Powering the future

Leading the digital transformation of the power industry

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Authors & Acknowledgments

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This paper is part of a series from GE, exploring the next generation of industrial progress. Other papers in this series include:

- *The Future of Work (2014)*
- *The value of interconnectedness (2014)*
- *The Industrial Internet @ Work (2013)*
- *Industrial Internet: Pushing the boundaries of men and machines (2012)*
- *By region:*
    - *The future of work in Australia: Building the third wave of growth (2014)*
    - *Mapping the future of work in MENAT (2014,2015)*
    - *The future of work in Turkey (2014)*
    - *The state of European innovation (2014)*
    - *Industrial Internet: A European Perspective (2013)*

Executive Summary

A set of technological and macroeconomic forces is converging to trigger a deep transformation of the energy industry. The world needs more power to extend electricity access to over one billion people and to support stable growth and rising living standards for billions more. This requires developing new energy supplies, while building and upgrading grid infrastructure.

At the same time, the convergence of digital and physical innovations, together with advances in energy technologies, has begun to impact the industry. These advances help open the way for bi-directional energy flows in the grid, for real-time demand adjustment, for a smarter combination of energy supply sources and to deliver higher electricity output from existing assets, as well as enhanced performance from future infrastructure investment.

These trends pose a new set of complex challenges to the industry: balancing the fuel mix, ensuring the reliability of power delivery and quality, improving asset level visibility, identifying new revenue sources, integrating new technologies, neutralizing cyber security threats and coping with an aging workforce.

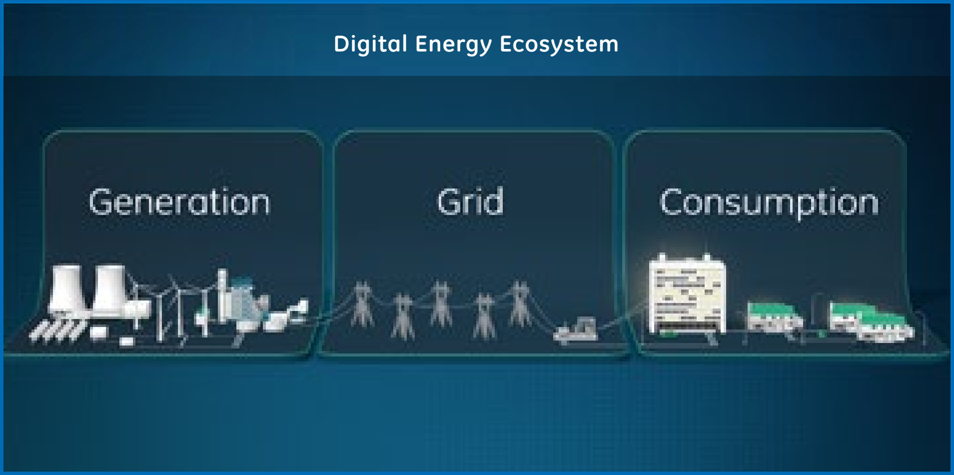
These challenges also present unprecedented opportunities. **The future of the power sector is a new value chain augmented and interconnected by digital technologies**—one where both power and information flow in multiple directions; all actors add value; **and the overall efficiency, cost-effectiveness, resilience, and sustainability of the system are enhanced** through information sharing, openness, collaboration, and coordination between stakeholders through the right set of incentives.

It will encompass three key elements: (1) a **digital centralized generation** pillar, relying on a mix of fossil fuel and renewable sources; (2) **a digital grid**, connecting generation and consumption, and enabling the multidirectional flows of energy and information; and (3) **a digital consumption** pillar, improving consumption patterns along with distributed generation and storage capacity.

Energy providers will join a new breed of digital-industrial companies. This will require changing their business models to take full advantage of new digital capabilities: **balancing the fuel mix** through big data analytics, accelerating the adoption of natural gas and renewables; **optimizing plant operation by using analytics to reduce cost and emissions while maximizing economic output**; and developing new ways to interact with customers. The power grid will realize its potential as a platform, accelerating innovation and efficiency gains.

This transformation will not be easy. It will require investing in infrastructure and new technologies; changing mindsets, public policies, and business models; investing in people through education and on-the-job skills upgrading; and developing open standards and ensuring interoperability. It will require the highest degree of cyber security against potential data privacy and system security risks.

The opportunity is unprecedented. **Imagine: A future of energy that realizes the goal of ubiquitous access to clean, reliable, sustainable and secure electricity, while fostering economic growth through the creation of new energy ecosystems. The convergence of digital and physical technologies brings this within reach.**



Converging pressures: Macroeconomic and technological forces setting new challenges for the energy industry

The power industry faces a complex set of challenges: extending electricity access to over one billion people around the world who are currently in the dark, and providing sufficient power to support stable growth and rising living standards for billions more; ensuring environmental sustainability and decarbonization across fossil fuels and renewables; improving efficiency across an increasingly multi-dimensional energy value chain.

The convergence of digital and physical technologies now brings this within reach. To map the digital future of energy, we must first understand the macroeconomic and technological drivers that will reshape the industry.

Macro drivers

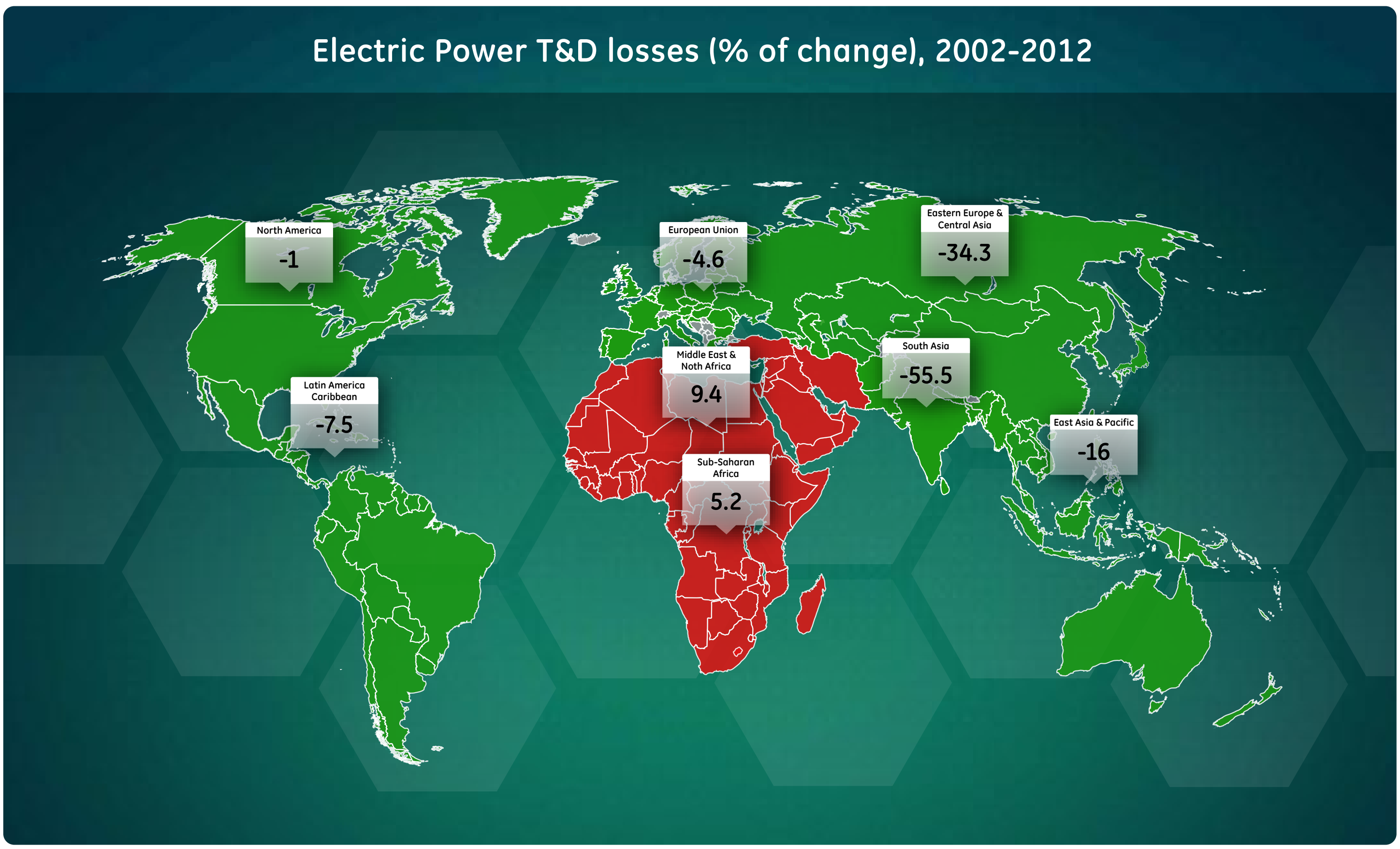
The world needs more power now, and it will need even more in the decades ahead. The global economy has expanded at an average annual pace of 3.9% during 2010–14, only marginally lower than the 4.2% average recorded in the decade prior to the crisis (1998–2007).

Emerging markets have become a primary engine of growth: in 2015 they will account for 57% of global GDP, compared to 42% in 2000.[1] **As emerging markets tend to be less energy efficient than advanced economies, their growing weight initially tends to make global growth more energy intensive.**[2] In order to sustain their rapid growth, **emerging markets will need to invest in their power generation infrastructure.** In some, a concurrent priority is to improve the transmission and distribution networks so as to reduce losses and leakages that are now a major cause of inefficiencies, as seen in Figure 1.

In several emerging countries or regions, there is a massive need to expand access to electricity. Today, about 1.3 billion people in the world lack access to electricity; just in India, 250 million people do not have access. Large areas of Sub-Saharan Africa face the same challenge, and, as illustrated in Figure 2, the deficit in many countries is growing, not shrinking.

[1] According to recent International Monetary Fund projections.
[2] Energy intensity is defined as the amount of energy required to produce one unit of output. For example, the World Bank calculates it as GDP at constant 2011 PPP $ per kg of oil equivalent. See for example the discussion in Arezki and Blanchard (2014, IMF).

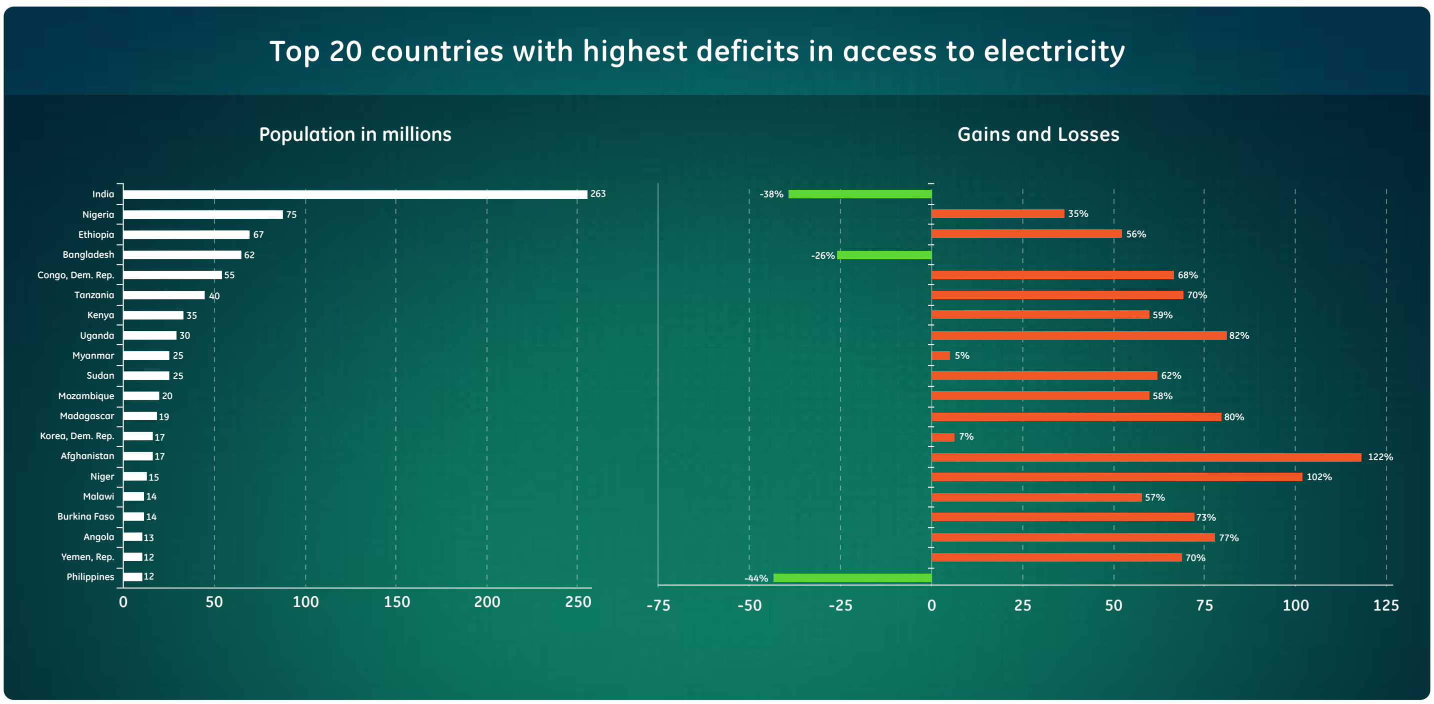
Figure 1



Source: World Bank

Reliable access to power is essential to improve the living conditions of populations across the world. It is also essential to enable the development of stronger manufacturing industries that can fuel economic growth and support the rise of a middle class. In short, access to power is absolutely necessary to allow emerging market countries to continue their economic convergence process.

Figure 2

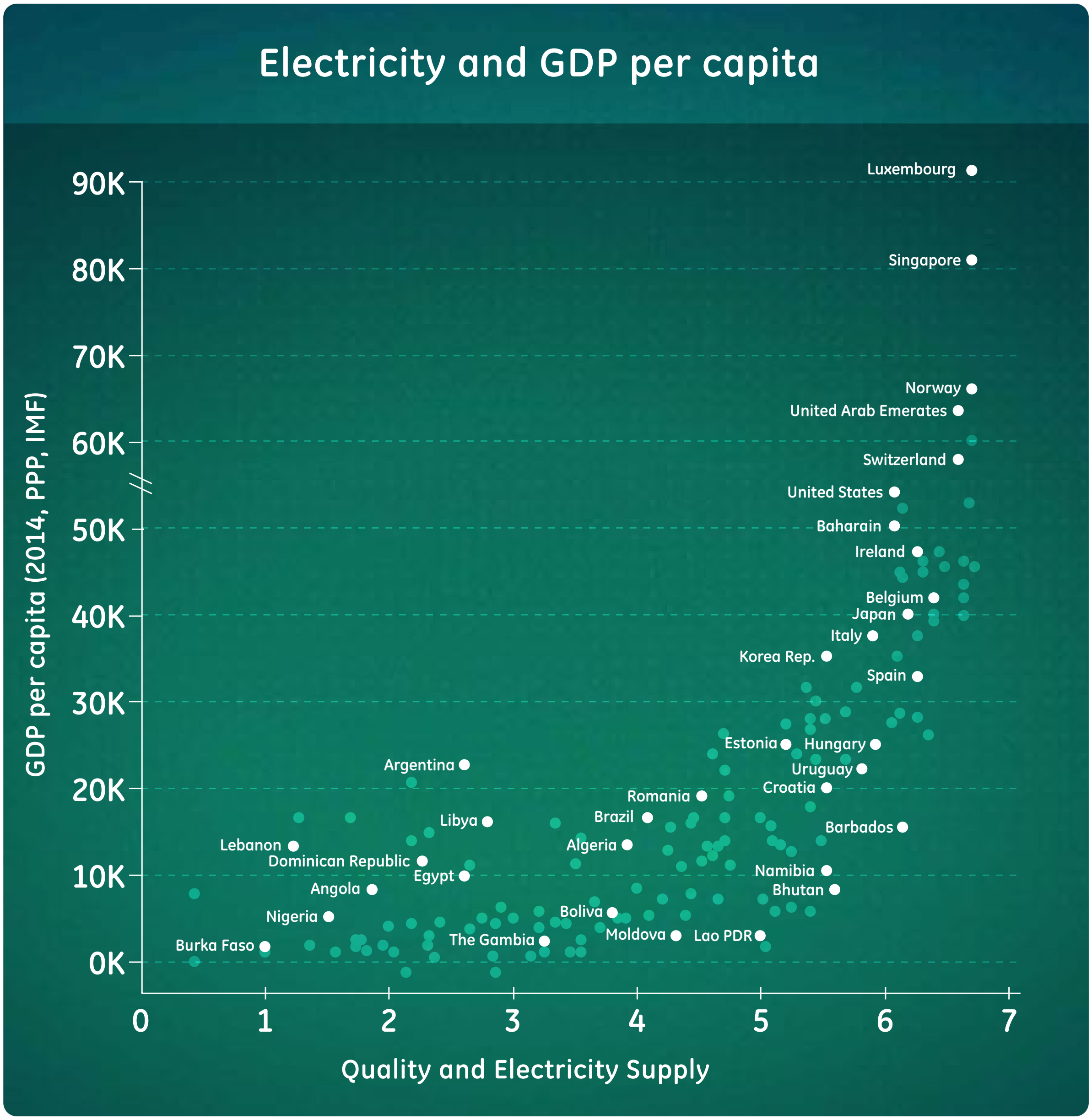


Source: World Bank

The World Economic Forum’s Global Competitiveness Report stresses that broad access to reliable electricity supply is essential for economic growth and competitiveness, and uses a “quality of electricity supply” index as a key component of its infrastructure pillar in calculating its global ctompetitiveness index. The index measures the availability and reliability of the electricity supply, defined as the incidence of outages and voltage fluctuations. As Figure 3 shows, the quality of electricity supply is very highly correlated with higher levels of GDP per capita.

As populations in large emerging markets populations improve their standards of living towards those currently enjoyed by advanced economies, natural resources consumption will grow at a fast pace. Sustainability is already a global priority—its importance will only grow in the coming decades. **Countries will have to develop new strategies and solutions to make energy consumption more efficient, and improve the effectiveness and resiliency of energy distribution networks.**

Figure 3



Source: World Economic Forum

Developed countries, where electrification rates are already at or close to 100%, will also need to reduce emissions from power plants and improve energy efficiency as their economies continue to grow. Moreover, aging infrastructure in both generation and grid, as well as, an aging workforce, represent significant challenges.

Meanwhile, there is still significant scope to further reduce inefficiencies and losses in generation, transmission and distribution, to help ensure sufficient electricity provision across the global economy in a sustainable manner.

- **8.1% of total global electricity output was lost in transmission and distribution losses in 2011.[3]**
- **Unexpected disruptions cost 3-8% of capacity, $10 billion annual lost production cost.[4]**
- **40% of abnormal events can be attributable to operator error.[5]**

Given its paramount importance for economic growth, **energy will be a national security priority for every country.** In developing new energy supply sources and infrastructure, ensuring the highest level of efficiency, security and resilience will be of the utmost importance.

This will include an optimal degree of supply diversification, including for imported energy, to reduce the risk of disruptions that may be caused by natural disasters or geopolitical shocks. It will also include a high standard of security safeguards around the energy infrastructure. As digital technology becomes pervasive, cyber security will become one of the most important pillars of energy security.

Technology drivers

These macroeconomic forces are now coming together with a new wave of major technological innovations that have begun to challenge the traditional setup of the energy sector. These innovations are driven by a convergence of digital and physical technologies that is starting to unfold across all industries. GE has defined this set of innovations as **The Future of Work**, and we believe it will be as transformational and powerful as the industrial revolution.[6]

The Future of Work consists of three mutually reinforcing trends:

1. The Industrial Internet merges big data and cloud-based analytics with industrial machinery, resulting in greater efficiency and increased operating performance. This is already making significant impact in the grid (smart meters), Next up is digitization of central generation and power consumption including distributed generation.

2. Advanced Manufacturing weaves together design, product engineering, manufacturing, supply chain, distribution and servicing into one cohesive intelligent system, delivering greater speed and flexibility at lower cost; this is transforming how capital intensive critical equipment such as gas or wind turbines are being manufactured.

3. The Global Brain integrates the collective intelligence of human beings across the globe through digital communication, resulting in crowdsourcing, open collaboration, and a much faster pace of innovation; this trend in the power industry will have the most impact from a developer oriented software platform and its constituent application economy development.

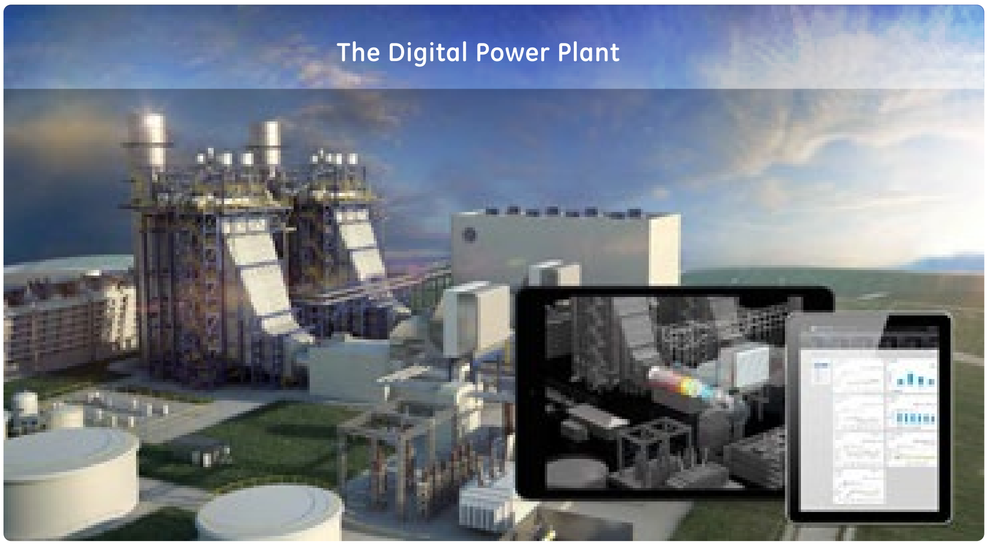
The Future of Work is changing the nature of economies of scale, and blurring the lines between manufacturing and services—and it is beginning to deliver substantial gains in productivity and efficiency for individual companies and entire industries. In 2012, we estimated that just a **1% efficiency improvement would yield over $60 billion in efficiency gains in the power industry over a 15-year period**, some $90 billion savings in the Oil and Gas industry; $60 billion in the healthcare industry, and about $30 billion each in aviation and in rail transport. At the time, we emphasized that these estimates were a lower bound, which could be attained with just a 1% efficiency improvement across the large installed base of industrial assets.

[3] Source: World Bank Data
[4] Source : ASM Consortium
[5] Source : ASM Consortium
[6] Annunziata and Biller (2014) "The Future of Work", GE White Paper

The Industrial Internet technologies that we have been developing since then are yielding efficiency improvements well in excess of those original lower-bound estimates. We are now seeing double-digit performance gains across our industries of operation.

In the power sector, the most recent GE estimates indicate that digitizing central generation could yield value of up to $100 million for new wind farms (up to 20% higher MW), up to $230 million for a new combined cycle gas power plant, and up to $50 million for an existing combined cycle gas powered plant. Across the whole power industry, this equates to up to $75 billion of impact for new combined cycle gas turbine and wind turbine orders, with additional value for upgrades to existing assets.

Figure 4



$230 million per plant

Figure 5

$100 million per farm

Digital innovations have already begun to transform the energy industry. They help open the way for multi-directional energy flows in the grid, for real-time demand adjustment in response to supply conditions, for a smarter combination of different energy supply sources and more. **Together, these changes brought about through digital innovation will increase the efficiency, affordability, reliability, and sustainability of the system.**

New challenges for energy players:

Balancing the fuel mix.

Power generation will be able to rely on an increasingly diverse and flexible range of supply sources: centralized generation through fossil fuels, nuclear or renewables, distributed generation, and stored energy. Balancing the supply mix on a real time basis will be essential to maximize the energy output and cost-effectiveness of the whole system.

Reliability of power delivery and quality.

The energy value chain will become more complex, encompassing a multiplicity of moving parts with different priorities and incentives, as well as a wider mix of supply sources. Ensuring that power can be delivered reliably, without outages or unforeseen changes in quality, will require a commensurately sophisticated effort of monitoring and control.'

Asset level visibility.

In order to achieve both of the above objectives, system operators will need to be able to monitor—in real time—the state and performance of all assets linked to the network. This will enable them to continuously assess demand and supply expressed by all elements on the system, as well as their responsiveness to price signals.

Identifying new revenue sources/correctly valuing and allocating the cost of invest-ments and other efforts that add value to the system.

The traditional model that compensated utilities with volumetric tariffs is becoming suboptimal. The energy system of the future will need to develop a set of incentives that induces all players to add value through actions and information provision, ensuring adequate compensation for investment and incentivizing sufficient risk-taking for innovation and experimentation.

Aging workforce and knowledge capture.

Population aging in advanced economies is mirrored by the agingof the workforce across a number of industries—and the power industry is no exception. The prospective simultaneous retirement of large cohorts of experienced workers is set to create a problematic skills shortage just as the industry faces a challenging transformation. While younger generations of workers will bring new skills to the industry, it is crucial that the knowledge and experience accumulated by more senior workers is captured and embodied in the companies' institutional memory, accessible to the new workforce. Digital innovations that facilitate communication and collaboration as well as the creation of a digital memory capturing the experience of the workforce should be used to this purpose.

Technology integration.

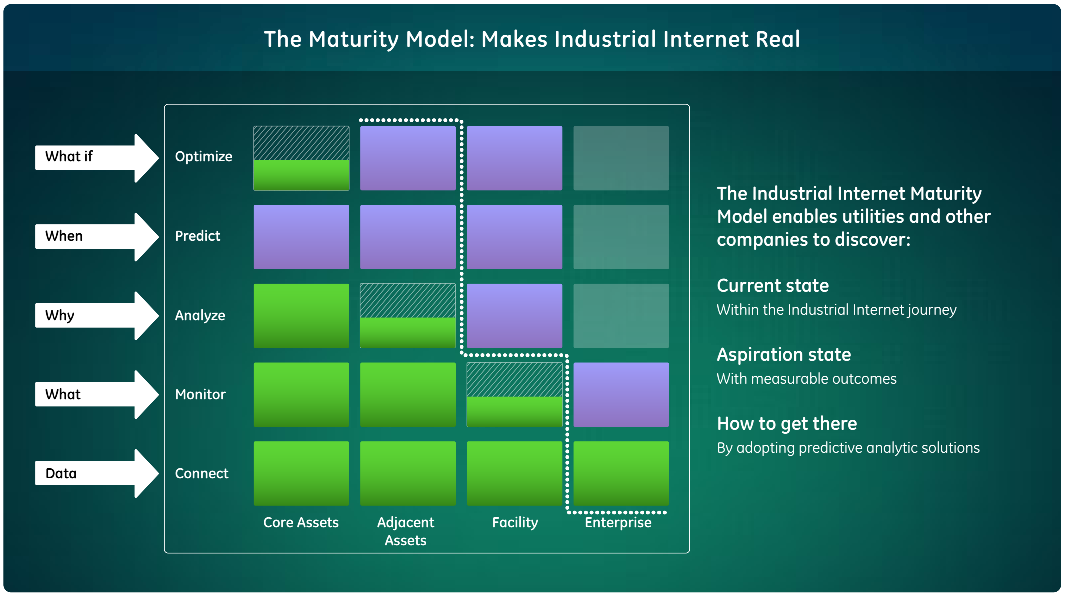
The management of industrial technology has traditionally been split between two separate fields: information technology (IT) and operations technology (OT). IT worked from the top down, deploying and maintaining data-driven infrastructure largely to the management side of business. OT built from the ground up, starting with machinery, equipment, and assets and moving up to monitoring and control systems. With smart machines, big data, and the Industrial Internet, the worlds of IT and OT suddenly collided. Data, once the purview of IT, is now ubiquitous on the operations floor. **In order to fulfill the promise of using data to enhance productivity, IT and OT, developed separately with independent systems architectures, need to come together** and find common ground to develop a new information-driven infrastructure.

Each of these challenges represents a powerful opportunity. The convergence of digital and physical innovation can dramatically accelerate progress across all the critical dimensions listed above. As is becoming evident in other industries, as digital intelligence becomes embodied in industrial equipment it opens up an entirely new dimension for efficiency improvements. **Digitally enabled interconnected devices can perform a much wider range of functions, benefit from faster performance improvements, and deliver disproportionately greater value to their users than their traditional versions.**[7]

[7] Annunziata (2014), "The Value of Interconnectedness", GE White Paper

The journey towards Digital Maturity

Figure 6



The first step of the Industrial Internet maturity is to connect all critical assets in the energy value chain. This is not a trivial task as we are referring to nearly hundreds of discrete components with at least a dozen different communications and networking protocols.

Based on Harbor Research and GE estimates, the table below shows that over seven billion devices across the energy value chain will be installed by 2020.

These devices will generate 24 exabytes of data by 2020. We estimate at least 50% of this data will be stored and analyzed in various forms of clouds (public, private or hybrid).

Figure 7

Data management growth access across the energy value chain.

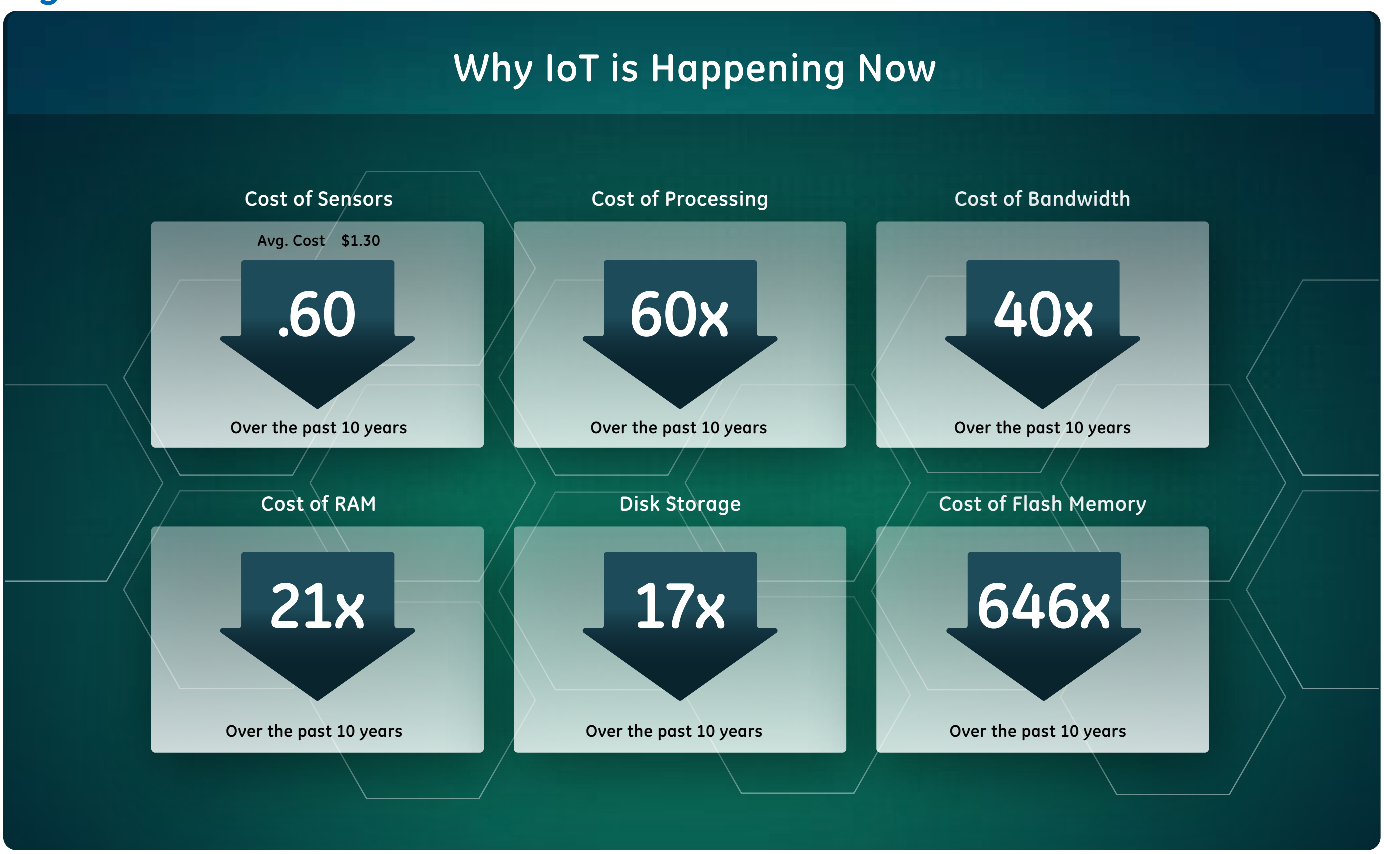
	Devices installed in millions			Data storage, on-premesis & Cloud (petabytes)		
	2014	2020	CAGR	2014	2020	CAGR
Power generation (fossil, nuclear, renewables, etc.)	169	577	23%	2,296	10,839	30%
Power transmission & distribution	1,327	5,008	25%	805	3,445	27%
Power consumption (non-residential lighting, power distribution & management, HVAC & climate control)	316	1,817	34%	1,403	9,875	38%
Total	1,812	7,402	26%	4,503	24,159	32%

[6] Annunziata (2014), “The Value of Interconnectedness”, GE White Paper

In many cases, utilities have already embarked on this digital journey. They are deploying operational technologies such as generation and distribution asset smart sensors & controls, substation and distribution automation and smart meters. The industry has begun to develop a vision for a digitized future through various smart grid initiatives such as improved grid resilience and energy efficiency. However many assets still lack the capacity to collect and transmit data. Those that are so enabled transmit volumes of data into local repositories that are not accessible remotely; the few that are connected do not have the cloud capabilities to generate actionable insights in real time.

Digital maturity will be achieved by equipping energy assets across the generation, transmission, distribution, and consumption value chain with sensors and cloud-based analytics. This is becoming increasingly possible as sensor, bandwidth, and computing costs continue to decline. Moreover, as information and operational technologies continue to converge, emerging digital platforms will create a more connected and intelligent power system. These platforms will do so by improving planning, operations and maintenance procedures for each asset in the energy value chain.

Figure 8



Source: Goldman Sachs Investment Research, John C McCallum Research, TCG Advisors

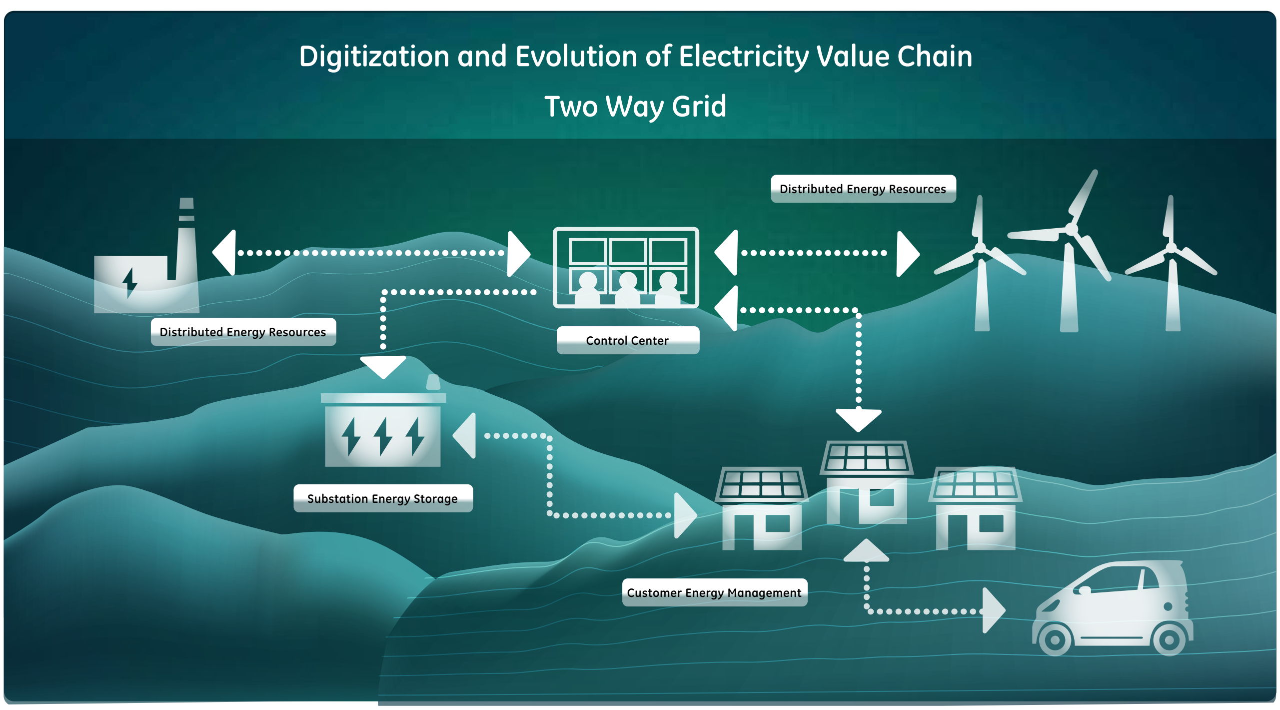
The Future of Digital Energy: Transforming the Industry Value Chain

The future of energy is a new value chain augmented and interconnected by digital technologies, where both power and information flow in multiple directions, all actors add value to the system, and the overall efficiency and resilience of the system hinge on information sharing, openness, collaboration, coordination, and the right set of incentives. **The end result will be a system that provides electricity in the most reliable, sustainable, and economic manner.**

It will encompass three key elements, highlighted in Figure 9 below:

1. *a **digital centralized generation** pillar, relying on a mix of fossil fuel and renewable sources;*
2. *a **digital grid**, connecting generation and consumption, enabling the multidirectional flows of energy and information; and*
3. *a **digital consumption pillar**, which will play an important role not just in improving consumption patterns, but in adding generation and storage capacity.*

Figure 9



Digital centralized generation

Centralized power generation will remain critical even with the rise of distributed energy resources. It will provide the majority of the power supply, and ensure the continuity and reliability of electricity provision. The longstanding goal of ensuring reliable, affordable and safe access to electricity remains unchanged in the future of energy, and can only be guaranteed by a strong centralized power generation system.

Digital technologies will transform power generation from the very earliest stages, starting with the design and siting of power plants, and continuing through the operations and maintenance phases.

Building the new Digital Power Plant and Digital Wind Farm:

The planning process will utilize comprehensive big-data analysis of the energy network. Data from distribution grid assets such as advanced meters, intelligent feeder monitoring and distributed resources can be combined with transmission data from phasor measurement units and other monitoring devices to develop predicted sub-hourly scenarios. These analyses will enable designers to simulate the load demand on a power plant. They will also estimate the financial viability of the plant under different alternative configurations, through a better understanding of the plant's complex interactions with all other resources in the energy system. This can also help utilities balance their generation portfolio.

Renewable power plants are particularly impacted by location. Shading or vegetation can affect how much light reaches a solar plant; wind farms are dependent on wind patterns. GE's research shows that current methods of siting for a new wind farm leave potential future revenue on the table. The reason is simple: Today, when building a new wind farm, the industry standard is to choose a single turbine model for all the pad mounts on the sites—even though given the wind patterns, some pads have greater output potential than others. Deploying a single turbine model across the whole farm, therefore, can maximize performance for only some of the pads, giving up the option of maximizing output for the farm as a whole, and leading to a lower energy output than could otherwise be obtained.

A Digital Wind Farm, instead of settling for the least common denominator model, will allow to customize every turbine to its unique location on the farm. This can only be done by integrating the advances in digital infrastructure (cloud computation, advanced load and weather simulation algorithms, satellite topology images, etc.) and hardware technologies (modular turbines that allow different configurations such as optimum hub height, blade length and generator rating).

The location of a new centralized power generation facility will also need to take into account the necessary Transmission and Distribution (T&D) infrastructure. T&D siting often involves a lengthy process of engaging multiple stakeholders to devise the appropriate pathway between power plants and load centers.

Today, new data tools such as advanced geospatial platforms and power flow modeling can evaluate the best grid layout and determine appropriate capacity requirements. Assessing sub-hourly interval data can help develop detailed scenarios to understand the tradeoff between installing or upgrading distribution lines and adding distributed energy resources, or how those resources may impact power flow. These digital capabilities are even more important when the environment becomes subject to faster, more frequent and more complex changes because of new revenue streams and system requirements such as frequency response, and new markets such as ancillary and capacity markets. These require more real time decisions and an improved transparency between plant capabilities and market dispatch.

Operating a Digital Power Plant and Digital Wind Farm:

Once the plant/farm is in operation, digital tools can enhance its performance and profitability. Today's power plant and wind farm do not use integrated data and plant or fleet level software applications to run their complex operations efficiently. A typical power plant is a complex system that requires constant optimization across various tradeoffs between availability, output, efficiency, maintainability, wear & tear and flexibility. If these trade-offs are not tackled by using all available data and the right software applications, the plant is operating at a lower-efficiency profile, resulting in lower returns on the capital investments already made. Use of various digitization tools can significantly increase the operating profile of an existing power plant.

Software can provide power producers with both "inside the fence" and system-wide views, enabling them to maximize the plant's operational efficiency while responding optimally to changing conditions on the grid and in the overall power market.

What power plants need today are “Software Defined Operations”. Deeper insights into a power plant or wind farm operations to help with more forward looking decisions, and breaking down the barriers between silos in turn providing inputs for how to manage the market side of the power generation business.

Software Defined Operations have 3 elements:

1. **Deeper Insights:** a single unified automation architecture—from sensor to the boardroom.
2. **Better, Faster Decisions:** Drive the best user experience across the workforce – from Operator to the CEO.
3. **Real Time Actions:** Develop advanced software, algorithms and analytics that allow various actors in a generation setting to make business optimal decision with the same lens of impact to overall business key performance indicators.

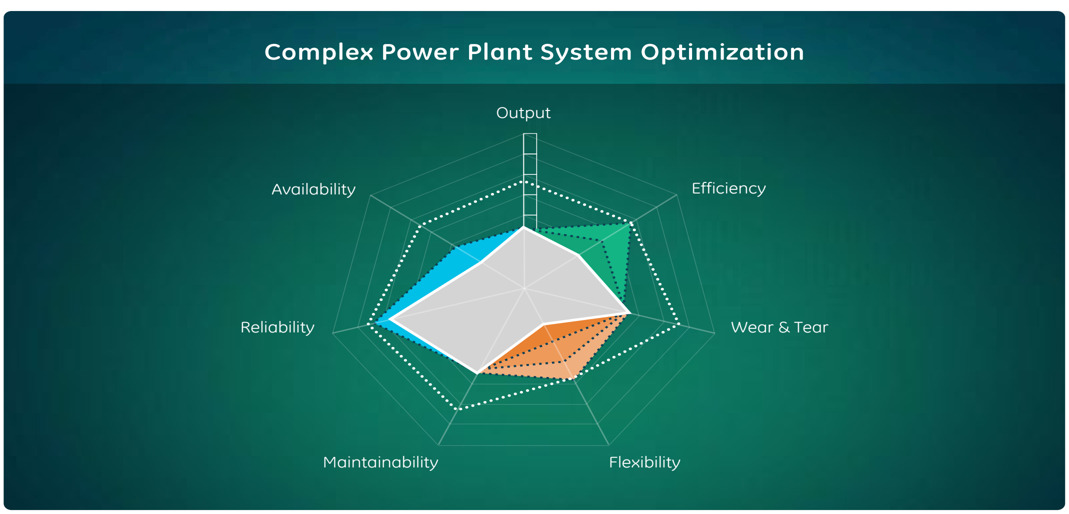
Predictive or condition-based maintenance is a defining benefit of the Industrial internet. Digital tools will track and maintain historical performance baselines for individual assets as well as the whole plant, comparing it to real time performance monitored on a continuous basis. Any variance from “expected behavior” derived from these baselines or expected operation will trigger an alert. Advanced analytics will then determine whether the variance signals a potential future malfunction, its root cause and the likely timeframe over which the malfunction will occur. Analytics will also provide a cost-benefit analysis of how much longer the unit can perform, and at what load, before the issue must be addressed. This will allow the power producer to address issues proactively, reorganize workflow around planned maintenance and avoid outages. The resulting increase in uptime will improve a plant’s economic value.

Digital technologies can also assess a machine’s expected performance characteristics given the prevailing ambient conditions. This combines a digital assessment of the machine’s “state of readiness” based on sensor readings with temperature, humidity, and other data that can impact its output. These data points can be compared with the historical baseline and expected performance curve to detect any variance or anomalies.

Software that understands a machine’s physical capabilities relative to its theoretical potential can do more than simply detect variance; **it can adjust operating parameters in real time to maximize efficiency and minimize cost.**

Aggregating and analyzing data across assets “within the fence” can establish operating levels for individual assets that optimize the entire plant system. **In turn, as the plant operates more efficiency, its overall emissions can decline**, improving the plant’s environmental footprint. **Without these analytics, each asset would be individually configured**, which might result in a suboptimal performance for the total plant. For example, digital wind farms that use analytics to adjust individual turbine performance to maximize system benefit can improve total plant output by up to 20%.

Figure 10



A plant’s economic evaluation combines an output assessment with system or market data. In deregulated markets, this entails analyzing energy and/or ancillary product pricing for real-time or advanced delivery commitments. In regulated contexts, this may include assessing zonal demand, available transmission capacity, and the cost of dispatching other available plants. Once digital tools have determined the machine’s output capability, they can **perform an optimization algorithm to provide suggested operating levels to maximize economic value**. This may include recommendations on how to bid a plant’s output among various energy or ancillary markets, or at what time a plant should be dispatched.

Digital technologies also hold huge potential to improve fuel procurement and storage, which can account for up to 90% of a plant’s operating cost. Digital tools can improve fuel procurement by identifying the most cost-effective fuel suppliers, and tracking fuel transport and storage. Online platforms can run reverse auctions to enable multiple fuel suppliers to compete.

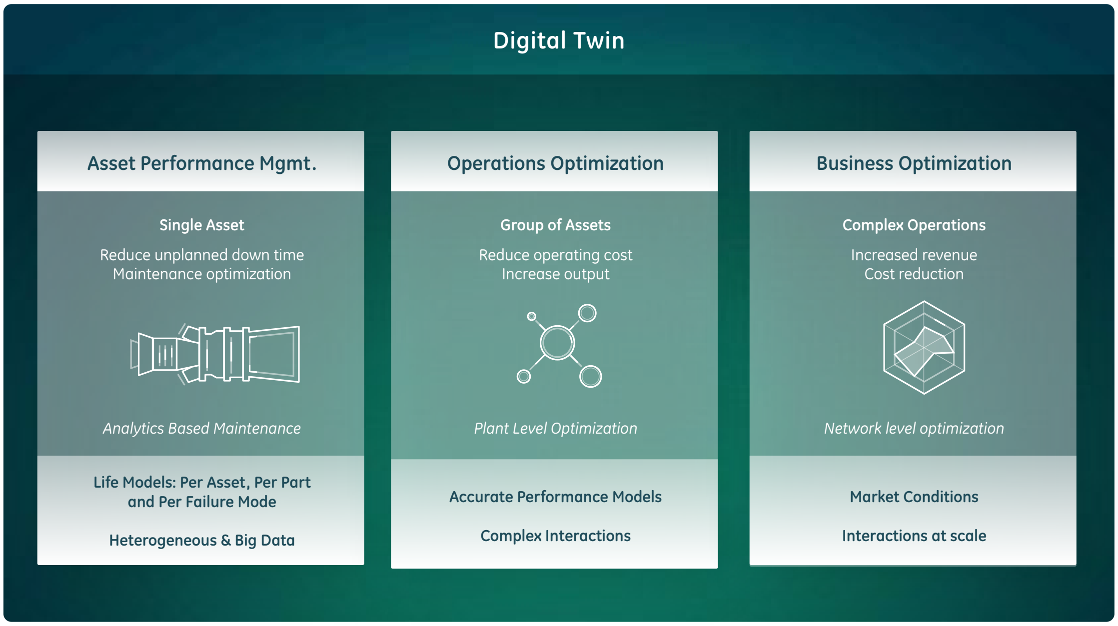
Once a supplier has been identified, digital tools can ensure that the power producer can track fuel delivery and storage, such as monitoring the location of LNG or coal deliveries and ensuring that appropriate quantities are transferred to reserves. Digital technologies can also help drive transparency around commodity pricing, enabling power producers to determine how they can adjust their hedging strategies to manage fuel cost volatility.

With digital power plants, utilities and other power producers will have the ability to conduct analyses that previously may have been difficult to perform across functional silos. Benchmarking across plants will now become possible, as data is transmitted back from assets “inside the fence” to be aggregated and analyzed. Operational anomalies can be identified and corrected, and plants that perform better than expected can be rewarded. Operational platforms that identify maintenance issues can proactively transfer data to IT systems that manage maintenance personnel and supply chain vendors, ensuring that the necessary parts are replaced by the right personnel at the most optimal time. **Through the use of analytics and a holistic IT/OT perspective, power producers can optimize their plant performance and improve their portfolio’s sustainability while minimizing maintenance costs.**

The black box behind applications that help digitize a power plant or a wind farm is a concept called “Digital Twin.” “Digital Twin” is a collection of physics-based methods and technologies that are used to model the present state of every asset in a Digital Power Plant or a Digital Wind Farm. The models start by providing guidance on “design limits” of a power generation unit at the commissioning stage or inferring the design limit for an existing plant/farm by matching the equipment to thousands of other similar equipment in the database.

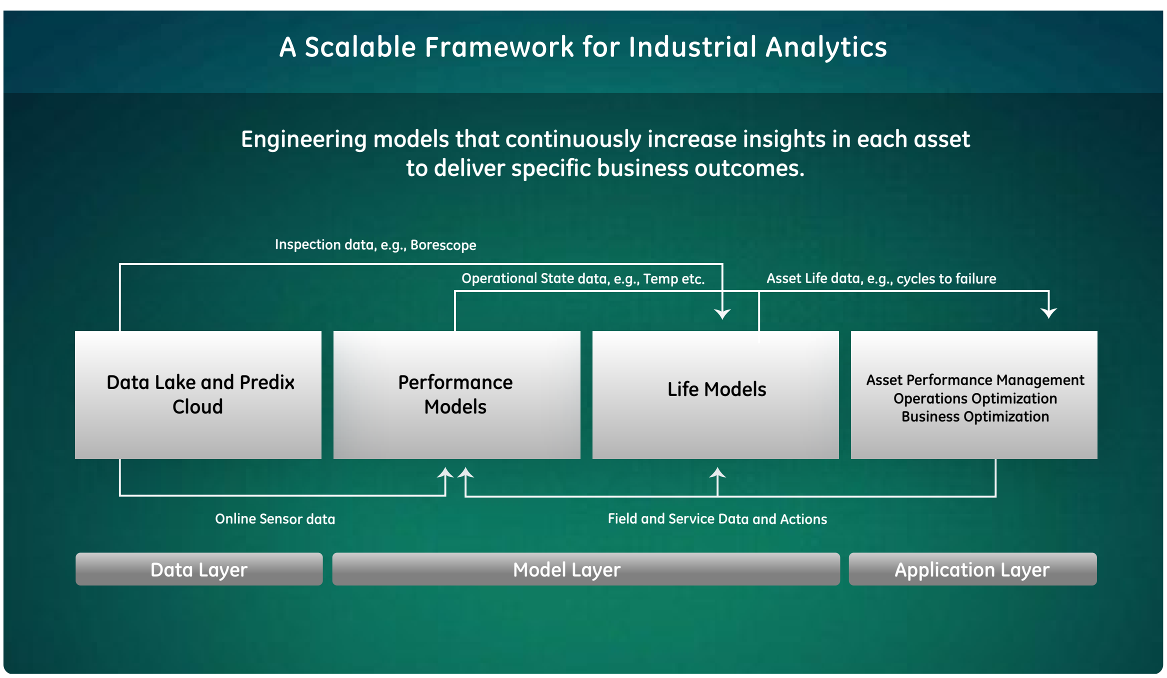
These models are then continuously updated, and learn to accurately represent the “present” state of a plant or farm during its lifetime. The models accurately represent the plant or farm under a large number of variations related to operation—fuel mix, ambient temperature, air quality, moisture, load, weather forecast models, and market pricing. Using these digital twin models and state-of-the-art techniques of optimization, control, and forecasting, the applications can more accurately predict outcomes along different axes of availability, performance, reliability, wear & tear, flexibility, and maintainability. The models in conjunction with the sensor data give us the ability to predict the plant’s performance, evaluate different scenarios, understand tradeoffs, and enhance efficiency.

Figure 11



The technology needed to run the complex algorithms described above is different from the traditional IT architecture prevalent in the industrial world currently. What is required is a scalable framework to run industrial analytics, as seen in Figure 12. It needs to have a seamless integration between the data layer (using a data lake and cloud computing paradigm), a model layer and the application layer. What the users will see is the experience captured in the application layer.

Figure 12



Digital Grid

The digital grid will underpin the future energy network: it will enable bi-directional flows of electricity, transmit information and price signals, and ensure optimal balance of supply and demand. **Together, this will enhance grid reliability, reduce losses, and integrate distributed resources which can help decarbonize the system**. Digital tools will play a significant role in achieving these outcomes. Utilities today manage their T&D operations through several technology systems, including outage management, customer information, maintenance management and meter data management among others. However, using digital tools and intelligent monitoring devices, T&D operators will be able to **utilize an integrated digital system that will enable them to identify reliability issues, address customer problems, and ensure optimal electricity delivery in a more efficient manner**.

Improve outage response: Today, T&D operators often rely on manual, reactive intervention to ensure reliable grid operation. For example, without the installation of advanced meters and other intelligent devices, utility operators must piece together customer phone calls and other input to detect a power quality issue or an outage, prolonging the time between identifying the root cause of a delivery problem and deploying a solution.

Digital tools can detect and locate an outage, identify the root cause, and rapidly restore power. For instance, advanced meters can indicate an outage; geospatial data platforms can help navigate personnel to the right geographic area, and advanced distribution systems can dynamically reroute electricity.

As more power is generated using distributed resources, microgrids can provide enhanced delivery and resilience. Digital tools can provide algorithms to island these resources from the grid, ensuring that critical load demand continues to be satisfied until main grid operation is restored.

Reduce losses: T&D operators must also address both technical and non-technical losses. To reduce technical loss due to natural power dissipation, software that processes voltage, current, real and reactive power, and phase can make real-time adjustments. To address non-technical loss, data from smart meters, intelligent devices, and distribution grid sensors can identify where there may be theft or other power loss.

Manage distributed resources: Distributed energy resource adoption is growing, driven by favorable economics and technical advances. Onsite generation has become increasingly cost-efficient due to greater gas availability and rapid cost declines in solar and storage technologies. Intelligent load devices that reduce or shift energy use are becoming mainstream through user-friendly mobile interfaces, turning consumers into "producers-consumers."

These technologies can bring benefits to the power system, including addressing demand more efficiently, deferring T&D investment, improving power quality, and increasing grid resiliency. However, distributed resources also present operational challenges. They may cause rapid voltage fluctuation, create bi-directional flows on radial distribution lines, or adversely affect transformer and other grid asset lifetimes.

Software can help monitor and control these distributed assets, as well as ensure that both consumers and the grid can benefit from their installation. It can analyze sensor data from substations, feeders, and connected devices to identify grid areas that may be at capacity, or experiencing volatile demand or power quality issues. Data from smart inverters or other devices can be analyzed and merged with operational grid data to provide utilities with a single view to monitor and control distributed resources.

As distributed resources gain traction, they can operate as a network, and in effect become a "virtual" power plant. For distributed resources where output can be dispatched or controlled, software can utilize local demand projections, relevant market pricing, and output potential to ramp distributed generation or curtail demand in a coordinated manner. Utility systems can monitor and control distribution grid devices to ensure stability when distributed resources are in operation.

In reshaping the digital grid, it will be important to build in a high degree of flexibility to allow for experimentation and to adapt to future technological breakthroughs. Grid flexibility will also be instrumental in ensuring high reliability in a context characterized by more flexible and variable consumer demand and intermittent renewable energy sources.

Digital consumption

The transformation of the energy system has arguably been accelerated by changes on the consumption side. Advances in solar and in energy storage are allowing traditional energy consumers to become energy producers. Advanced meters, connected devices, and energy management systems are providing consumers with greater transparency and control over their energy use. Together, these trends will help **consumers lower their energy spend while enabling them to provide overall benefits to the system in the form of lower peak demand and more economic energy and ancillary services**.

Producer–Consumer: With solar panels on the roof and an electric vehicle (EV) in the garage, a traditional consumer can start to play a much more active and multi-dimensional role in the energy system. When her photovoltaic (PV) energy generation falls short of her consumption needs, she will supplement it with energy supply from the digital grid; when her generation exceeds her needs she can turn into a supplier, feeding energy into the digital grid. The battery of her electrical vehicle can act as a distributed storage system and help manage the demand and supply fluctuations in her household and potentially in the energy system as a whole.

Digital energy management can interface between a consumer's equipment and the grid, regulating both energy consumption and the mix of supply sources utilized based on the price signals provided by the grid itself. At times when the grid faces peak demand, its prices will rise, and the home energy management system will respond by reducing consumption and/or switching from grid-provided power to locally-sited generation or battery-stored power, where those are available.

Energy Usage Visibility: Consumers can gain better visibility into when and how they consume electricity, thanks to the continued rollout of smart meters and other connected devices, enabling advanced analytics to deliver data-driven insights through intuitive user interfaces on computers and mobile devices.

This is a big shift from a situation where most consumers still limit their interaction with the energy provider to paying their bills and reporting outages. **Now consumers can better understand their energy consumption and change their strategies accordingly**: residential customers can benchmark themselves against similar households and identify a menu of possible actions to reduce their spending; commercial and industrial customers can shift some of their consumption to off-peak periods to benefit from lower tariffs, or they can identify operational inefficiencies that can be addressed to lower consumption.

Through the digital grid, this process will generate a **continuous flow of data on consumption behaviors, load fluctuations, adaptation to price signals and supply responses—data that will help raise the efficiency of the entire system.** To maximize the potential benefits of greater consumer engagement—**where consumers are seen in their new and greater role of co-suppliers**—the energy system of the future will need to satisfy two conditions:

- Provide a system of price incentives designed to reward contributions to the system and to nudge consumers towards a behavior that can maximize system-level efficiency;

- Offer a monitoring and control system flexible enough to accommodate different degrees of customer engagement according to individual preferences.

Some consumers will embrace the opportunity to actively reshape their consumption strategy, whether driven by concern for the environment or a desire to minimize costs; these consumers should have the opportunity to closely monitor and modify their consumption with the high frequency they desire. Other consumers will be content with setting basic goals, parameters and constraints without having to spend too much time understanding load fluctuations and pricing schemes. These consumers should be able to rely on a smart energy system that will maximize efficiency subject to the consumer's choice of basic settings.

Pricing schemes should reward consumption and distributed production behaviors that contribute to maximizing system efficiency; they should also recognize the value of the information that different patterns of behavior provide, while similarly assessing the value that consumers and other distributed actors derive from access to the grid's infrastructure.

Digital Consumption – Smart Home

Futuristic version of a smart home to highlight PV generation, EVs, control and connectivity to the grid

Figure 13

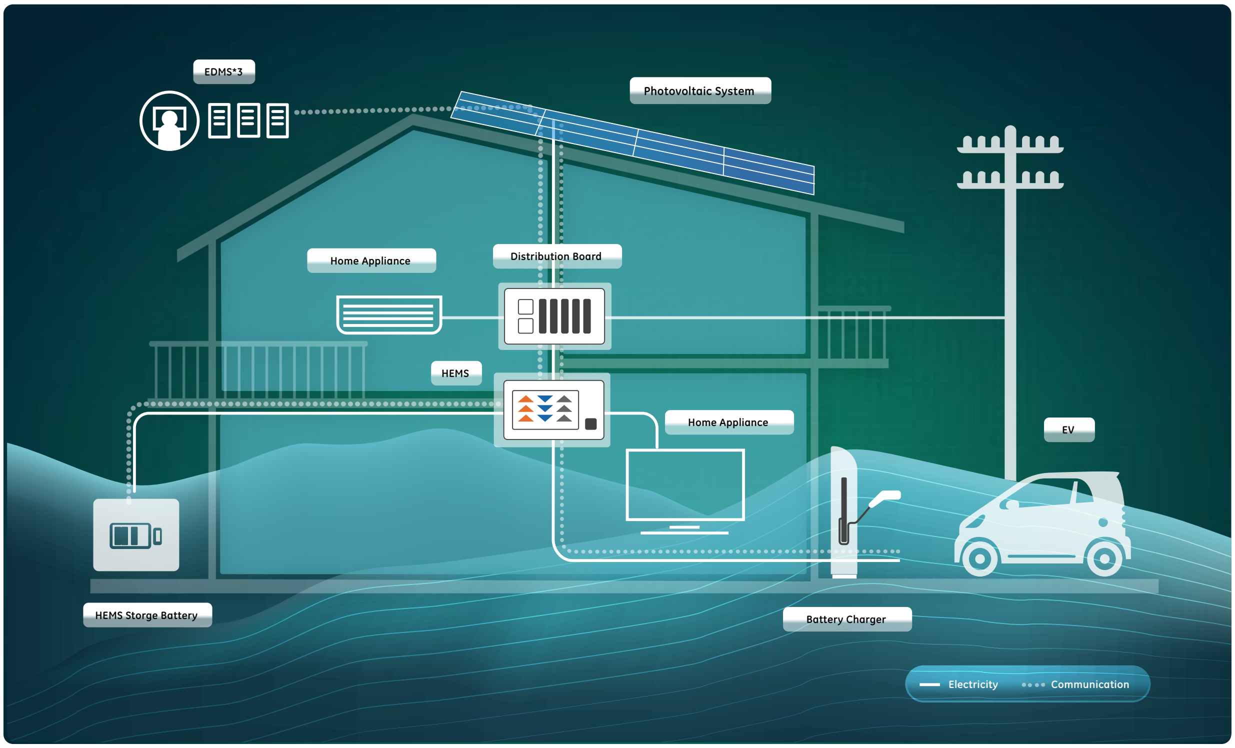


Figure 14

Enhancing the value: New business models and enablers

New business models

As we have outlined above, digital technologies are set to completely transform the entire power sector value chain. This will require utilities and other traditional entities to adapt and adopt new business models, while emerging players introduce new services and capabilities. It will also require a set of enabling conditions for new investments, policies and regulations.

Energy providers will join a new breed of digital-industrial companies.[8] This will require changing their business model to fully take advantage of new digital capabilities. A first priority will be to use the insights provided by big data analytics in order to balance the fuel mix. Conventional thermal generation will remain a vital component of the energy mix for decades to come,[9] but new technologies will accelerate the adoption of natural gas and renewables, requiring software to manage and optimize the generation portfolio.

Switching from reactive to proactive and predictive maintenance so as to maximize uptime will also require a mindshift. In general, management and operations of power producers will have to adopt a "data-first" mentality, always thinking in terms of the potential insights that can be gleaned from data and analytics to improve the value of the service.

Digital tools can also give energy providers new ways to interact with consumers. **Many utilities and other energy service organizations are seeking to transition from electricity provider to trusted energy advisor.** This requires utilities to work with customers in new ways to identify and tailor solutions. For example, detailed interval data as well as information from connected devices can help utilities and other service providers to develop onsite power solutions to increase reliability or efficiency retrofits to reduce spend. Social media can help utilities communicate with customers regarding outage restoration or peak demand events, or simply engage customers in a discussion around energy services or conservation.

[8] See Annunziata (2014), "The Future of Interconnectedness", GE White Paper.
[9] World Economic Forum (2015), "The future of electricity"

The electric grid as a platform

Platforms have quickly emerged as a defining characteristic of the digital economy. Their role and value in consumer sectors is by now recognized: they are both an enabler of efficiencies and a key avenue of value monetization. Platform business models have revolutionized the way that value is created, delivered and monetized across a set of interdependent providers, users and intermediaries. As a concept, platform-driven businesses are not new. They have existed in the physical realm for centuries: a "bazaar" or "market" is a platform that brings sellers and consumers together in some central location for a trade, enabling faster diffusion of information (through physical co-location) and more efficient transactions.

Digital-age platforms do a lot more, however. They unlock the potential of under-utilized capacity. They enable instantaneous and universal access to information through digital apps on mobile devices; they turn data into analytical insights that can dramatically increase efficiency by accelerating the feedback loop between price changes, and supply and demand responses. They also accelerate innovation and value creation. Common operating systems that enable the rapid and wide deployment of new digital consumer apps have reached the point where "there is an app for everything". A similar proliferation will take place in the industrial world: **Predix, the operating system for industrial apps, is set to spur the rapid development of an industrial app economy** that will accelerate efficiency gains across industrial sectors.

The electric grid embodies many of the platform characteristics. It connects multiple users of a network, enabling the exchange of products, services and information. Traditionally however, the platform potential of the electric grid has been limited by the very specific nature of the sector. Economies of scale, the exclusive role of centralized generation and the lack of data collection and response mechanisms dictated a very simple hub-and-spokes model, with centralized power producers supplying electricity and charging bulk tariffs regulated to allow them to cover investment and operational costs while ensuring affordable safe and reliable power access to consumers.

With the rise of distributed generation and demand management set to complement centralized power, the electric grid has for the first time, an opportunity to become a true platform, enabling a symbiotic relationship between central and distributed resources, utilizing a wide range of data such as weather and vegetation changes, granular load projections by neighborhoods, central generation and distributed resource output capabilities, demand response capability, and grid asset health to **find the optimal resource mix and power flow path to maximize grid reliability and minimize delivered electricity cost.**

These digital platforms will enable central and distributed resource providers to determine locational prices for energy and ancillary services, and consumers to determine how best and when to use energy. In the event that a reliability issue such as an outage must be handled, the digital platform will autonomously communicate with grid devices to reroute power flow, island critical loads using microgrids, and ensure that the proper steps are taken to restore the grid to proper operation safely and quickly.

Enabling conditions

While there will be tremendous benefit gained from further digitizing the energy sector, challenges beyond technology and policy remain. In particular, **a grid with seamless interaction between central and distributed resources will require open standards and interoperability**. Any platform that manages assets as critical as the energy infrastructure will need to be secure physically, but especially digitally. Finally, a new generation of personnel will be required to facilitate the industry's transition to a digital future as a significant portion of the current workforce retires.

Open standards and interoperability: As with any ecosystem that includes a multitude of technologies, products and stakeholders, a common set of standards is necessary for industry development and continued innovation. This need is magnified in the case of the Industrial Internet—a convergence of multiple technologies with advanced connectivity across devices and systems. **To maximize the potential value of Industrial Internet innovations, it is essential that different systems and assets be able to communicate with each other**, share data and respond to common monitoring and control systems. Moreover, as these connected devices interact with utility and other personnel, data standards can help drive consistent analytical views to aid in decision making.

While progress has been made, more will need to be done to involve the emerging technology and service providers, along with the existing set of utility and OEM stakeholders. Even in the pre-digital age, the efficiency and value of power grids has often been held back by a tendency to "balkanize" the grid along state lines; in the digital age, artificial and arbitrary barriers to interconnectedness and interoperability would carry a much larger opportunity cost.

Cyber security: The digitization of energy opens a new form of vulnerability, exposing network participants to potential data privacy and system security risks. **Reducing these risks to a minimum is a top priority.**

There has been progress on multiple fronts. Vendors are developing and deploying solutions that include assessment services, firewall and security infrastructure. The U.S. Department of Energy and National Institute of Standards and Technology have put forth comprehensive programs to develop frameworks that address the risk to the electric grid, as well implementation guidelines and maturity models for cyber security. As government and private enterprises invest in digital technologies, they must continue to implement a robust cyber security infrastructure.

Education and skills development: Energy companies need people with software and analytical skills to reap the benefits of the digital transformation. They must invest in employee education and training, distribute and encourage the use of mobile devices, and partner with universities and other vocational training institutions to build data science capabilities.

Attracting new talent and workers with digital skills is becoming increasingly important as utilities also face a retiring workforce. Digital knowledge management systems can be used to capture processes, institutional knowledge, and other relevant operational data from the current workforce. Through the use of blogs, social media, conferencing, and other real-time knowledge-transfer platforms, retiring specialists can ensure that their experienced perspective can be captured and disseminated to newer employees in a fast and seamless way.

Conclusions

The power industry has begun an exciting digital journey, one that will bring a deep transformation of the entire value chain. A set of macroeconomic and technological forces have catalyzed this transformation, creating new challenges but also new opportunities for the industry.

Access to electricity across developed and emerging markets is critical to global growth. Today with over a billion people without electricity access and growing energy demand from rising living standards of billions more, the industry faces a formidable challenge. **Supplying secure and reliable power in a sustainable manner will require investment in new generation and transmission-distribution infrastructure**, making the existing system more energy efficient as well as diversifying the fuel mix.

Advances in distributed energy technologies, energy storage, and connected devices are making it possible for consumers to also play a role in the generation and distribution of energy, opening the way for bi-directional energy flows and optimizing peak demand. Utilities are deploying digital technologies to integrate distributed technologies, manage fluctuating demand and quickly resolve outages to realize industry goals. The penetration of digital technology adoption however is limited. Operational challenges of sustained profitability, data deluge and an aging workforce still remain significant.

The convergence of digital and physical technologies that is unfolding across industry can turn these challenges into unprecedented opportunities. **The power sector needs a digital strategy that enables a new value chain augmented and interconnected by digital technologies**. Our vision of this value chain links digital generation and digital consumption by a new digital energy grid that can also serve as an intelligent technology platform and a marketplace for new revenue sources, pricing schemes that incentivize innovation for existing and new players in the energy ecosystem. **A digitized value chain will yield a system with greater reliability, affordability and sustainability**.

In the energy sector, machines will merge with data analytics at a scale like never before. This will result in substantial value gains starting from the planning and siting of power generation plants to their operations. Moreover it will enable a more dynamic management of central and distributed power. Meanwhile, digital consumption will become more efficient, participative and responsive to demand and power supply conditions.

Power producers and utilities are embarking on a journey to digitize their processes. This will require not just investment in new technologies, but also a shift in mindset and business models—and the shift will need to be faster than ever before. Digital innovations rely on openness and collaboration to realize their full value. Therefore, power producers and utilities will need to break down barriers separating their organizational silos. To do so, their CEOs, CIOs and COOs need to select the right technology partners that can help them bridge the IT and OT domain expertise. Internal and external collaboration will be mutually reinforcing. As this new wave of innovations brings together very different areas of expertise at an accelerated pace, partnerships are essential to succeed.

This transformation will need high coordination among stakeholders. Energy providers will join a new breed of digital-industrial companies, by investing in new technologies and finding new ways to provide tailored solutions to customers. It will need development of **open standards and interoperability** between products, the nurturing of a new generation of personnel, and the **highest level of cyber security**.

The opportunity for all participants in the future of electricity is unprecedented—it is full of digital promise.