: Diesel Electric Engines	Wheel Motors, Engine, Drives, Alternators	120,000	2,160,000
Aircraft: Commercial Engines	Compressors, Turbines, Turbofans	43,000	129,000
Marine: Bulk Carriers	Steam Turbines, Reciprocating Engines, Pumps, Generators	9,400	84,600
Oil and Gas			
Big Energy Processing Plants (1)	Compressors, Turbines, Pumps, Generators, Fans, Blowers, Motors	990	36,900
Midstream Systems (2)	Engines, Turbines, Compressors, Turbo Expanders, Pumps, Blowers	16,300	63,000
Drilling Equipment: Drillships, Land Rigs etc.	Engines, Generators, Electric Motors, Drilling Works, Propulsion Drives	4,100	29,200
Power Plants			
Thermal Turbines: Steam, CCGT, etc.	Turbines, Generators	17,500	74,000
Other Plants: Hydro, Wind, Engines, etc. (3)	Turbines, Generators, Reciprocating Engines	45,000	190,000
Industrial Facilities			
Steel Mills	Blast and Basic Oxygen Furnace Systems, Steam Turbines, Handling Systems	1,600	47,000
Pulp and Paper Mills	Debarkers, Radial Chippers, Steam Turbines, Fourdrinier Machines, Rollers	3,900	176,000
Cement Plants	Rotary Kilns, Conveyors, Drive Motors, Ball Mills	2,000	30,000
Sugar Plants	Cane Handling Systems, Rotary Vacuums, Centrifuges, Cystalizers, Evaporators	650	23,000
Ethanol Plants	Grain Handling Systems, Conveyors, Evaporators, Reboilers, Dryer Fans, Motors	450	16,000
Ammonia and Methanol Plants	Steam Turbines, Reformer and Distillation Systems, Compressors, Blowers	1,300	45,000
Medical Machines			
CT Scanners	Spinning X-Ray Tube Rotors, Spinning Gantries	52,000	104,000
		Total	3,207,700

Notes: Not exhaustive. (1) includes LNG processing trains, Refineries, and Ethylene steam crackers. (2) includes Compressor and pumping stations, LNG regasification terminals, Large Crude carriers, gas processing plants. (3) Only counting engines in large scale power generation greater than 30 MW

Sources: Multiple aggregated sources including Platts UDI, IHS-CERA, Oil and Gas Journal, Clarkson Research, GE Aviation & Transportation, InMedica, industrial info, RISI, US Dept. of Energy, GE Strategy and Analytics estimates of large rotating systems

Commercial Jet Aircraft

The number of rotating parts and the potential for instrumentation in the commercial jet engine fleet is significant. According to Jet Information Services, there are approximately 21,500 commercial jet aircraft and 43,000 jet engines in service around the world in 2011. Commercial jets are most commonly powered by a twin jet engine configuration. These aircraft take approximately 3 departures per day, for a total of 23 million departures annually.¹³ Each jet engine contains many moving parts; however, there are three major pieces of rotating equipment: a turbo fan, compressor, and turbine. Each of these components will be instrumented and monitored separately. In total, there are approximately 129,000 major pieces of spinning equipment operating in the commercial fleet today. Beyond the commercial jet fleets, instrumentation opportunities exist in the military and non-commercial general aviation fleets, which are over 10 times as large as the commercial jet aircraft fleet.¹⁴ The bottom line is that the opportunities for instrumentation of jet airline fleets are vast and increasing daily. GE Aviation estimates that to meet the growing needs of air travel another 32,000 engines might be added to the global fleet over the next 15 years. This represents another 100,000 pieces of

rotating machinery in the global fleet of commercial engines.

Combined Cycle Power Plants

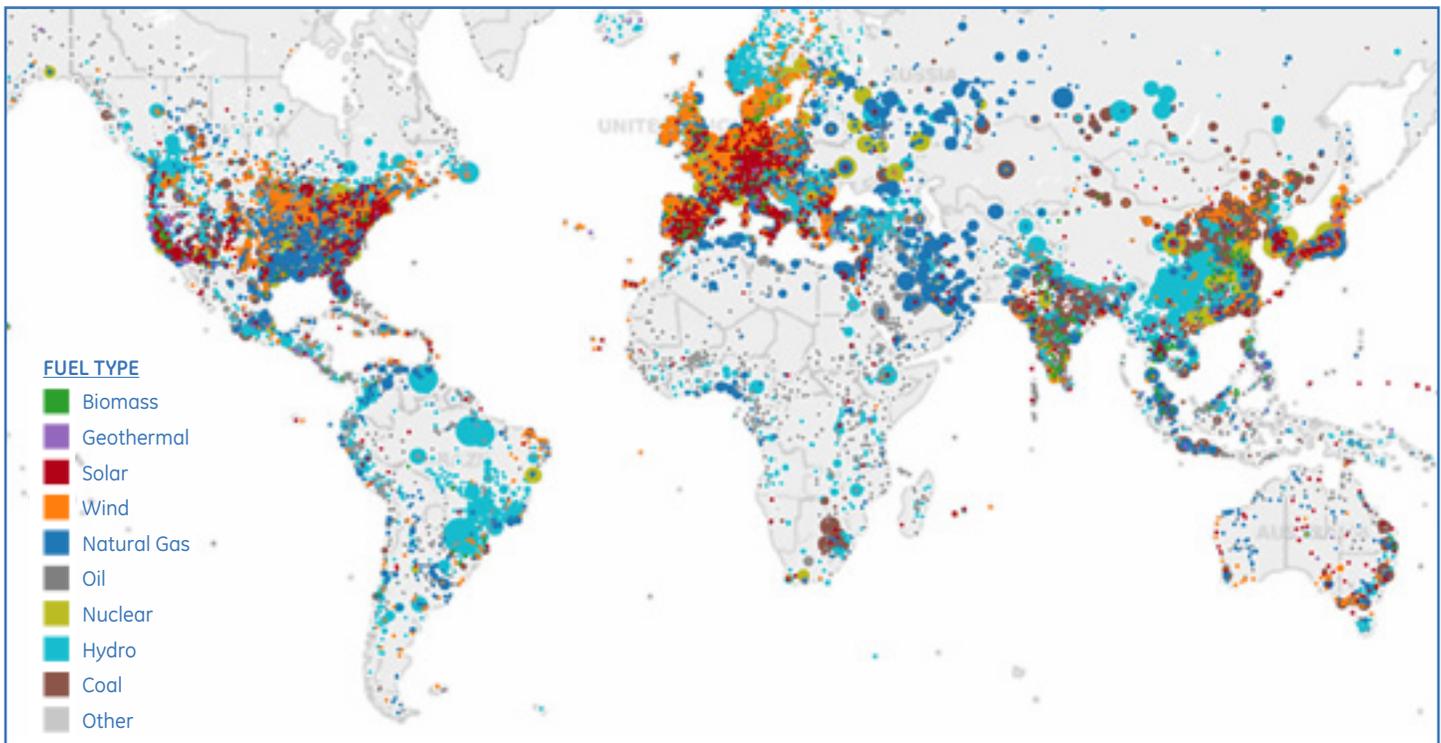
The opportunities for Industrial Internet instrumentation are just as vast in the global fleet of power plants. There are 62,500 power plants operating around the world today with a capacity of 30 megawatts or greater. The total global capacity of power plants is approximately 5,200 gigawatts (GW). These plants are displayed in Figure 7. Consider only the large amount of instrumentable rotating parts in just one small slice of this fleet: combined cycle power plants, which represent just 2.5 percent of global power plants, or 1,768 plants. These plants have a global installed capacity of 564 GW.¹⁵

Combined cycle gas turbines use both gas turbines and steam turbines in tandem, converting the same source of heat—natural gas—into mechanical and then electric energy. By combining gas and steam turbines, combined cycle gas turbines use two thermodynamic cycles (gas turbine Brayton cycle and a steam turbine Rankine cycle) to improve efficiency and reduce operating costs. A combined cycle gas turbine power plant typically uses multiple sets of gas turbine-steam turbine combinations.

The most common combined cycle configuration today is a 2x1, which uses two gas turbines and one steam turbine. In this example, there are 6 major rotating components: 2 gas turbines, 2 gas turbine generators, one steam turbine and one steam turbine generator. Beyond the big critical systems, we estimate that there are another 99 rotating components in the balance of plant—from feed water pumps to air compressors. In all, there are 105 rotating components in a 2x1 combined cycle power plant that are instrumentable.

Consider the implications for the global combined cycle fleet. If instrumentation was applied to every component in all 1,768 plants, this would represent about 10,600 major system pieces and 175,000 smaller rotating parts available for instrumentation. Looking forward over the next 15 years, another 2,000 combined cycle plants amounting to 638 GW of capacity are likely to be added to the global industrial system.¹⁶ This will add another 12,000 units of large rotating equipment and at least another 200,000 pieces of smaller rotating equipment to complete these plants. If other types of power plants are considered, the scope for further expansion of Industrial Internet technologies is clearly significant.

Figure 7. Global Power Plant Fleet by Technology



Source: Power plant data source Platts UDI Database, June 2012

Note: Circle size represents installed capacity (MW).

Locomotives

Locomotives haul vast quantities of raw materials and goods around the world. In 2011, there were more than 9.6 trillion tonne-kilometers of freight transported via the world's 1.1 million kilometer rail system. In that system today, there are approximately 120,000 diesel-electric powered rail engines worldwide. There are about 18 major rotating components within a diesel-electric locomotive that can be grouped into six major systems: traction motor, radiator fan, compressor, alternator, engine, and turbo. If instrumentation was applied to every component of the rail fleet, this would represent more than 2.2 million rotating parts available for instrumentation. Conservative forecasts expect about 33,000 new diesel-electric locomotives to be delivered in the next 15 years— which would entail significant monitoring as 396,000 sensors will be deployed by 2025 in diesel-electric locomotives alone.

Oil Refineries

Refineries and petrochemical plants have been targets for advanced monitoring and control for many years. Older facilities with vintage technologies are being forced to compete with new state-of-the-art greenfield facilities. At the same time, the boom and bust cycles of the oil business, coupled with stricter environmental compliance, are driving the need for continuous process enhancements and adjustments. Rotating machines such as reciprocating and centrifugal compressors, along with hundreds of pumps, are the critical components of energy processing plants including refineries. Today, operators are monitoring and modeling these devices for preventative maintenance and safety along with total plant optimization. Managing these plants for efficiency, safety and enhanced productivity is one of the places where the Industrial Internet is working today.

To give a sense of scale, there are 655 oil refineries in the world, representing 88 million barrels per day of crude input capacity—approximately equal to daily world oil consumption.¹⁷ Each modern refinery has approximately 45 large rotating systems within the various critical refinery processes including crude and vacuum distillation, coking, hydrocracking, hydrotreating, and isomerization. Some refineries will be smaller, others more complex, as each refinery in the world is essentially a customized industrial

plant depending on the crudes it processes and the consumers it serves. Key equipment sets in most refineries include centrifugal charge pumps, wet and dry compressor sets, power turbines, and air coolers. If just the major systems are considered, there are approximately 30,000 big things that spin in a refinery. Beyond this, there are hundreds of pumps and smaller devices that are targets for system monitoring. Over the next fifteen years, the world could need more than 100 new refineries, and major expansion to existing refineries, to meet the increasing needs of emerging markets.¹⁸ This represents incremental need for process management and automation on more than 4,500 large rotating systems in oil refineries alone.

Health Care

Although it is not commonly recognized, health care delivery also involves rotating machinery. One example is computed tomography (CT) scanners. These machines are used to visualize internal structures of the body. CT scanners employ a rotating x-ray device to create a 3-D cross-sectional image of the body. Globally there are approximately 52,000 CT scanners. They are used for diagnostic and treatment evaluation across a wide spectrum of applications including: cardiac, angiography, brain, chest, abdomen, and orthopedic.

These examples are only a portion of the millions of machines and critical systems that can be monitored, modeled, and remotely controlled and automated. The rise of more robust global networks will only improve the ability to more efficiently deploy assets, improve servicing and safety, and optimize the flow of resources. The gains from technology integration will require adoption of new equipment along with retrofitting and refurbishing of older machines. This will create new possibilities in process optimization, increased total factor productivity, and decreased cost structures. These systems are expected to change the competitive balance in various industries, forcing rapid adoption by many businesses to survive. The next sections examine the potential benefits and challenges facing the deployment of the Industrial Internet.



imagination at work



V. The Benefits of the Industrial Internet

The Industrial Internet promises to have a range of benefits spanning machines, facilities, fleets and industrial networks, which in turn influence the broader economy. As discussed above, the global industrial system is vast. In this section, we review the potential industry-specific benefits in more detail and conclude that even relatively small improvements in efficiency at the sector level could have sizeable benefits when scaled up across the economic system. Further, we examine how productivity trends have impacted economic growth over the last few decades and estimate what broad diffusion of the Industrial Internet could yield in the global economy over the next twenty years.

The Industrial Internet opens the door to a variety of benefits for the industrial economy. Intelligent instrumentation enables individual machine optimization, which leads to better performance, lower costs and higher reliability. An optimized machine is one that is operating at peak performance and enables operating and maintenance costs to be minimized. Intelligent networks enable optimization across interconnected machines.

Some companies have been early adopters, realizing benefits and overcoming challenges related to capturing and manipulating data streams. Historically, many of these efforts have centered on the digital controls systems of industrial assets with performance scope that is narrow and compartmentalized relative to what is now becoming possible. Given the size of the asset base involved, broader integration of systems and sub-systems at the product level through intelligent devices is expected as sensing and data handling costs fall.

At the other end of the spectrum, enterprise management software and solutions have been widely adopted to drive organizational efficiencies at the firm level. The benefits of these efforts include better tracking and coordination of labor, supply chain, quality, compliance, and sales and distribution across broad geographies and product lines. However, these efforts have sometimes fallen short because while they can passively track asset operations at the product level, the ability to impact asset performance is limited. Optimizing the system to maximize asset and enterprise performance is what the Industrial Internet offers.

System-wide optimization allows people at work to achieve efficiency improvements and cost reductions beyond those achievable through individual machine optimization. Intelligent Decisioning will

allow smart software to lock-in machine and system-level benefits. Further, the benefits of continued learning holds the key to the better design of new products and services—leading to a virtuous cycle of increasingly better products and services resulting in higher efficiencies and lower costs.

Industrial Sector Benefits: The Power of One Percent

Industrial assets and facilities are typically highly customized to the needs of the sector. Benefits will vary and different aspects of the Industrial Internet are emphasized. However, there are common themes of risk reduction, fuel efficiency, higher labor productivity, and reduced cost. To illustrate the benefits of the Industrial Internet in greater detail, we examine a number of sector-specific examples. Each example highlights how small improvements, even as small as one percent, can yield enormous system-wide savings when scaled up across the sector.

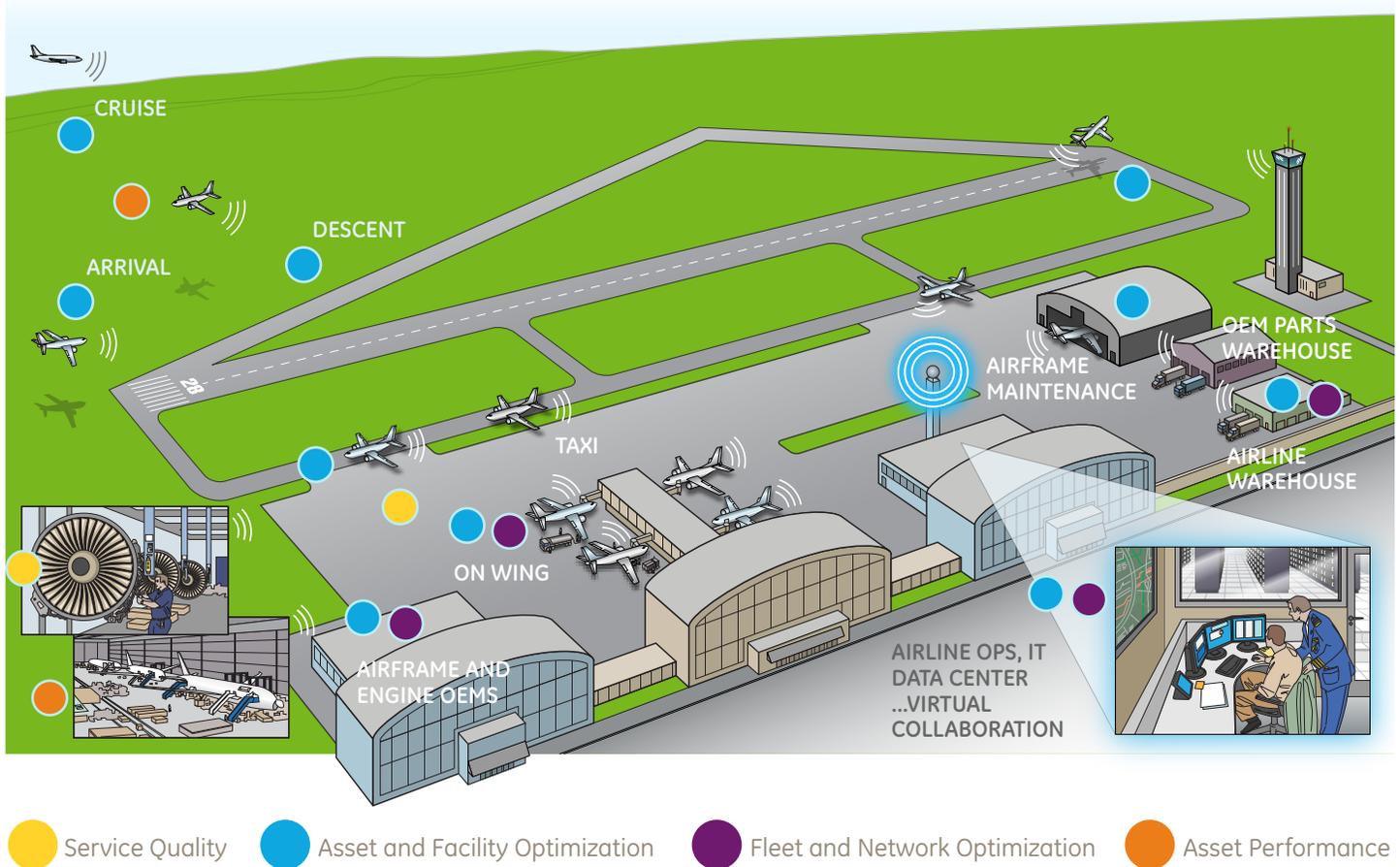
COMMERCIAL AVIATION

The airline industry, like other commercial transportation systems, is ideally positioned to further benefit from deployment of the Industrial Internet. By focusing on optimizing operations and assets while improving safety at every phase of airline operations, Industrial Internet applications have the potential to transform the airline industry.

The Industrial Internet has the potential to improve both airline operations and asset management. Operations can be transformed through fuel reduction, improvement in crew effectiveness, reduction in delays and cancellations, more efficient maintenance planning and parts inventory, and optimal flight scheduling. Airline assets can be better optimized through improved preventive maintenance which will extend engine lives and limit unscheduled interruptions.



Figure 8. Aviation Industrial Internet



One vision for how the Industrial Internet can impact aviation comes from the area of aircraft maintenance inventory management. An intelligent aircraft will tell maintenance crews which parts are likely to need replacement and when. This will enable commercial airline operators to shift from current maintenance schedules that are based on the number of cycles to maintenance schedules that are based on actual need. The combination of sensor, data analytics, and data sharing between people and machines is expected to reduce airline costs and improve maintenance efficiency. These systems will act like virtual proactive maintenance teams, determining the status of the aircraft and its subsystems to supply real time, actionable information to help aircraft operators predict failures before they occur and provide a quick and accurate “whole plan” view of health.

As the industry becomes more comfortable with the ability of intelligently monitored equipment to signal the need for replacement, there is an opportunity to move away from traditional part replacement cycles. Regulations require

airlines to service or replace parts after a certain number of flight cycles. The efficiency benefits from replacing parts at the right time, rather than when the part cycles dictate, look to be substantial. Assuming all safety measures can be met or improved, parts inventories can be reduced, aircraft utilization can be increased, and costs can be reduced. Operators can detect a problem and see exactly where it has occurred in an easily accessible, accurate, and concise manner.

Over the last few decades, the global commercial airline industry has grown 2-3 times faster than the global economy, expanding generally at the same pace as world trade.¹⁹ Today, global commercial airline revenues are around \$560 billion per year. However, profitability and return on capital invested remain significant challenges for the industry.²⁰ These challenges highlight the focus on fuel costs—which account for nearly 30 percent of industry costs, and the potential benefits of improving asset utilization. In the US, the Federal Aviation Administration (FAA) conducted a study that showed that over

an 8-year period, flight inefficiencies boosted costs by an average of 8-22 percent.²¹ The implication is there are large potential savings if higher productivity can be achieved.

The global commercial airline business is spending about \$170 billion per year on jet fuel. Estimates within the industry point to perhaps 5 percent cost reduction from better flight planning and operational changes: a benefit of over \$8.0 billion per year. If Industrial Internet technologies can achieve only one percent in cost reduction, this would represent nearly \$2 billion per year—or about \$30 billion in fuel cost savings over 15 years.

Another potential benefit comes from avoided capital costs. From 2002 to 2009 the commercial aviation industry spent almost \$1.0 trillion dollars or \$135 billion per year.²² If better utilization of existing assets from the Industrial Internet results in a one percent reduction in capital expenditures, the savings benefit could total \$1.3 billion dollars per year or a cumulative benefit of approximately \$29 billion dollars over 15

years. From an operations perspective, the average cost of maintenance per flight hour for a two engine wide-body commercial jet is approximately \$1,200.²³ In 2011, commercial jet airplanes were in the air for 50 million hours. This translates into a \$60 billion annual maintenance bill. Engine maintenance alone accounts for 43 percent of the total, or \$25 billion. This means that commercial jet engine maintenance costs can be reduced by \$250 million for every one percent improvement in engine maintenance efficiency due to the Industrial Internet.

RAIL TRANSPORTATION

The primary networks in the global ground transportation system are the commercial motor fleets and railway systems. The scope for Industrial Internet application within global transportation systems is tremendous. At the machine level, vehicle and locomotive instrumentation will provide a foundation for insightful analytics to solve velocity, reliability, and capacity challenges. Real-time diagnostics and predictive analytics will reduce maintenance costs and prevent machine breakdowns before they occur. At the fleet level, fleet instrumentation holds the promise of eliminating waste in fleet scheduling. Furthermore, there is flexibility in optimization targets. Fleets can be optimized for cost minimization, speed, or optimal supply or distribution chain timing.

One example from the railway system is movement planning software. These tools can deliver real-time overviews of network operations from a single, sophisticated display, giving operators the information they need to make optimal decisions. With this software, rail operators can monitor trains in both signaled and non-signaled territories using global positioning systems, track-circuits, automatic equipment identification readers, and time-based tracking. Built-in traffic management applications give operators the ability to effectively manage train schedules and swiftly respond to unexpected events. These software solutions create the basis for future Industrial Internet-enabled global railway systems. This digital architecture is a critical component to realize potential benefits in improved rail operations.

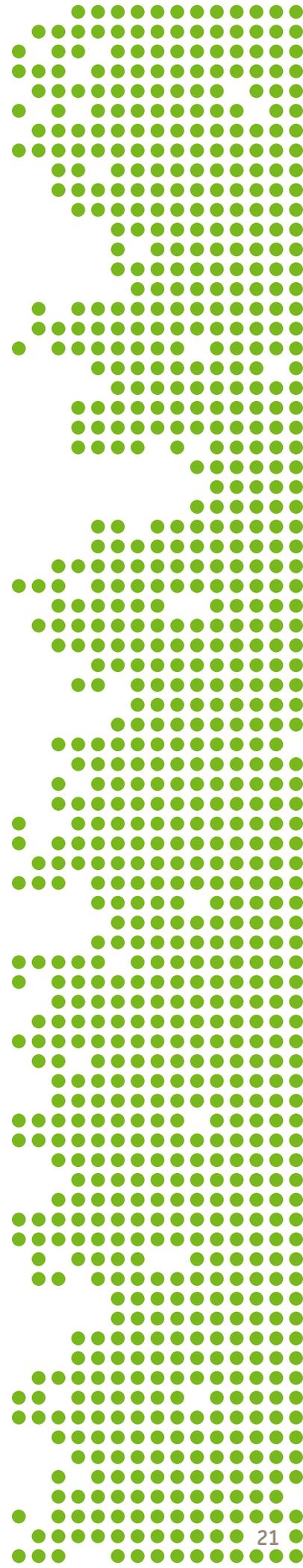
Globally, transportation logistics costs are estimated to be \$4.9 trillion dollars per year, or approximately 7 percent of global GDP.²⁴ Rail transportation investment, operations

and maintenance costs account for 5 percent of this total, or \$245 billion per year. Rail operations costs represent 75 percent of total rail transport costs, or \$184 billion per year. GE Transportation estimates that 2.5 percent of rail operations costs are the result of system inefficiencies. This amounts to \$5.6 billion per year in potential savings. If only one percent savings can be achieved, the amount saved would be about \$1.8 billion per year or about \$27 billion over 15 years. Similar types of efficiencies appear possible in heavy duty trucking, transport fleets and marine vessels, meaning much larger transportation system benefits can likely be realized.

POWER PRODUCTION

Energy production is another key sector where the Industrial Internet benefits look to be substantial. The global power system encompasses about 5,200 GW of generation capacity. For reference, 1 GW of capacity can power about 750,000 US homes. In addition, there are millions of miles of high voltage transmission lines, sub-stations, transformers, and even more distribution lines. Many of the concepts such as machine preventative maintenance or fleet optimization that apply to the transportation sector can be applied to the power sector as well, along with the broad objectives of reliability, enhanced safety, increased productivity, and fuel efficiency.

Power outages are not only costly, but disruptive and dangerous. Many times outages are not restored, sometimes for weeks, because the location of a broken power line is not known immediately, or a massive system overhaul is needed and parts may be on the other side of the world. With the Industrial Internet, everything from the biggest machines generating power to transformers on power poles can be connected to the Internet, providing status updates and performance data. From that, operators take preemptive action on a potential problem before it causes millions or billions of dollars of company and customer time. Additionally, field representatives would avoid the costly 'go see' approach to the problem before planning to repair, and they will be able to anticipate the issue and be prepared with the parts to fix it. This includes supporting utilities in minimizing the costs associated with tree trimming. By combining information about their transmission assets, vegetation, and climate, the probability of an outage due to



New data compression techniques are allowing plant operators to track changes in massive data streams instead of tracking every piece of data all of the time.

vegetation can be determined, as well as the potential impact of the outage. This would allow operators to better prioritize tree trimming operations and minimize costs.

Another example highlights how power plant operations are changing with the rise of the Industrial Internet. New data compression techniques are allowing plant managers to track changes in massive data streams instead of tracking every piece of data all of the time. For the operator, it may only be the relationship between two data sets that is monitored. Before, an operator might have missed the correlation between hot weather, high loads, high humidity, and poor unit performance. Now it is much easier to compare and visualize the changes in big data sets in relation to each other. This enables companies to engage in constant learning. In the future, the engineer can just ask a question concerning an irregularity, and historic analogs are mined across thousands of units in service over time—and an answer materializes in seconds. The expectation is faster response can improve efficiencies and reduce costs.

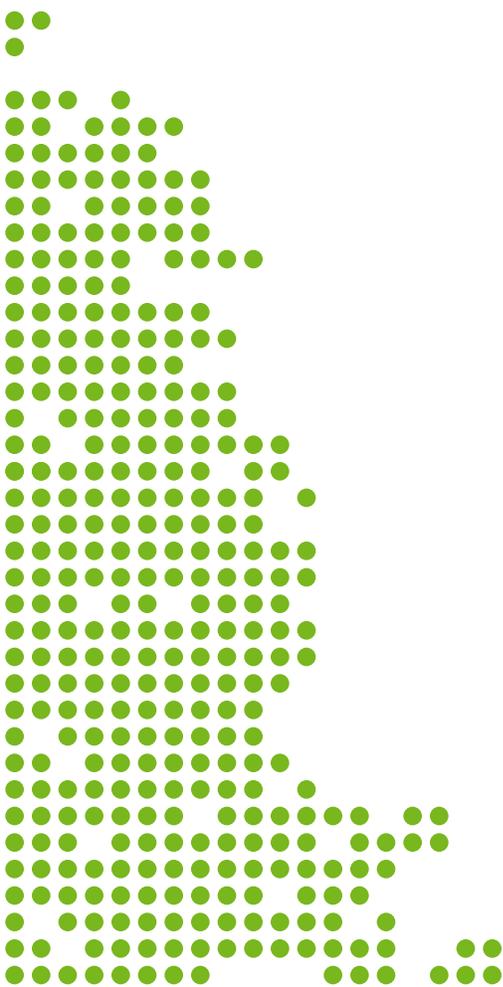
As these techniques and practices expand across the world, it is interesting to think about how the impact of the Industrial Internet could scale up. This next example relates to fuel costs. Globally, GE estimates that about 1.1 Btoe of natural gas is consumed in gas-fired power plants to create electricity.²⁵ The price of natural gas varies dramatically around the world. In some countries, natural gas prices are indexed to the price of oil. In other countries like the US, natural gas prices are determined in a free market based on supply and demand fundamentals. Globally, GE estimates that the power sector spent more than \$250 billion last year on fuel gas, and by 2015 spending is expected to grow to about \$300 billion and may exceed more than \$440 billion by 2020.²⁶ Efficiency gains can likely be realized from Industrial Internet technologies tied to improved integration of the natural gas and power grids. Using a conservative assumption that the fuel savings from a one percent improvement in country-level average gas generation efficiency can be realized, fuel spending would be reduced by more than \$3 billion in 2015 and \$4.4 billion in 2020. Over a 15-year period, the cumulative savings could be more than \$66 billion.

OIL & GAS DEVELOPMENT AND DELIVERY

The oil and gas industry provides some rich examples of how the Industrial Internet is getting deployed to achieve productivity gains and optimization of industrial processes. The upstream side of the oil and gas industry has been increasingly forced to look further and further to the frontiers for new large-scale supplies of oil and gas as traditional reserves deplete. Many industry observers note that while resource potential remains enormous, it will take more capital and technology to bring these to market. The age of easy oil and gas resource development is ending; however, scrutiny of oil and gas activities is only increasing. Companies are operating in an environment of increasing transparency, in part from information technology, but also because the risks and capital intensity of the business are driving the need for more collaboration between industry, regulators, and society. This reality is driving the oil and gas industry to achieve a number of important goals including:

- Increased operational effectiveness and enhanced productivity
- Lower life cycle costs in project development, operations, and maintenance
- Constant improvement in safety, environmental, and regulatory compliance
- Refurbish aging facilities and adjust to shifting workforce demographics
- Develop local capabilities and support increasingly remote logistics

While the complexity of operations is increasing by many measures, the potential for cost savings and efficiency gains from the Industrial Internet remains high. Clear examples are emerging of how the Industrial Internet can boost availability of key equipment sets, reduce fuel consumption, enhance production rates, and reduce costs. Traditionally, the oil and gas industry has been a slow adopter of new technologies. Companies prefer strong references and proof of technology before new technologies get deployed, given the enormous sums of capital in play. While technology uptake has traditionally been slow, there have been three distinct phases of technology adoption that are occurring in direct response to the key challenges facing the industry. Each phase of technology integration has brought significant benefits to the industry and these efforts are directly responsible for widening the necessary resource base.



The industry has moved over the last decade toward adoption of selected technologies along the upstream value chain.

Examples include:

- Downhole sensors tracking events in the wells, intelligent completions optimizing product flow, and well stimulation to increase productivity
- Wireless communication systems that link subsurface and above-ground information networks in local facilities with centralized company sites
- Real-time data monitoring for safety and optimization
- Predictive analytics to better understand and anticipate reservoir behavior
- Temporal monitoring, like 4-d seismic, to understand fluid migration and reservoir changes as a result of production efforts over time

These efforts in many cases have lowered costs, increased productivity, and expanded resource potential.

The notion of oil resource potential offers a perspective on the value of the Industrial Internet. The global oil resource base is vast, but recovery rates are relatively low. Globally, average recovery rates are only 35 percent or 35 out of 100 barrels in the ground are brought to the surface using current technology.²⁷ The idea of the digital oil field has been popular for more than a decade.²⁸ Early estimates pointed to 125 billion barrels of additional oil reserves over ten years if digital technologies were aggressively deployed.²⁹ Since this time, the industry has been progressively moving from broadly scoping the concepts and overcoming reliability and connectivity concerns, to now successfully managing data and running operations centers— to create the most value for each technology dollar spent. Today, global oil production is about 84 million barrels per day or 31 billion barrels per year (4.0 Btoe).³⁰ Current proved oil reserves are estimated at about 1,600 billion barrels. The potential for gains remains high, especially in less mature oil regions. Assuming that another wave of Industrial Internet technologies adoption can increase proved reserves by one percent, this would translate to 16 billion barrels or one-half of the world's oil requirements for a year. While the above example is illustrative, and realistically, these new reserves would be realized over a longer time period, the point remains—the volume potential

from small improvements in recovery appear substantial.

Another way to think about the benefit is from a capital expenditure efficiency perspective. Oil and gas upstream spending is estimated at \$600 billion dollars in 2012.³¹ Going forward, GE estimates spending rates could increase at perhaps 8 percent per year to fuel the world with the oil and gas it needs.³² If only one percent of reductions in capital expenditure can be achieved by Industrial Internet technologies, in addition



to what is already being deployed, this translates into more than \$6 billion per year in savings or \$90 billion over 15 years.

HEALTH CARE

The digitization of health care holds the unique promise of transforming our lives by providing a greater quality of life for people across the globe. The global health care industry is another prime sector for Industrial Internet adoption because of the strong imperatives to reduce costs and improve performance. Health care is a priority challenge for nearly every country today: most advanced economies need to improve efficiency and contain costs in the face of rapidly aging populations; meanwhile, many emerging markets need to extend the reach of health care services to burgeoning urban centers and sprawling rural populations.

The global health care industry is vast, accounting for 10 percent of global GDP in 2011. The scope for efficiency improvements is just as large. It is estimated that more than 10 percent of those health expenditures are wasted from inefficiencies in the system, meaning the global cost of health care inefficiency is at least \$731 billion per year.³³ Clinical and operations inefficiencies, which can be most directly impacted by the Industrial Internet, account for 59 percent of healthcare inefficiencies representing \$429 billion per year. It is estimated that deployment of the Industrial Internet can help to drive these costs down roughly 25 percent, or about \$100 billion per year in savings.³⁴ In this case, a one percent reduction in costs translates to \$4.2 billion per year—or \$63 billion over 15 years.

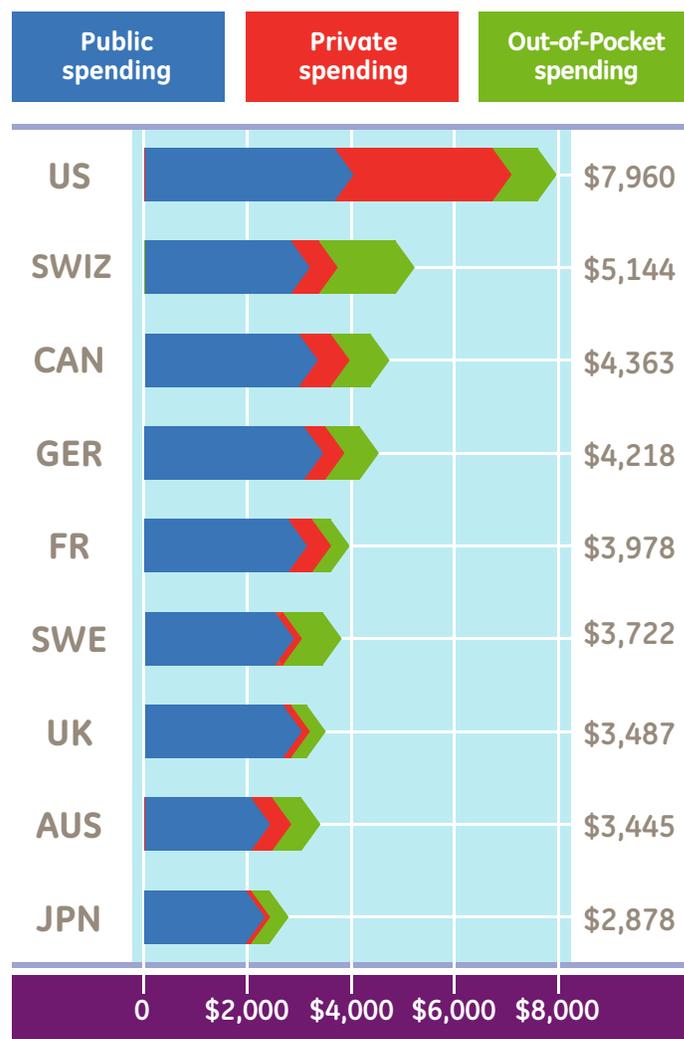
The range of Industrial Internet applications in the global health care industry is as large as the potential cost savings. The role of the Industrial Internet in health care is to enable safe and efficient operations to reclaim hundreds of millions of hours in lost utilization and productivity, and the resulting patient throughput. Consider the personal benefits of enhanced MRI scanning and diagnostics that are enabled by the Industrial Internet. While effective in helping to diagnose multiple sclerosis, brain tumors, torn ligaments and strokes, today data produced by imaging machines are not as connected to the people that need it the most—the doctors and the patients—as they could be. At the operations level, there are many individuals working as a team to make the scan happen. A nurse administers medications or contrast agents that may be needed for the exam; an MRI technician operates the scanner; and a radiologist identifies the imaging sequences to be used and interprets the images. This information is then given to the nurse, who then passes it to the primary doctor to review and take action accordingly. This is “Big Data,” but it is not making information more intelligent.

To make information intelligent, new connections need to be developed so that Big Data ‘knows’ when and where it needs to go, and how to get there. If imaging data is better connected, the right doctor could automatically receive a patient’s rendered images – so the information is finding the doctor instead of the doctor finding the information. Additionally, when the right doctor has viewed the image, further connections could enable these images to ‘know’ they need to be filed in the patient’s digital medical record. This type of proactive, secure routing of digital medical data may seem like a simple upgrade in workflow, but in actuality

it represents one of the promising ways that the Industrial Internet can boost productivity and treatment outcomes.

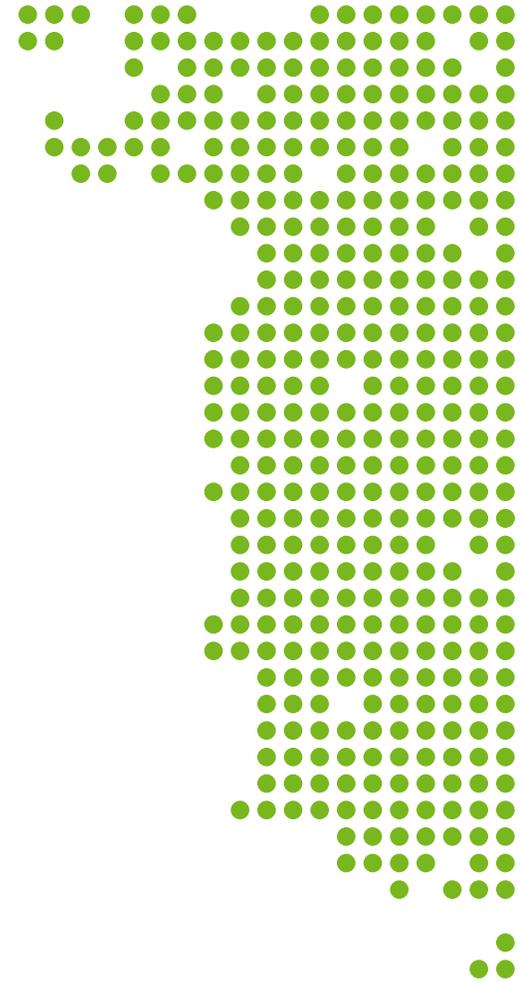
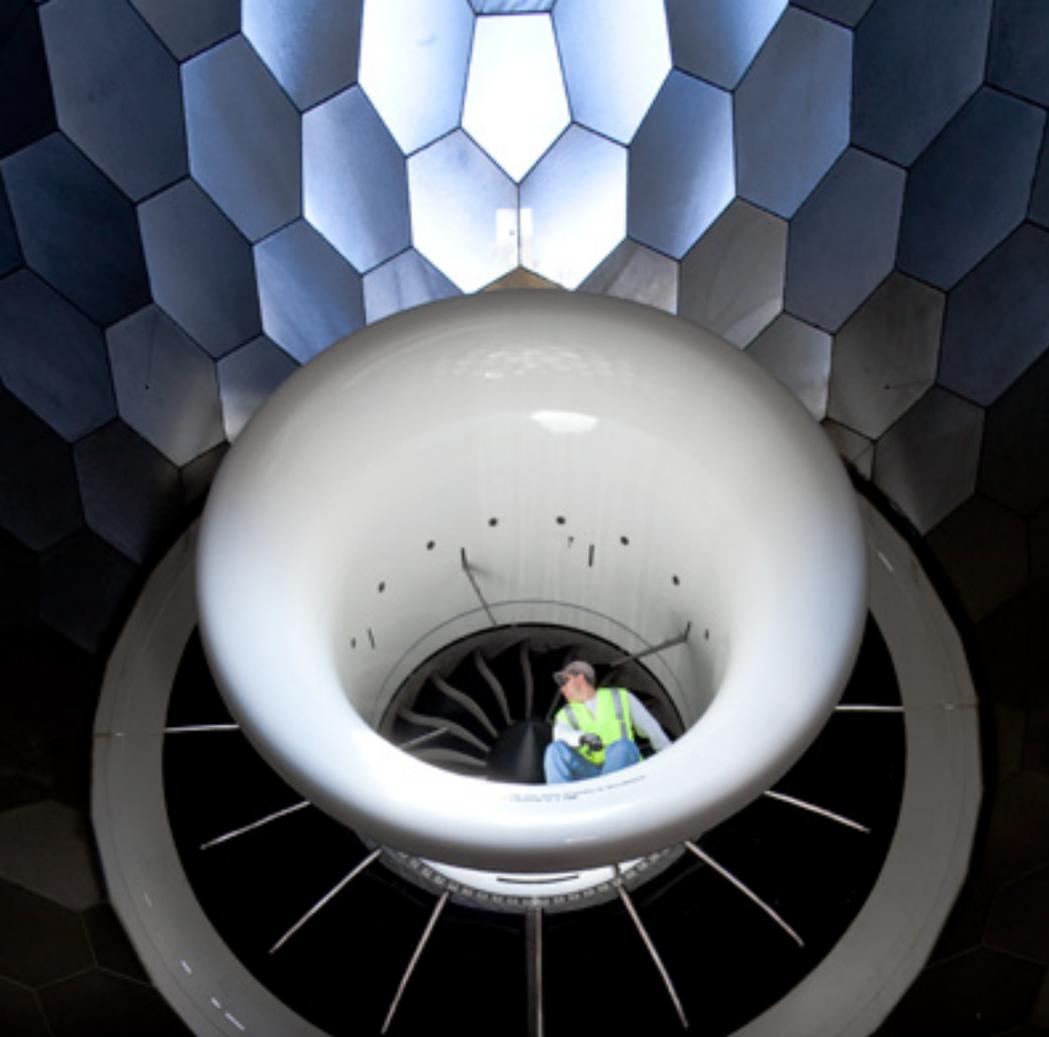
A system-level Industrial Internet application opens the possibility of creating a “care traffic control system” for hospitals. Hospitals are comprised of thousands of pieces of critical equipment, much of which is mobile. The key is knowing where it all resides, and having a system that can alert doctors, nurses and technicians to changes in status, and provide metrics to improve resource utilization and patient and business outcomes. These types of systems are beginning to be deployed today and represent the beginning of the Industrial Internet in health care. GE Healthcare estimates that these innovations can translate into a 15 to 30 percent reduction in hospital equipment costs and permit healthcare workers to gain an additional hour of productivity on each shift. These approaches also increase asset capacity utilization, workflow and hospital bed management. This results in a 15 to 20 percent increase in patient throughput. Clearly, the

Figure 9. Health spending per capita*



GDP Per Capita (USD\$)

*Health spending per capita by source of funding, adjusted for cost of living. Source: OECD Health Data 2011 (June 2011)



way in which the Industrial Internet will operate across various sectors is complex and diverse. Furthermore, the scope for significant benefits in terms of operational efficiency, reduced expenditures, and increased productivity are vast. Using a conservative improvement measure of just one percent, the larger picture of enormous industrial system-wide savings starts to emerge. The measurable benefits will be not just reduced costs and more effective capital spending, but improved productivity.

Economy-wide Gains: The Next Productivity Boom

Productivity is the ultimate engine of economic growth, a key driver of higher incomes and better living standards. Faster growth in labor productivity allows a workforce to produce more and to earn increased wages. And in an era where constraints are powerful and pervasive, productivity is even more important: higher productivity delivers greater benefits to firms and governments that need to make every dollar of investment count; and higher productivity makes every gallon or ton of natural resources go a longer way,

a crucial contribution to sustainability as large emerging markets populations strive to achieve better living standards and greater consumption levels.

The Industrial Internet can therefore be the catalyst for a new wave of productivity, with powerful beneficial consequences in terms of economic growth and incomes. Just how large could the benefits be? The first wave of the Internet Revolution boosted US labor productivity growth to an average annual rate of 3.1 percent during 1995-2004, twice the pace of the previous quarter-century. If that productivity growth differential can be recaptured and maintained, by 2030 it would translate to an average income gain of \$20,000 or about 40 percent of today's US per capita GDP. If productivity growth were to rise to a more conservative 2.6 percent, lower than the Industrial Revolution-driven pace of 1950-68, it would still deliver an average income gain equivalent to one-quarter of today's per capita GDP.

As the US and other early adopters push the technological frontier, this increases the need for faster productivity and resulting

income growth in the rest of the world. The benefits of the Industrial Internet should prove immediately obvious in advanced manufacturing; in the US, this could give an important boost to restoring employment to its pre-crisis levels. Emerging markets will keep boosting infrastructure investment; if they become early adopters of the new technologies, they could greatly accelerate and amplify the impact of the Industrial Internet on the global economy. During 1995-2004, the surge of information technology investment across the world boosted global GDP growth by nearly one percentage point; now that emerging markets account for nearly half of the global economy, their impact could be even greater.

Whether productivity growth slows or accelerates will make a huge difference to the U.S. and to the rest of the world. And yet, productivity growth is a relatively recent phenomenon. For much of human history, until about 1750, there was virtually no productivity growth—and very little economic growth. Then came the Industrial Revolution—as discussed earlier in this

paper—and economic growth took off. The impact of the Industrial Revolution was long-lived. While the second wave of innovation stopped in 1900, its discoveries continued to be incorporated in new products and exploited in new ways for several more decades. US productivity growth, which had been close to zero before the Industrial Revolution started, was running at close to 3 percent per year during the 1950's and '60's.

The Great Fizzling

Starting in the late 1960's, however, productivity growth decelerated precipitously, dropping close to zero in the mid-1980's. Later productivity rebounded somewhat, but only to hover at about 1.5-2 percent, well below the heights of previous decades. In comparison, between 1950 and 1968, US productivity growth averaged 2.9 percent; between 1969 and 1995 it averaged only 1.6 percent. Why did productivity growth decelerate so significantly? Adverse supply shocks probably played a role, in particular the oil shocks of the 1970's, but they are not enough to explain a productivity slump which lasted a quarter century, and which saw productivity in the service sector virtually stagnate. A more plausible explanation is that the adoption of waves of innovation from the Industrial Revolution had reached a more mature stage, running into diminishing marginal returns (see for example Gordon 2012).

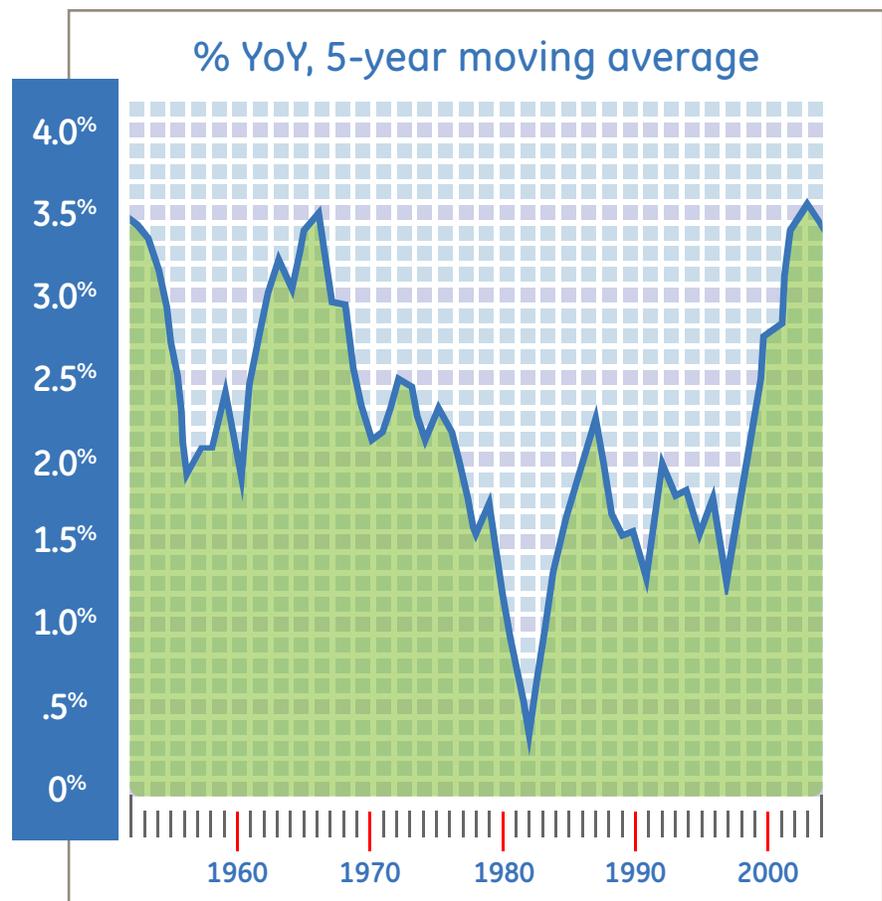
The Internet Revolution

While productivity decelerated sharply, innovation had not stopped: quite the contrary, computers had come onto the scene, and so had the internet. But the lack of a visible economic impact bred skepticism, famously encapsulated by Robert Solow's quip "You can see the computer age everywhere but in the productivity statistics." Solow spoke in 1987, and nearly ten years later his remark still seemed appropriate.

And then suddenly it happened: US labor productivity accelerated sharply in the mid-1990's, jumping back to the record levels of the mid-1960's.

The acceleration carried over into the early part of the following decade: between 1996 and 2004, productivity growth averaged an impressive 3.1 percent, nearly double the rate of the preceding quarter century-long slump.

Figure 10. US Labor Productivity Growth, 1952 - 2004



Source: United States Department of Labor, Bureau of Labor Statistics, Labor Productivity and Costs Database, Annual Data, November 2012. <http://www.bls.gov/lpc/>

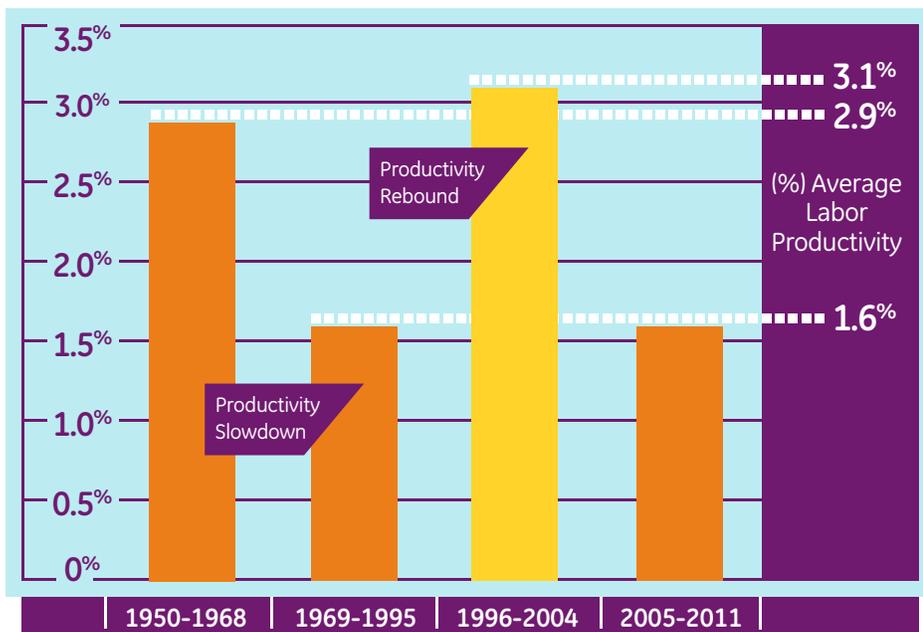
How did it happen? There is extensive academic literature devoted to the productivity revival of the mid-1990's, and the broad consensus is that the acceleration in productivity growth was driven by the combination of expanded information and communication technology, integrated through the rise of the Internet Revolution and computing technology that helped to enable it.

A few points are worth making in this context:

- First, the acceleration in productivity occurred in a relatively late period of economic expansion. Productivity growth exhibits marked cyclical fluctuations, and it tends to pick up at the beginning of an economic recovery; the fact that the mid-1990's surge bucked the trend suggests a more structural driver.
- The revolution was fueled by an impressive pace of innovation (Moore's law³⁵), which resulted in a rapid decline in the prices of information and telecommunication equipment.



Figure 11. The US Productivity Decline and Rebound



Source: United States Department of Labor, Bureau of Labor Statistics, Labor Productivity and Costs Database, Annual Data, November 2012. <http://www.bls.gov/lpc/>

- The revolution then spread to the rest of the economy as the equipment was adopted on an increasingly broader basis. Empirical evidence shows that service-intensive industries experienced faster productivity gains than other industries, again suggesting that the Internet Revolution was the driving force.³⁶
- Investment played a key role in leveraging the hardware and software innovations, as declining prices spurred companies to more rapidly upgrade their capital stock.
- Services also experienced a major acceleration in productivity, confounding another economic misconception, known as “Baumol’s Disease.” The prominent economist William Baumol had argued in the 1960’s that (i) productivity gains would derive mostly from innovation embodied in capital equipment; and (ii) service industries were more labor intensive and less capital intensive than manufacturing; therefore (iii) service industries were condemned to lower productivity growth. In fact, service industries turned out to be some of the most intensive adopters of ICT, and recorded some of the most impressive productivity gains. The wholesale and retail trade sector is a case in point, as ICT transformed integrated supply chains and distribution networks.³⁷

Return of the Skeptics

Productivity growth decelerated again starting in 2005. Predictably, this sparked another wave of dismissive skepticism. The

way we interact and communicate has been further transformed with smartphones and tablets and with the flourishing of social media, which have been quickly mirrored in commercial applications.

But as productivity growth declined, it has become tempting to dismiss these innovations as mere entertainment and silly games. Martin Wolf, the Financial Times’ economics editor, put it most effectively: “Today’s information age is full of sound and fury signifying little.”³⁸

The global financial crisis and ensuing Great Recession have also affected the mood and muddled the waters. The criticism of the latest wave of ICT innovation echoes that of the market economy. The refrain that all these innovations, however superficially impressive they might be, will not have an impact on living standards, meshes well with the doom and gloom that too often dominates the headlines in economic and financial reporting. Moreover, the deep 2008-09 recession and the weak recovery, as well as the dramatic reduction in employment levels, make it impossible to draw any meaningful conclusions from the swings in productivity growth rates of the last few years (labor productivity growth accelerated sharply in 2009-10 and then collapsed in 2011).

Robert Solow’s premature disappointment should counsel caution, but it has become

too tempting to conclude that the productivity revival of 1996-2004 was just a blip.

In a recent paper, Prof. Robert Gordon of Northwestern University, who has published extensively on productivity and economic growth, argues that the innovations of the Internet Revolution are simply not as transformative as those of the Industrial Revolution. In an explicitly provocative argument, he posits that some of the key changes brought about by the Industrial Revolution are simply of a once-and-for-all kind: the speed of air travel is no higher than in the late 1950’s, and the scope for urbanization in the US has been exhausted.

Industrial Internet: Here Comes the Next Wave

The Industrial Revolution unfolded over a period of 150 years, with some of the most powerful innovations materializing at the tail end. Even if we place the dawn of the Internet Revolution in the 1950’s, it might well be too early to conclude that it has no durable economic impact.

In fact, we believe that the second, most powerful and disruptive wave of the Internet Revolution is arriving now: it is the Industrial Internet. And the Industrial Internet is vested in productivity. Earlier in the paper we have argued that the Industrial Internet is poised to directly impact a very large portion of the global economy. And we have discussed some concrete and detailed examples of how the Industrial Internet will yield substantial efficiency gains and cost savings in a number of key sectors of the economy, from health care to aviation, from transportation to energy.

Nothing like this has been seen before. The Industrial Internet promises to optimize the speed of improvement of operation in a vast range of economic activities. The speed at which the Industrial Internet will spread will likely be boosted by a cost-deflation trend very similar to that which characterized the adoption of ICT equipment: cloud computing now allows us to analyze much larger amounts of data, and at lower cost, than was ever possible. The price of data processing is declining, helping to unlock the productivity gains.

Similarly, the mobile revolution will accelerate this deflation trend, making it more affordable to efficiently share

information, leading to decentralized optimization and personalized optimization. Remote monitoring and control of industrial facilities, distributed power, personalized and portable medicine are just some of the most powerful examples.

How Much of a Difference Would it Make?

Forecasting productivity growth is a challenging exercise, subject to a wide margin of uncertainty. Nonetheless, our analysis of the Industrial Internet's potential impact in a number of key sectors suggests that its productivity-boosting potential should be at least comparable to that of the first wave of the Internet Revolution.

The Industrial Internet is not just "Industrial." This is a crucial point. We have dubbed this second wave of the Internet Revolution the "Industrial Internet" because its key distinctive feature is the way that intelligence is embodied in machines and devices, and these are produced in the industrial sector. But as was the case in the first ICT wave, many service sectors are among the heaviest adopters of the new technology. Health care and transportation are just two examples of services that will benefit heavily from the Industrial Internet, and that we have seen earlier. This is a key multiplier: remember that services account for nearly 80 percent of US GDP.

How much of a difference could the Industrial Internet make to productivity growth? If its potential impact is at least as strong as that of the first wave of the Internet Revolution, it would not be

unreasonable to expect that it would boost productivity growth to the levels prevailing during the 1996-2004 period, when labor productivity growth averaged 3.1 percent. And much as was the case with the Industrial Revolution, we would expect this impact to be quite long-lived.

To get a sense of what this could mean, consider the following simple example. Assume that the productivity boost lasts until 2030, which would be a bit less than twice the duration of the first ICT boost. Assume for simplicity that the faster productivity growth is entirely reflected in higher per capita income growth. Per capita GDP in the US is currently about \$50,000. If between now and 2030 per capita incomes were to rise at 3.1 percent rather than at the 1.6 percent annual productivity growth that prevailed in the quarter century to 1995, this would translate in an income gain of \$20,000 measured in today's dollars. In other words, the faster productivity growth would be worth about 40 percent of today's average GDP.

To take a more conservative assumption, let's assume that productivity growth would accelerate by just one percentage point, to only 2.6 percent, that is below the rate prevailing during the Industrial Revolution-driven boom of 1950-68. This would still deliver an average income gain of \$13,000, or one-quarter of today's per capita GDP.

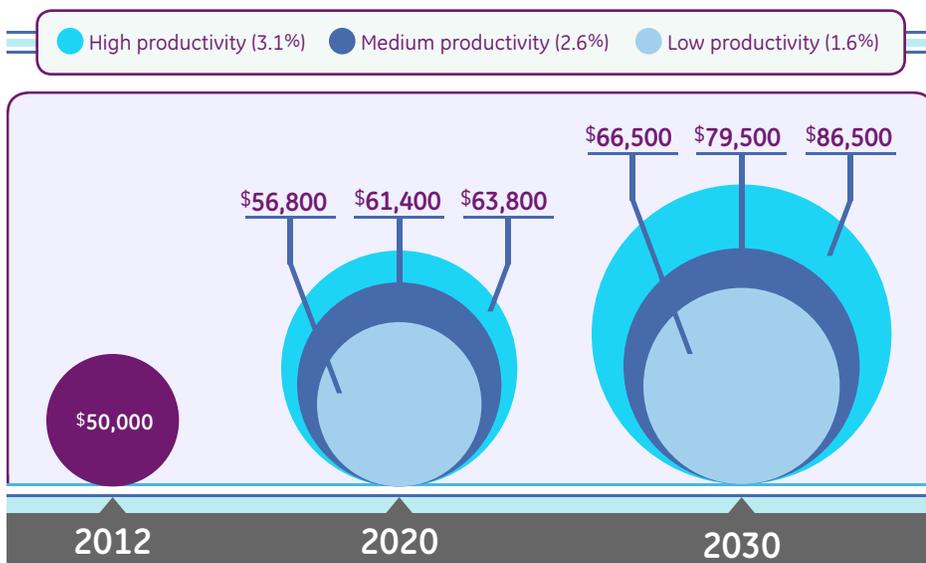
It is the magic of compounding at work: growing at just 1.6 percent per year, it takes 44 years for incomes to double;

at 3.1 percent per year, it takes just 23 years. In other words, at the faster rate incomes would double in the space of one generation, whereas at the slower rate it takes two generations.

There is of course a large margin of uncertainty in these estimates. For the productivity gains to be translated one-for-one in faster GDP growth, we would need for example to see the factors of production, labor and capital, accumulating at the same pace as they would without these innovations taking place. A reduction in the labor force, for example, would offset some of the impact of faster productivity growth. We would expect that investment would proceed at least at the same pace as in a no-innovation scenario: the higher return on investment promised by new generation equipment will constitute a powerful incentive to renew the capital stock. Indeed, investment is going to be a key condition and enabler for innovation to take hold—as was the case for the first wave of the internet revolution.

But what about labor? Will a further wave of productivity-enhancing innovation destroy jobs? In the current situation of already excessively high unemployment in the US and other advanced economies, this is a crucial issue. There is no doubt that further innovation will make some jobs unnecessary—for example to the extent that some processes can be automated. But as some of the old jobs are no longer necessary, new, better jobs will be created. As we discuss below, the development of the Industrial Internet will require a large number of workers skilled in analytics and engineering, among other things. The education system will need to adapt, and its alignment with industry will need to improve—it will be essential to ensure that the supply of new skills keeps pace with demand. But if we can do that, the creation of new professional profiles together with faster economic growth will lead to more and better jobs.

Figure 12: Potential Change in US GDP Per Capita



Note: Nominal US Dollars

Source: IMF World Economic Outlook Database, October 2012; GE projections.

Industrial Internet and Advanced Manufacturing

There is more. While its benefits would reverberate throughout the economy, the initial impact of the Industrial Internet is likely to be felt especially strongly in the area of advanced manufacturing.³⁹

The sharp rise in US unemployment during the Great Recession, and its persistence at very high levels since then, have intensified the debate on the importance of manufacturing versus services. While a thorough analysis lies outside the scope of this study, it is worth highlighting a few observations:

- A shift from manufacturing towards services is a commonly observed feature of economic development; in most advanced economies, services account for by far the largest share of GDP and employment. For example, services account for close to 80 percent of the economy (measured in terms of gross value added) in the US, the UK and Australia; 73 percent in the European Union, and 72 percent in Japan.

- Whether this shift in the US may have gone too far, however, is a legitimate question. Professors Spence and Hlatshwayo⁴⁰ show that all the additional jobs created by the US economy between 1990 and 2008 (about 27 million) were in the non-tradable sector, that is largely in services. Two-thirds of these additional jobs were created in five sectors: government, health care, retail, accommodation and food services, and construction. Spence and Hlatshwayo argue persuasively that the pace of job creation in these sectors going forward is unlikely to match that of the past three decades. A much higher public debt, escalating health care costs, and a real estate sector still recovering from an unprecedented bubble constitute powerful headwinds.

- Manufacturing might therefore need to play a stronger role if US employment is to go back to the pre-crisis levels. And to be consistent with a sustained rise in wages and living standards, a revival of manufacturing in an advanced economy needs to be driven by higher productivity growth. The discovery of lower cost energy sources like shale gas might give an important boost to the competitiveness of the US as a manufacturing base, but the Industrial Internet could prove an equally, if not more powerful engine of transformation.

Impact on the Global Economy

The discussion so far has focused mostly on the US. There is a simple reason for this. Since the US is currently the most advanced economy, at the frontier of productivity⁴¹, it is in the US that technological innovation has to play the key role in pushing the boundary.

But once the frontier has been moved outwards, everybody—in principle—can reach it.

The first wave of the Internet Revolution again provides a useful benchmark: after 1995, ICT investment surged not just in the US, but across the world, with advanced economies and emerging Asia in the lead. Jorgenson and Vu estimate that after 1995 the contribution of ICT investment to growth roughly doubled in emerging Asia, Latin America, Eastern Europe, Middle East and North Africa, and Sub-Sahara Africa.⁴²

This surge in ICT investment globally was accompanied by a marked acceleration in world growth, by nearly one percentage point.

How quickly the benefits of the Industrial Internet can be leveraged across the global economy will depend on the speed of adoption of the new technologies. And since emerging markets have already grown to account for about one half of the global economy, the speed at which they will adopt the new technology will matter much more than it did during the Internet

Revolution, and incomparably more than in the Industrial Revolution.

A positive factor in this respect is that emerging markets still have enormous need to increase infrastructure investment, a priority for generating rapidly rising levels of production and incomes. If emerging markets could this time around prove to be early adopters of the new technologies, rather than late adopters, the Industrial Internet Revolution could have a much more powerful and rapid impact on the entire global economy. Its impact in alleviating the constraints in sustainable global growth, for example in terms of commodities consumption and environmental impact, would be that much more significant.

A simple simulation exercise is useful to give a sense of the potential impact on the global economy. Assume that the Industrial Internet can boost US labor productivity growth back to the 3.1 percent which prevailed during the Internet boom. Suppose that, via investment embodying the new technologies, the rest of the world is able to generate just half the productivity gains of the US. This would be 0.75 percentage point higher than in a baseline where the Industrial Internet has no impact. If these productivity gains are sustained through 2030, they would add about \$15 trillion to global GDP over the period (in constant 2005 dollars). In other words, the faster productivity growth would translate in additional GDP creation equivalent to the

Figure 13. Benefits of Industrial Internet Diffusion to World Economy



Source: GE projections.



size of today's US economy. Per capita incomes would benefit correspondingly, and by 2030 per capita GDP in the world economy would be nearly one-fifth higher than in a baseline without Industrial Internet impulse.

Alternatively, consider the more conservative scenario discussed above, where US productivity growth accelerates by only one percentage point to 2.6 percent, and assume again that the rest of the world can generate half of these productivity gains, that is a 0.5 percentage point acceleration in productivity growth. This would still add about \$10T to global GDP over the same horizon.

Role of Business Practices and the Business Environment

The speed at which the benefits of the Industrial Internet can feed through the global economy will also depend on firms' ability to incorporate them in their business processes; and this in turn will also depend on the business environment and the economic policies that help shape it.

The benefits of the Industrial Internet derive not just from the greater efficiency of capital equipment, from the ability to push machines and devices to their technical limits. They derive also from the ability to optimize operations, and to optimize the speed of improvement of operations.

This requires changes in business practices to go hand in hand with the technical innovation. MIT's Brynjolfsson has highlighted the role of data-driven decision

making (DDD), and showed that firms that adopt DDD can reap gains of 5-6 percent higher productivity compared with firms that do not.⁴³

The benefits, therefore, are as substantial at the level of the individual firm as at the level of the entire economy. But they need the right conditions to thrive. We noted above that after 1995, investment in ICT surged across the world, with advanced economies in the lead. But while productivity growth accelerated significantly in the US, it decelerated just as significantly in Europe (by almost a full percentage point).⁴⁴ This divergent trend in productivity has been the object of intense academic study and debate.

Management practices and business process seem to play an important role: a recent study by Bloom, Sadun and Van Reenen finds evidence that US multinationals operating in Europe experience higher productivity gains than non-US multinationals, and tend to be more ICT-intensive.⁴⁵ The authors point to the fact that US multinationals also score better on "people management practices," i.e. in a more efficient use of hiring, firing and promotions. New and disruptive technologies require quick and significant changes in work and management practices, and these are best achieved through a more nimble management of a firm's human capital.

The external environment matters enormously in this respect. Rigid labor markets, for example, with more draconian

restrictions on hiring and firing, will inevitably hamstring a company's human resources management strategy. In Europe, labor market rigidities have gone hand in hand with weaker productivity and losses in international competitiveness, contributing in no small part to the predicament currently faced by high-debt Eurozone members.

Similarly, restrictions in product and services markets can hamper the transformational potential of new technologies. We have seen earlier that a large part of the surge in US productivity came via the services sector. Similar gains in productivity growth in services took place in Canada, Australia, the UK and the Netherlands. But in much of continental Europe, labor productivity growth during 1995-2004 was less than one-third that of the US.⁴⁶



imagination at work



VI. Enablers, Catalysts and Conditions

The realization of the Industrial Internet is not a foregone conclusion. Key enablers, catalysts and supporting conditions will be needed for meshing the physical world of machines with the digital world of data and analytics to reach its full potential. Some of the most important elements will clearly be continued progress across innovation, and vigorous cyber security management, enabling infrastructure and new talent development.

Innovation

The Industrial Internet is the outcome of innovations already underway, some of which are innovations of technology, and others are innovations of systems, networks, and processes. Although the specific innovations that will be needed are yet unknown, it is clear that collectively they represent a set of vital catalysts and enablers.

Below are some high-level innovation categories necessary for development of the Industrial Internet:

EQUIPMENT: Integration and deployment of sensors into the design of new industrial equipment, as well as solutions for retrofitting existing equipment; hardware needed for efficient collection and faster transmission of information, etc.

ADVANCED ANALYTICS: New data standards to enable deeper integration of data from similar assets from different Original Equipment Manufacturers (OEM) or from different asset categories; technical architecture that enables faster transformation of data into information assets, ready for integration and analysis, etc.

SYSTEM PLATFORMS: Beyond technical standards and protocols, new platforms that enable firms to build specific applications upon a shared framework/architecture; new relationships between suppliers, OEMs, and customers that support the sustainability of the platform

BUSINESS PROCESSES: New business practices that fully integrate machine information into decision-making; processes for monitoring machine data quality; advances in legal processes that enable faster and more flexible arrangements between collaborating firms, etc.

Innovations like these will require investment on the part of firms, industry groups, governments, and educational institutions. Each of them has something to gain from the investments – industry wants sales and customer relationships, governments want to capture employment and tax revenue but are also interested in efficiency gains for their own operations, while educational institutions will seek to attract students and funding by taking on some of the complex challenges in this evolving space. Fortunately, their investment horizons will be somewhat different, which has the potential to create a healthy diversification of innovation efforts.

In addition to innovations, there is existing technology that will need to achieve greater levels of penetration and deployment, such as in sensors and monitors – technology that already exists today.

Infrastructure

The Industrial Internet will require an adequate backbone. Data centers, broadband spectrum, and fiber networks are all components of the ICT infrastructure that will need to be further developed to connect the various machines, systems, and networks across industries and geographies. This will require a combination of inter- and intra- state infrastructure order to support the significant growth in data flows involved with the Industrial Internet.

The growing demand for data centers provides an example of the scale of the challenge. The majority of the data centers that will be processing data around the world in 2025 have not yet been built. A key reason is the demand for data processing is currently more than doubling every two years and will increase 20 times by 2020.⁴⁷ If this trend continues then we can expect a 40x increase in data processing demand by 2025. While more modular designs and efficiency improvements are reducing the amount of energy required to run data centers, the demand for high quality electricity is expected to increase significantly. Today, the world's data centers consume approximately 130 GWh per year of electricity. This is equivalent to 2.6 times the amount used by New York City, one of the world's largest megacities. By 2025 the amount of power required by data centers



will grow to the equivalent of between 9 to 14 megacities. This will require significant growth in the capital expenditures associated with data centers. By 2015, global capital spending is likely to approach \$100 billion and will double again to over \$200 billion a year by 2025.⁴⁸ The future of efficient, clean, and resilient data centers obviously has important implications for the Industrial Internet.

Cyber Security Management

Attaining the vision set forth for the Industrial Internet will require an effective internet security regime. Cyber security should be considered in terms of both network security (a defense strategy specific to the cloud) and the security of cutting-edge devices that are connected to the network.

Maintaining a protected IT infrastructure is a vital requirement. Security processes and controls should be designed to have multiple layers of defense. According to Barry Hensley, Director of Counter Threat Unit/Research Group for Dell SecureWorks, "Security processes and controls should include vulnerability lifecycle management, endpoint protection, intrusion detection/prevention systems, firewalls, logging visibility, network visibility, and security training."⁴⁹ Defense strategies need to span every layer, starting from the network down to the user.

Protection of sensitive and valuable information is at the forefront of security management. It is essential to develop and maintain network trust, in both business-to-business and business-to-consumer settings. Information security and privacy are the backbone of building this trust. Measures to ensure the security of restricted data, including intellectual property, proprietary information, and personally identifiable information (PII) are critical. Measures include encrypting data on devices as well as encrypting the transmission of such data to the cloud. Some of these data protection measures are already being implemented at the enterprise level, thus facilitating its expansion/deployment to the industrial network.

Expansion of the Industrial Internet will require all stakeholders to become proactive participants in security management. Every actor has a role to play in promoting cyber security. The following are some potential responsibilities:

TECHNOLOGY VENDORS: The focus will be on supply chain security, as well as product design and product performance. Products (devices and software) should contain embedded security features to maximize the layers of defense against cyber threats.

ASSET OWNERS/OPERATORS: The priority will be on securing facilities and

networks. Cooperation with regulators, law enforcement, and the intelligence community can help improve the visibility of evolving threats. Courses of action include sharing threat information and mitigation efforts.

REGULATORS/POLICYMAKERS: An effective cyber security regulatory regime should promote innovation, encourage the education of all stakeholders, and support the development of a capable workforce. To build a stable foundation, government should pursue the development and broad adoption of voluntary industry standards and best practices for cyber security. There needs to be industry-based performance and technical standards that encourage a "culture of security." Ideally, standards and data privacy policies would be consistent across states and countries. Currently there are several standards bodies, but they are fragmented. The promotion and adoption of common and consistent standards on data structure, encryption, transfer mechanisms, and the proper use of data will go a long way in advancing cyber security.

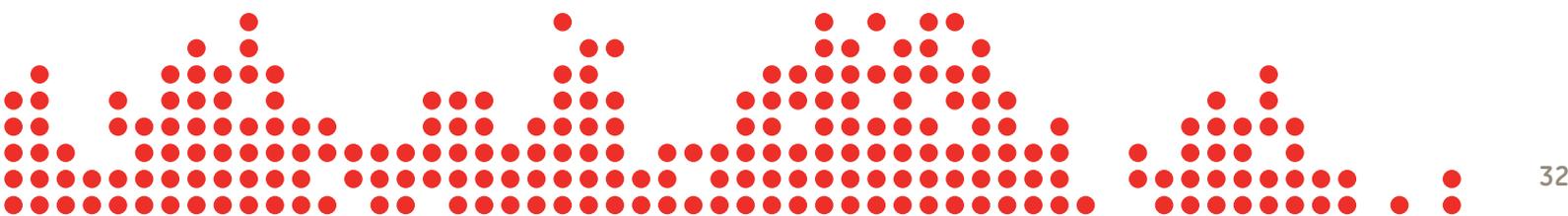
INTERNATIONAL INSTITUTIONS: Although countries will develop national guidelines, the development of international norms and standards will also be required. The focus should be on developing norms related to IP protection and international data flows (e.g. server localization requirements), as well as the "weaponization" of the internet.

ACADEMIA: Further research on data security and privacy should be pursued, including research on enhancing IT security metrology, inferencing concerns with non-sensitive data, and legal foundations for privacy in data aggregation.⁵⁰

The pursuit of a cohesive cyber security strategy will minimize the risks and enable society to take advantage of the opportunities associated with the Industrial Internet.

Talent Development

Innovation doesn't exist without specialized talent. The rise of the Industrial Internet will require new talent pools to be created and grown. Beyond the obvious technical skills in mechanical or electrical engineering, there will be need for a wave of new technical,



There is a great need for educational programs to be developed to formalize the knowledge foundations that “data talent” will require.

analytical, and leadership roles that are explicitly cross-discipline. Like the “data scientist” today, a role emerges in name and is populated by those who are already practicing in it. Over time it gains clarity, partly through self-definition by the initial talent pool, and sets of loosely accepted practices are developed.

The following are sets of various job categories that will be needed to drive the Industrial Internet:

NEXT GEN ENGINEERING: There will be a growing need for variety of cross-cutting roles that blend traditional engineering disciplines such as mechanical engineering with information and computing competencies to create what might be called “digital-mechanical” engineers.

DATA SCIENTISTS: Will create the analytics platforms and algorithms, software, and cyber security engineers, including statistics, data engineering, pattern recognition and learning, advanced computing, uncertainty modeling, data management, and visualization.

USER INTERFACE EXPERTS: Industrial design field of human-machine interaction, to effectively blend the hardware and software components required to support minimal input to achieve the desired output; and also that the machine minimizes undesired output to the human.

Where will this talent come from? There are shortages today in many of the potential foundational capabilities in many geographic regions: cyber security, software engineers, analytics professionals, among others. Talent markets should eventually realign but firms will probably need to create a talent pool of their own by drawing upon their most versatile (and adventurous) employees. Labor markets that are more “sticky” either from culture or regulation will be less able to adapt to meet these new demands.

Other alternatives for sourcing cross-discipline talent might include developing the existing resources in the native domain through collaborative approaches. Instead of building or buying talent that has multiple skills, create environments that accelerate the ability of people with different skills to interact and innovate together. On a larger scale, approaches such as crowdsourcing might be able to close some of the capabilities gaps that are sure to occur.

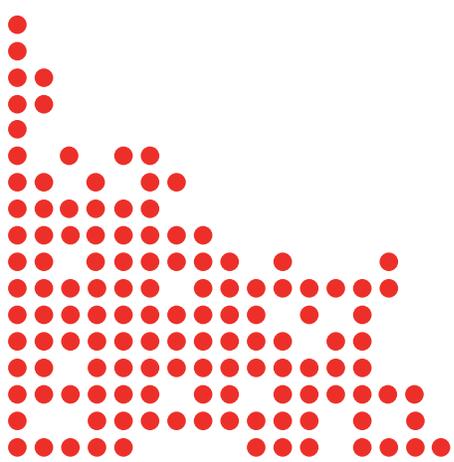
The changes required upstream in the educational system will need to be driven through stronger collaboration between firms and universities. There is a great need for educational programs to be developed to formalize the knowledge foundations that “data talent” will require. Today, the people that manage big data systems or perform advanced analytics have developed unique talents through self-driven specialization, rather than through any programs that build a standard set of skills or principles. Co-development of curriculum, integration of academic staff into industry, and other approaches will be needed to ensure that the talent needs of the Industrial Internet do not outpace the educational system. Some programs have already started to emerge in this area, but many more will be needed.

Crafting and promoting the vision of the Industrial Internet, its value and applications, is ultimately a leadership role. These visionaries will need support from company leadership to sustain the investments through business cycles and through the peaks and troughs of specific industries. Innovation requires risk tolerance, and many of aspects of the Industrial Internet may stretch firms beyond their comfort zone and into new partnerships. Firms will need a new generation of leaders that can form and execute on the vision, and build the organizations, culture, and talent that it requires.

In summary, the growth of the Industrial Internet will rest on important key enablers, catalysts and supporting conditions. Key among these are continued dynamic innovation, an effective internet security regime; supporting IT infrastructure and the right talent, skills and expertise.



imagination at work



VII. Conclusion

The long cycles of innovation and evolution within the economy and society that have occurred are reasonably well understood. When new technologies are brought forward and adopted at scale, tremendous waves of transformation and disruption are unleashed. This transformative cycle is happening again as traditional industrial systems integrate intelligent technologies, not only layered on the periphery of an industrial system, but within the designs and functions of a new generation of machines. While still early in the process, the meshing of the industrial world with the internet and associated technologies could be as transformative as previous historical waves of innovation and change.

The scope for transformation is tremendous. The potential impact of Industrial Internet technologies spans almost half of the global economy and more than half of the world's energy flows. In a host of industries, linking intelligent devices, facilities, fleets and networks with people at work and on the move will offer new possibilities in process optimization, increased productivity, and efficiency. Early adopters have charted some of the paths forward, laying the groundwork of the Industrial Internet. Going forward, broader adoption of Industrial Internet technologies are expected to drive deeper beneficial changes in industry cost structures. This will alter the competitive balance and force rapid adoption by the rest of the industry to survive. This clearly will happen at a different pace in different industries, but as adoption increases the impact will be felt more broadly across the economy.

The compounding effects of even relatively small changes in efficiency across industries of massive global scale should not be ignored. As we have noted, even a one percent reduction in costs can lead to significant dollar savings when rolled up across industries and geographies. If the cost savings and efficiency gains of the Industrial Internet can boost US productivity growth by 1-1.5 percentage points, the benefit in terms of economic growth could be substantial, potentially translating to a gain of 25-40 percent of current per capita GDP. The Internet Revolution boosted productivity growth by 1.5 percentage points for a decade—given the evidence detailed in this paper, we believe the Industrial Internet has the potential to deliver similar gains, and over a longer period.

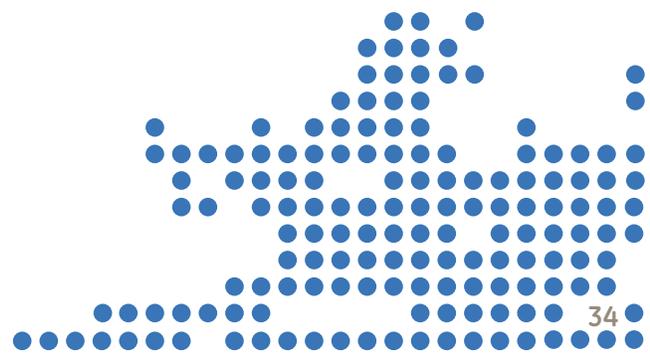
While the US is currently pushing the technological frontier in relative terms, the benefits of the Industrial Internet will be felt across the world. Emerging markets still have enormous need to increase infrastructure investment, a priority for generating rapidly rising levels of production and incomes. If they become early adopters of the new technologies, the Industrial Internet revolution will have a powerful impact on the global economy. If the US can secure a 1.5 percentage points acceleration in productivity growth, and the rest of the world achieves just half that increase, within the next twenty years the Industrial Internet will have added to the global economy an additional \$15 trillion—about the size of the US economy today—and boosted world per capita GDP by nearly one fifth.

In a context where the largest advanced economies struggle with disappointing economic growth, resulting in high unemployment and disappointing income dynamics, the benefits of such an



acceleration in productivity and growth would be enormous. Moreover, the Industrial Internet would play a substantial role in alleviating the constraints to strong and sustainable global growth, in terms of commodities consumption and reduced environmental impact.

Innovation has always been the single most powerful ingredient to help us create more with less, to ease constraints, to generate improving living standards for larger and larger numbers of people. The Industrial Internet holds the potential to drive the next wave of innovation for the world by pushing even further the boundaries of minds and machines.



VIII. Endnotes

- ¹ Jan Luiten Van Zanden, *The Long Road to the Industrial Revolution*, (Leiden: The Netherlands: Koninklike Brill, 2009).
- ² For an excellent overview see Robert Gordon, *Is US economic growth over? Faltering innovation confronts the six headwinds*, (CEPR Policy Insight nr. 63, September 2012).
- ³ See Chris Freeman and Francisco Louca, *As Time Goes By: From the Industrial Revolutions to the Information Revolution* (Oxford University Press: New York, 2010).
- ⁴ Johnny Ryan, *A History of the Internet and the Digital Future* (London: Reaktion Books, 2010), p. 125.
- ⁵ Ryan, p. 82.
- ⁶ The Associated Press, "Number of active users at Facebook over the years," October 23, 2012; The Wall Street Journal, "Facebook: One Billion and Counting," October 4, 2012; Facebook, One Billion – key metrics, <http://newsroom.fb.com/News/One-Billion-People-on-Facebook-1c9.aspx>.
- ⁷ Industry sectors discussed here correspond to the international standard industrial classification (ISIC) divisions 10-45 and include manufacturing (ISIC divisions 15-37). It comprises value-added in mining, manufacturing, construction, electricity, water, and oil and gas. Manufacturing refers to industries belonging to ISIC divisions 15-37. In North America (US, Canada, Mexico), the more detailed North American Industry Classification System (NAICS) is the standard used by Federal statistical agencies. For the NAICS, the industrial sector is defined as the (21-23) and (31-33) groupings at the two-digit level. Both systems are generally comparable at the most aggregate reporting levels.
- ⁸ The economic share calculations are developed by multiplying the most recent percentage shares of GDP at the country level to the 2011 nominal GDP statistics provided by the World Bank.
- ⁹ The transport sector defined here aligns with ICIS Division I – Transport, storage and communications. Health services aligns with ICIS Division N- Health and social work.
- ¹⁰ GE estimate based on August 2012 forecast in current dollars.
- ¹¹ Statistics in this section are GE estimates based on BP Statistical Review of World Energy 2012, International Energy Agency (IEA), and internal GE analysis except as noted.
- ¹² IEA (2009) Energy Technology Transitions for Energy: Strategies for the Next Industrial Revolution.
- ¹³ Boeing Commercial Airplane Statistical Summary, July 2012, <http://www.boeing.com/news/techissues/pdf/statsum.pdf>
- ¹⁴ General Aviation Manufacturers Association, 2011 Statistical Databook and Industry Outlook, http://www.gama.aero/files/GAMA_DATABOOK_2011_web_0.pdf
- ¹⁵ Platts UDI Database, June 2012
- ¹⁶ GE Strategy and Analytics power generation outlook 2012.
- ¹⁷ Oil and Gas Journal refinery survey (December 5, 2011), <http://www.ogj.com/ogj-survey-downloads.html>.
- ¹⁸ GE estimate based on Oil and Gas Journal Nov 5, 2012 world-wide construction survey 2012 which shows more than 130 new refinery projects and expansion to existing refineries.
- ¹⁹ International Air Transport Association (IATA) Vision 2050 2011. http://www.iata.org/pressroom/facts_figures/Documents/vision-2050.pdf
- ²⁰ International Air Transport Association (IATA) Annual Report 2011 and September 2012 Industry outlook presentation.
- ²¹ Federal Aviation Administration (FAA). Estimation of NAS inefficiencies. 2006. Includes estimates of potential fuel savings from better flight planning and operations along with other operational changes. This supports the assumption that 5 percent in fuel savings is possible.
- ²² Idem IATA Vision 2050
- ²³ IATA, Airline Maintenance Cost Executive Commentary, January 2011, http://www.iata.org/workgroups/Documents/MCTF/AMC_ExecComment_FY09.pdf
- ²⁴ Sources: GE Transportation, Transport Expenditures United Nations Statistics Division, MIT Research: Commoditization of 3rd party logistics. Journal of Commerce: <http://www.joc.com/logistics-gdp-and-rising-costs>.
- ²⁵ GE Strategy and Analytics calculations based on country-level generator gas demand estimates derived from historic data sources including International Energy Agency (IEA), and the BP Statistical Energy report, EIA..
- ²⁶ GE Strategy and Analytics estimates based on country level natural price estimates multiplied by power sector gas demand estimates.
- ²⁷ Maugeri, Leonardo. "Oil: The Next Revolution" Discussion Paper 2012-10, Belfer Center for Science and International Affairs, Harvard Kennedy School, June 2012. <http://belfercenter.ksg.harvard.edu/files/Oil-%20The%20Next%20Revolution>.

Endnotes (Cont.)

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²⁸ See the Digital Oil Field: Oil and Gas Investor Supplement April 2004 for an early discussion of the potential of the Industrial Internet. <http://www.oilandgasinvestor.com/pdf/DOF0404.pdf>

²⁹ Ibid Digital Oil Field: page 3.

³⁰ Biofuels and use of natural gas liquids account for the differences in crude oil production and global oil product consumption of about 88 million barrels per day. Source: BP Statistical Review of World Energy June 2012

³¹ Barclay's Equity Research Global E&P capital spending update May 2012.

³² GE Oil and Gas estimate based on internal project tracking supplemented by external sources like Barclays, Petroleum Finance Consultants (PFC) and Rystad Consulting.

³³ PricewaterhouseCoopers Health Research Institute (2010)

³⁴ Ibid.

³⁵ Intel's co-founder Robert E. Moore observed in 1965 that the number of transistors in integrated circuits doubled approximately every two years. He predicted the trend would last at least another ten years—in retrospect, “at least” was a crucial qualifier.

³⁶ Kevin Stiroh, Information Technology and the US Productivity Revival: What Do the Industry Data Say? (Staff Report, Federal Reserve Bank of New York, nr. 116, January 2001).

³⁷ Barry Bosworth and Jack Triplett, Productivity Measurement Issues in Services Industries: “Baumol's Disease” Has Been Cured, (Federal Reserve Bank of New York Economic Policy Review, September 2003); and Barry Bosworth and Jack Triplett, Services Productivity in the United States, (Hard-to-measure goods and services: Essays in Honor of Zvi Griliches, University of Chicago Press, 2007).

³⁸ Martin Wolf, Is the age of unlimited growth over? Financial Times, 03 October 2012.

³⁹ For a detailed discussion of the possible definitions of advanced manufacturing, see Science and Technology Policy Institute (2010) and references therein.

⁴⁰ Michael Spence and Sandile Hlatshwayo, The evolving structure of the American economy and the employment challenge, (Council on Foreign Relations Working Paper, March 2011).

⁴¹ Gordon (2012)

⁴² Dale W. Jorgenson and Khuong M. Vu, Potential growth of the world economy, (Journal of Policy Modeling, Vol. 32, nr. 5, 2010).

⁴³ Erik Brynjolfsson, Lorin M. Hitt and Heekyung Hellen Kim, Strength in numbers: How does data-driven decision making affect firm performance?, (ICIS Proceedings, Paper 13, 2011).

⁴⁴ Bart Van Ark, Mary O'Mahony and Marcel P. Timmer, The productivity gap between Europe and the United States: Trends and causes, (Journal of Economic Perspectives Vol. 22, nr. 1, 2008)

⁴⁵ Nicholas Bloom, Raffaella Sadun and John Van Reenen, Americans do it better: US multinationals and the productivity miracle, (American Economic Review nr. 102, 2012)

⁴⁶ Van Ark, O'Mahony and Timmer (2008)

⁴⁷ Ganz, John; Reinsel, David; The 2011 Digital Universe Study: Extracting Value from Chaos, IDC: Sponsored by EMC Corporation, 2011.

⁴⁸ Forecast by GE Energy, Global Strategy and Planning, 2012. Note that this is the cost of the building infrastructure and mechanical and electrical equipment but does not include the cost of the servers.

⁴⁹ GTCSS2011, Emerging Cyber Threats Report 2012 http://www.gtisc.gatech.edu/doc/emerging_cyber_threats_report2012.pdf

⁵⁰ National Institute of Science and Technology. http://csrc.nist.gov/groups/SMA/forum/documents/june2012presentations/fcsm_june2012_cooper_mell.pdf

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