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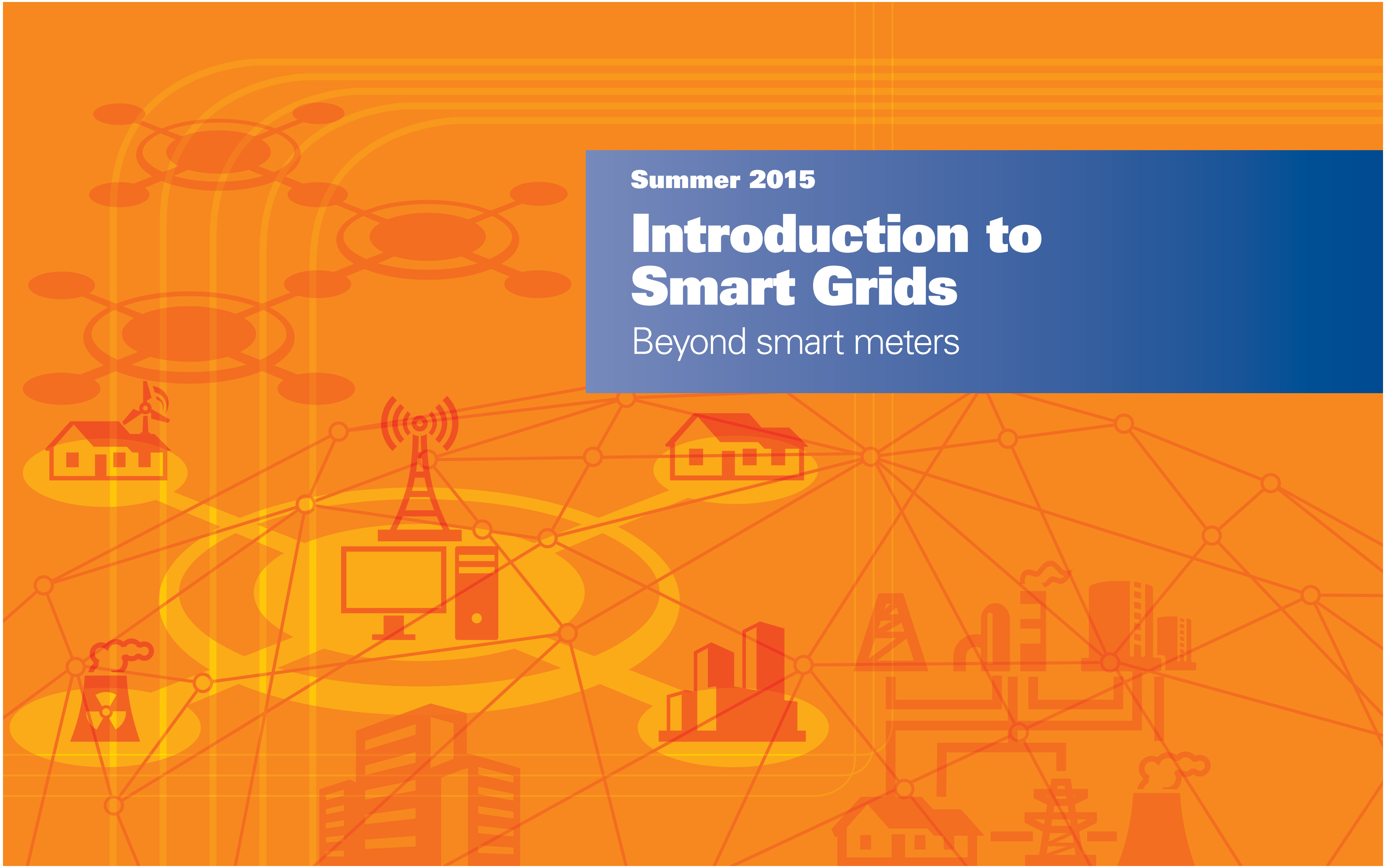
Introduction to Smart Grids

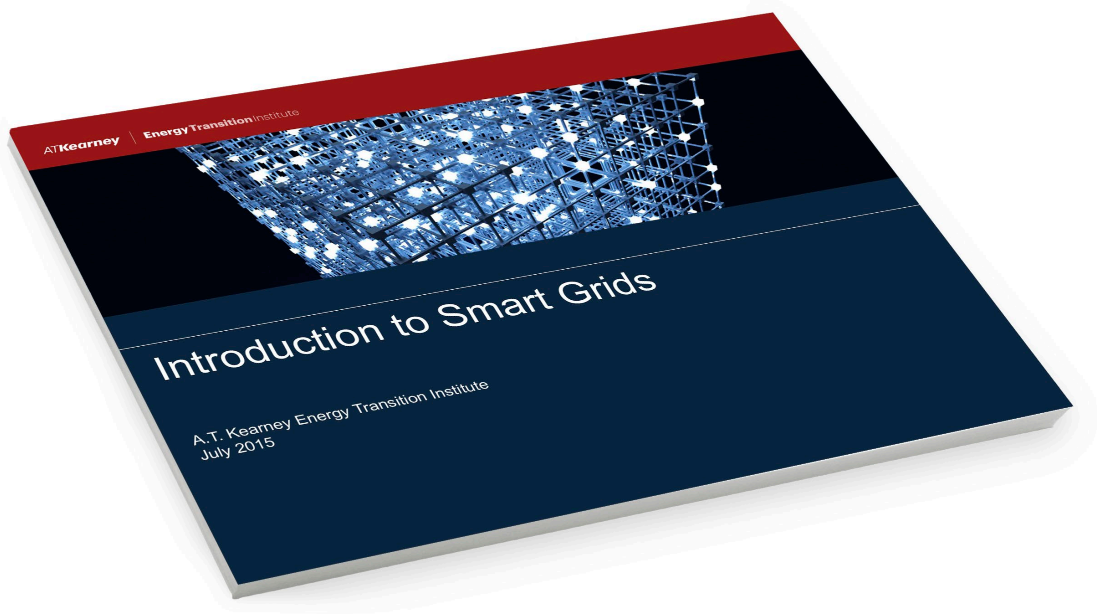
Beyond smart meters



Introduction to Smart Grids

Beyond smart meters

Smart-grid technologies have the potential to address today's grid challenges, including rising electricity demand, aging infrastructure, and the increasing penetration of variable and distributed energy sources in the supply mix. Numerous innovations can already contribute to the modernization of electricity networks. They aim to: enable the use of all generation and storage options; optimize energy efficiency and asset utilization; improve power quality for end-user devices; self-heal; resist physical and cyber attacks; and enable new business solutions in a more open-access electricity market. But social acceptance, cybersecurity, regulation, and international collaboration on standardization and best practices are vital to successful deployment.



The content of this summary is based upon the FactBook "Introduction to Smart Grids"

For the complete FactBook and other FactBooks by the A.T. Kearney Energy Transition Institute, please visit www.enery-transition-institute.com.

Electricity grids need to be modernized to meet growing demand and integrate new applications

Century-old by design, today's grids were built to accommodate centralized generators, unidirectional electricity transport through high-voltage transmission lines, dispatch to consumers via lower-voltage distribution feeders, and centralized control centers collecting information from a limited number of network hubs, called substations. The goal of such power grids is to optimize, for a given combination of power plant fleets and consumer-demand pattern, both reliability (the frequency and extent of outages) and quality of power supplied (in terms of voltage signal shape, frequency and phase angle) at a minimal cost.

Today's grids are facing four principal problems and these are growing in severity:
First, electricity demand is rising faster than demand for any other form of final energy globally (2% per year until 2040), and intensifies around peak times because of the progressive shift in consumption from a steady industrial baseload to variable household and commercial demand. As a result, grids are being increasingly stressed, making rapid expansion a necessity.

Second, aging infrastructure tends to compromise the reliability of power supply and exacerbate energy losses to the detriment of economies undergoing rapid electrification. In India, inadequate distribution networks result in the loss of 20% of transmitted electricity, while, in the U.S., aging transmission network is causing a decline in the reliability of power supply.

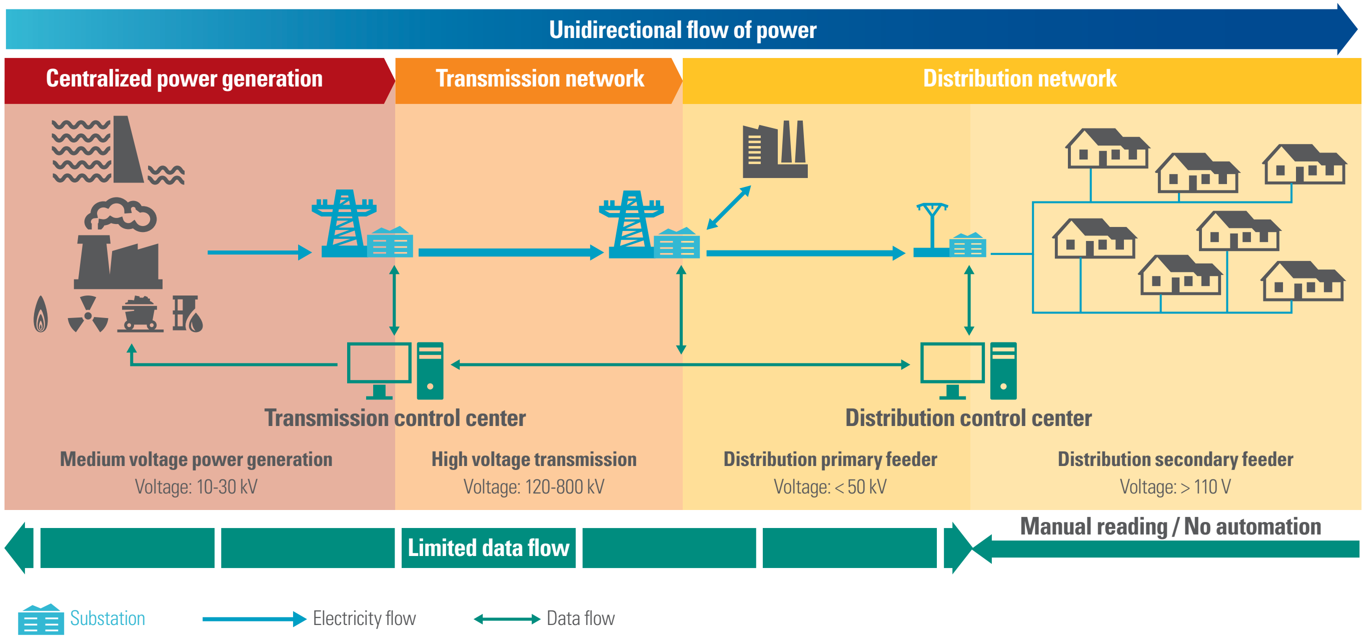
Third, as the share of Variable Renewable Energy (VRE) in the energy mix grows, the power grid will need to become more flexible to match supply and demand in real time.

Finally, as the penetration of Distributed Generation (DG) rises to very high levels in some areas, issues relating to power quality and bi-directional electricity flows arise that cannot be properly managed by traditional grids.

The need for grid modernization differs from country to country, depending on the state of the existing transmission & distribution (T&D) infrastructure, generation capacities and demand patterns.

Power grids, which bring electricity to 85% of the world's population, are arguably one of the most important engineering achievements of the 20th century.

Figure 1. Simplified view of the traditional grid



Source: A.T. Kearney Energy Transition Institute

A smart grid refers to a modernized electricity network that monitors, protects, and optimizes the operation of its interconnected elements

A smart grid is generally characterized by the use of digital information and communications technologies to manage both the bi-directional flow of data between end-users and system operators, and the bi-directional flow of power between centralized and decentralized generation.

The goal of these modernized networks is to address previously identified grid challenges at a minimal cost.
To fulfil this purpose, grids must be able to accommodate all generation and storage options, optimize energy efficiency and asset utilization, improve power quality for end-user devices, self-heal, resist physical and cyber attacks, and enable new business solutions in a more open-access electricity market, such as demand-response programs and virtual power plants.

Key differences between traditional and smart grids

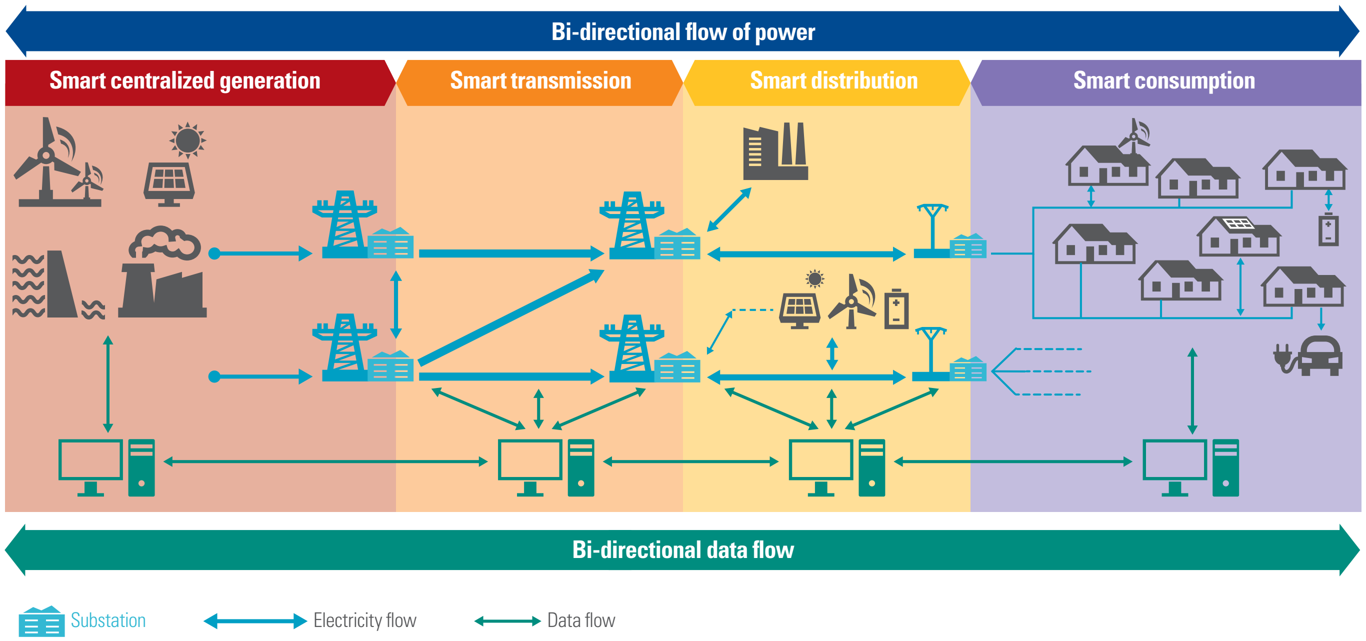
Area	Traditional grid	Smart grid
Communication	Electromechanical	Digital
	One-way	Two-way
Power	Centralized	Centralized & distributed
Monitoring & control	Few sensors	Sensors throughout
	Manual monitoring	Self-monitoring
	Manual restoration	Self-healing
	Failures and blackouts	Adaptive & islanding
	Limited control	Pervasive control
Market	Few customer choices	Many customer choices

Source: Fang et al. (2012), "Smart Grid – The new and improved power grid: a survey"

Beyond incremental changes in traditional grids, smart grids facilitate the expansion of independent micro-grids that are capable of "islanding" themselves from the main grid during power-system disruptions and blackouts. The modular nature of micro-grids may allow for their independence, interconnection and, ultimately, the construction of a new type of super-reliable grid infrastructure.

The introduction of renewables and distributed capacity requires the modernization of the grid such that it can handle variable and bidirectional electricity flows

Figure 2. Simplified view of the modernized grid



Source: A.T. Kearney Energy Transition Institute

The transition to a smart grid requires the deployment of new technologies, which can be segmented into three main categories of application

The transition to a smart grid requires the deployment of new power infrastructure, electronic devices and computer systems, interconnected via high-speed communications networks, using standardized protocols. This FactBook covers the most important smart-grid technologies, which can be segmented into three main categories of application.

The first application involves the optimization of grid monitoring and control, with advanced sensors and IT solutions interconnected via modern communications networks in Wide-Area Monitoring & Control (WAMC) or Distribution Automation (DA) systems. Such systems enhance control over dispatchable power plants; improve routing of electricity flows; anticipate demand patterns or grid weaknesses
by virtue of predictive algorithms and condition-based maintenance; react automatically to incidents threatening the reliability of power supply with the use of smart reclosers, which make distribution grids self-healing.

The second purpose of smart grids is to enable consumers to contribute to grid management through the medium of intelligent end-user devices. Combining advanced metering infrastructure with smart appliances makes dynamic demand-response programs possible. These can contribute to system flexibility (in addition to peaking power plants or electricity storage) to compensate for fluctuations in VRE output or to flatten out aggregated peak loads. Bi-directional smart meters enable net metering and vehicle-to-grid programs that incentivize individual customers to become local suppliers of power and storage capacity. In addition, automated meter readings reduce the operating costs of distribution-system operators and provide greater visibility into pilferage.

The third principal aim of smart-grid technology is to enhance the physical capacity of the network. Ultra-high voltage lines, direct-current underground cables or superconductors transport more power with lower energy losses and a smaller visual footprint than conventional power lines. These new technologies could be especially effective in connecting remote offshore wind farms to distribution grids or interconnecting asynchronous grids. Finally, the maximum admissible power throughput of existing lines could also be dynamically enhanced by installing along them special temperature sensors, voltage or current control devices. This would allow the deferral of expensive and sometimes-controversial grid-extension plans.

Beyond smart meters, flourishing technologies are driving grid modernization

Figure 3. Smart-grid technologies by application and device type

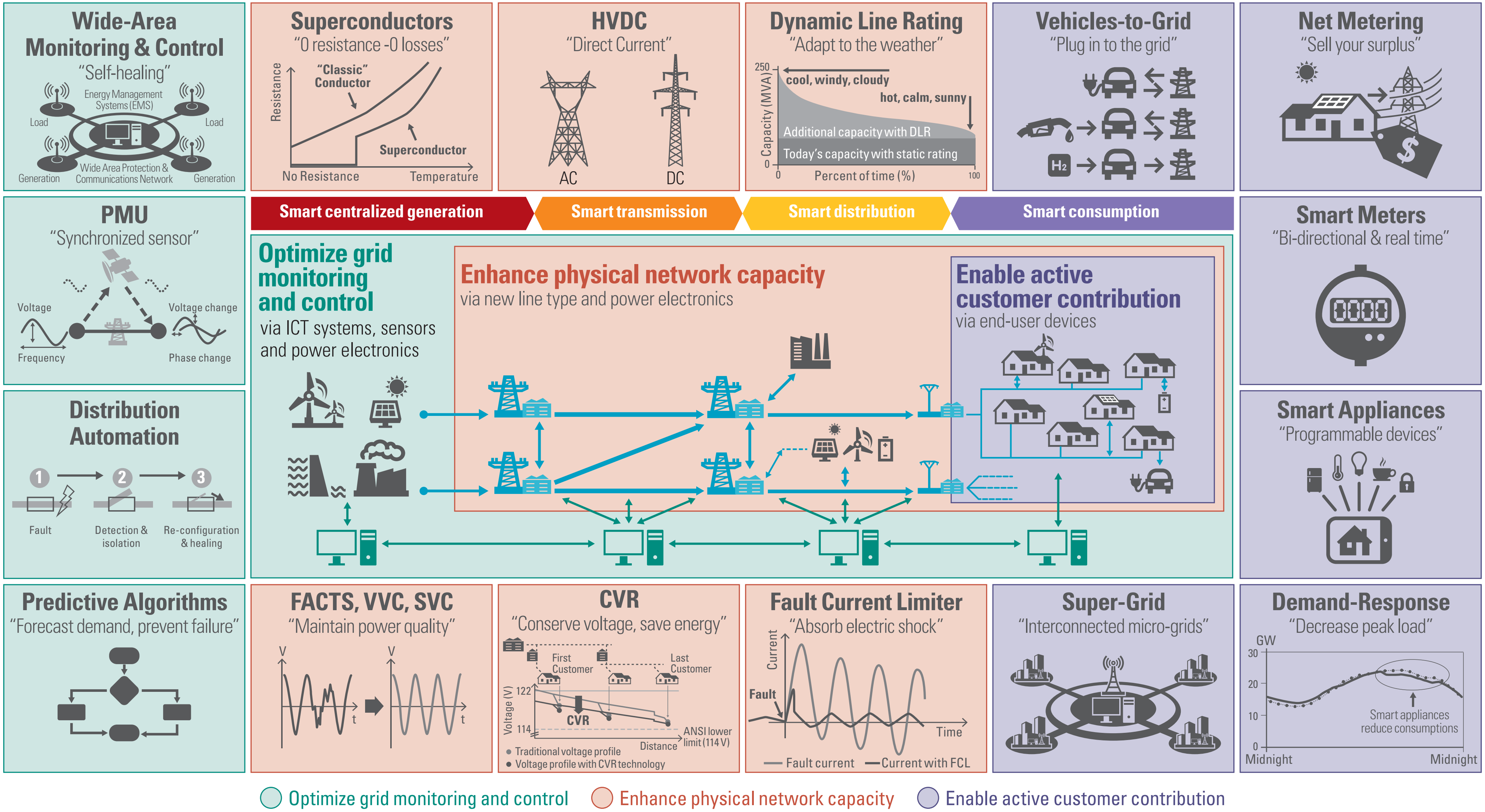
<table>
<tr><th>Type of device
Main stakeholders</th><th>Generation
Utilities, cooperatives, end users…</th><th>Transmission
Transmission System Operator (TSO)</th><th>Distribution
Distribution System Operator (DSO)</th><th>Consumption
End-users (residential, industrial…)</th></tr>
<tr><td rowspan="2">Communication networks</td><td>Micro-Grids and Smart Cities</td><td>(no transmission)</td><td colspan="2">Micro-Grids and Smart Cities</td></tr>
<tr><td colspan="2">Wide Area Network (WAN)</td><td>Field Area Network (FAN)</td><td>Home Area Network (HAN)</td></tr>
<tr><td rowspan="3">Electric-power infrastructure</td><td></td><td>High Voltage Direct Current (HVDC), Superconductors</td><td>Smart Switches
Capacitor Banks</td><td>Vehicle-to-Grid (V2G)
Smart Inverters</td></tr>
<tr><td></td><td>Flexible AC Transmission Systems (FACTS)</td><td></td><td></td></tr>
<tr><td></td><td colspan="2">Fault Current Limiters (FCL)</td><td></td></tr>
<tr><td rowspan="2">Electronic devices and sensors</td><td></td><td>Dynamic Line Rating (DLR)</td><td colspan="2">Advanced Metering Infrastructure (AMI, Smart meters, MDMS…)</td></tr>
<tr><td colspan="3">Phasor Measurement Unit (PMU)</td><td>Smart Appliances and In-Home Display (IHD)</td></tr>
<tr><td rowspan="5">Systems and processes</td><td colspan="2">Wide-Area Measurement System (WAMS)
Wide-Area Monitoring & Control (WAMC)</td><td>Distribution Management System (DMS), Distribution Automation (DA)</td><td>Building and Home Energy Management Systems (HEMS)</td></tr>
<tr><td colspan="3">Supervisory Control and Acquisition Data (SCADA)</td><td>Demand Response (DR)</td></tr>
<tr><td></td><td colspan="2">Volt/VAR Control (VVC), Conservation Voltage Reduction (CVR)</td><td>Net Metering</td></tr>
<tr><td></td><td colspan="2">Smart Protection: Predictive (Failure Prediction Algorithms) or Reactive (Fault Detection, Isolation and Restoration, FDIR)</td><td>Virtual Power Plant (VPP)</td></tr>
<tr><td></td><td></td><td></td><td>Demand Forecasting</td></tr>
</table>

Technology application: ○ Optimize grid monitoring and control ○ Enhance physical network capacity ○ Enable active customer contribution

Note: Numerous technologies have been deliberately excluded from the scope of this report for the purposes of simplification. Segmentation by application is only indicative. Overlaps exist, and smart-grid technologies only offer maximal benefits when integrated together.

Source: A.T. Kearney Energy Transition Institute analysis

Figure 4. Key smart-grid technologies covered in the FactBook



Source: A.T. Kearney Energy Transition Institute

Figure 5. Smart-grid benefits by technology application and related grid challenges

Smart-grid technologies have the potential to answer numerous grid challenges, and achieve their best efficiency when integrated altogether

Smart-grid technology applications

Existing grid challenges	Enhance physical network	Optimize grid monitoring & control	Enable active customer contribution
Rising and intensifying electricity demand	**Increase power-line capacity** via electronic devices and sensors installed along the lines (DLR, FCL, FACTS, CVR…)	**Predict and optimize electricity flow** via new sensors and algorithms of higher spatial and temporal granularity, and Wide-Area Monitoring & Control (WAMC, PMU…)	**Flatten aggregated peak demand** via dynamic demand-response programs
Aging infra-structure (losses & unreliability)	**Reduce transport losses** by using more efficient cables (HVDC, superconductors…)	**Improve power reliability** via smart protection systems, both in anticipation (failure prediction algorithms and condition-based maintenance), and in reaction (distribution automation, self-healing grid, FDIR)	**Track down thefts** via advanced metering infrastructure
Increasing share of Variable Renewable (VRE)	**Connect offshore wind-farms** via subsea HVDC cables	**Smooth variability of VRE output** by enlarging grid inter connections via Wide-Area Monitoring & Control	**Provide additional flexibility means** by pooling of customers into virtual power plants that can store or supply large amounts of electricity in a dispatchable manner
Increasing share of Distributed Generation (DG) & Electric Vehicles (EV)	**Achieve customer energy savings** by stabilizing voltage delivered to end-users as closely as possible above nominal values, optimizing appliance efficiency (CVR)	**Preserve power quality** by absorbing voltage instability caused by back-flows of electricity or re-synchronization of islanded micro-grids thanks to voltage control (VVC, capacitor banks, PMU…)	**Incentivize DG and EV deployment** via net metering programs and vehicle-to-grid technologies, which turn individual customers in to local suppliers of electricity

Source: A.T. Kearney Energy Transition Institute

Smart grids promise numerous economic and environmental benefits, provided social acceptance and cybersecurity issues are thoroughly addressed

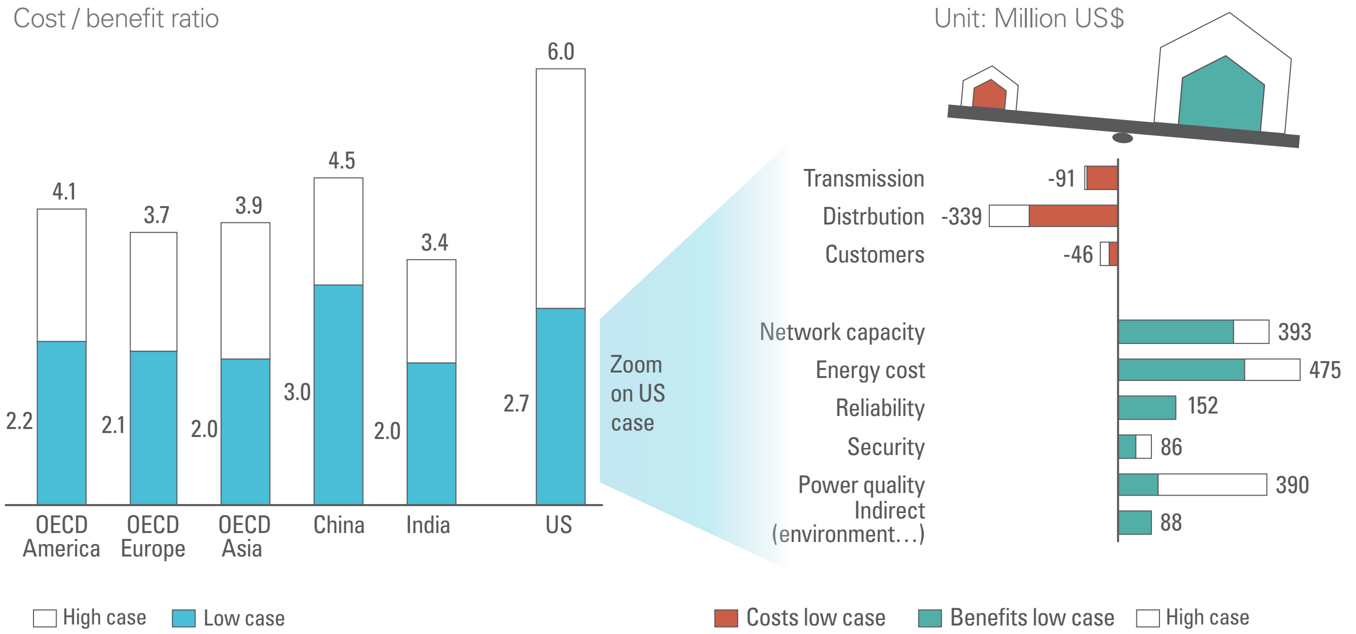
Economic impacts. It is estimated that a smart-grid roll-out would generate net economic and environmental benefits in all regions where studies have taken place, although impacts are difficult to quantify. The U.S.' Electric Power Research Institute (EPRI) estimates that the benefits for U.S. society as a whole would outweigh its costs by a factor of between 2.7 and 6. Restricting the scope to electricity-grid stakeholders, the International Energy Agency (IEA) estimates the ratio to be between 2 and 4 in OECD countries, and between 3 and 4.5 in China.

Environmental benefits. Although environmental sustainability is not the primary driver behind the adoption of smart grids, they help limit greenhouse-gas emissions both directly (through energy savings) and indirectly (by encouraging the development of electric vehicles and renewables). The IEA estimates that smart grids could contribute to 4% of cumulated CO2 emissions-reduction efforts by 2030, in the lowest-cost pathway towards the 2°C target.

Costs and benefits related to smart grids are difficult to quantify independently of other developments in the electricity landscape

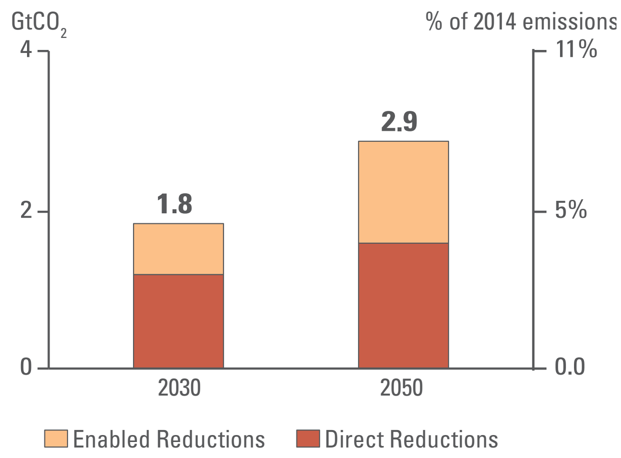
Societal impacts. The concept of a smart grid relies to a large extent on active consumer participation and, for this reason, requires social acceptance. As future electricity grids will collect, communicate and store operational and private data, the issues of cybersecurity, data protection and data sharing must be carefully addressed.

Figure 6. Economic impact of smart grid roll-out



Source: A.T. Kearney Energy Transition Institute based on Electric Power Research Institute EPRI (2011), "Estimating the costs and the benefits of the Smart Grid" and IEA (2012) "Energy Technology Perspective"

Figure 7. Annual CO_2 emission reductions from smart-grid deployment under the IEA 2DS Scenario



Source: IEA (2011) "Technology Roadmap Smart Grids"; PBL (2014) "Trends in global CO2 emissions"

Smart-grid technologies are attracting investor interest, but proper regulation and collaboration in standardization and best practices are vital to successful deployment

As smart-grid benefits are spread among many parties, and electricity markets evolve as a result of the unbundling of monopolies, the design of smart-grid business models is becoming more complex

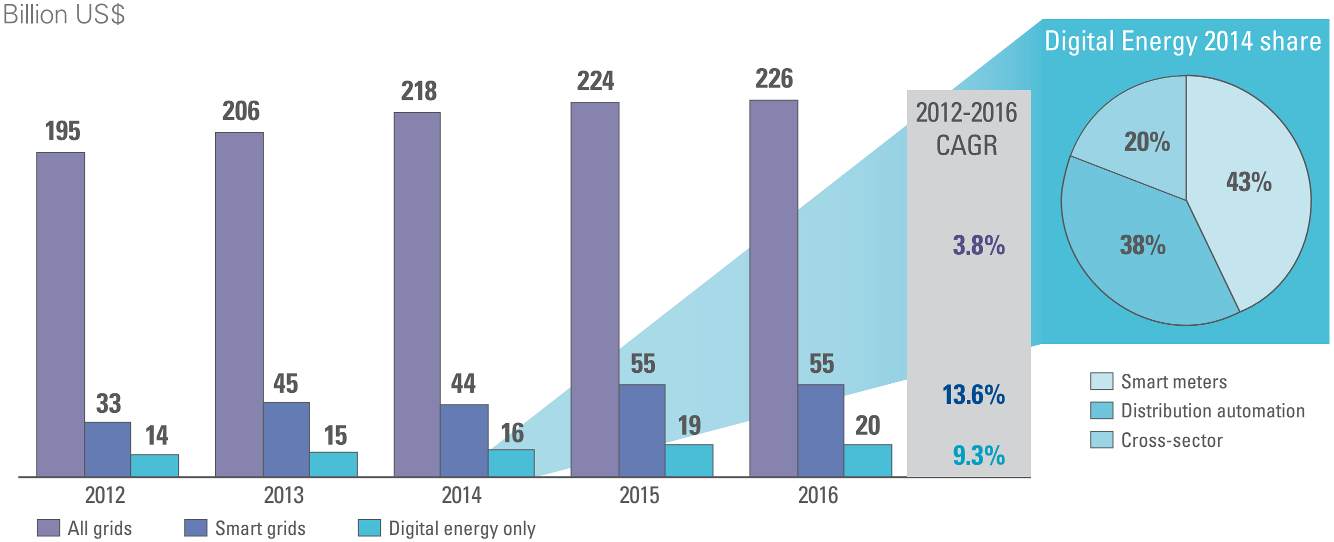
Global annual investments in electricity grids amounted to $218 billion in 2014 and are growing by 4% a year. Smart-grid technologies currently represent 20% of these investments ($44 billion), or $16 billion if the scope is restricted to digital energy technologies. Smart-grid investments are expected to grow by 5% a year until 2020, led by digital energy (9% a year), due in particular to rapid smart-meter roll-out: 100 million units were installed in 2014, and the penetration rate globally is set to increase from 22% to 40% in 2020.

Private investors' interests in smart-grid RD&D intensified after 2008, following announcements of support from the U.S. DOE ($4.5 billion committed), and EU (€3 billion already allocated). Although raised funds have stabilized since 2011, venture capitalists remain highly interested in digital-energy technologies, which are among the most sought-after clean-energy investments – only just behind solar PV in terms of numbers of deals in 2014.

If smart-grid investments are mostly borne by system operators, benefits are spread among many parties (including customers and all citizens, if environmental benefits are taken into account). Yet, as electricity markets evolve through the unbundling of monopolies, the design of smart-grid business models is becoming more complex. Therefore, carefully planned regulatory frameworks are required to encourage smart-grid roll-outs. Finally, standards covering interoperability, compatibility and industry best practice are among the most crucial prerequisites for smart-grid deployment, in avoiding the premature obsolescence of smart-grid devices.

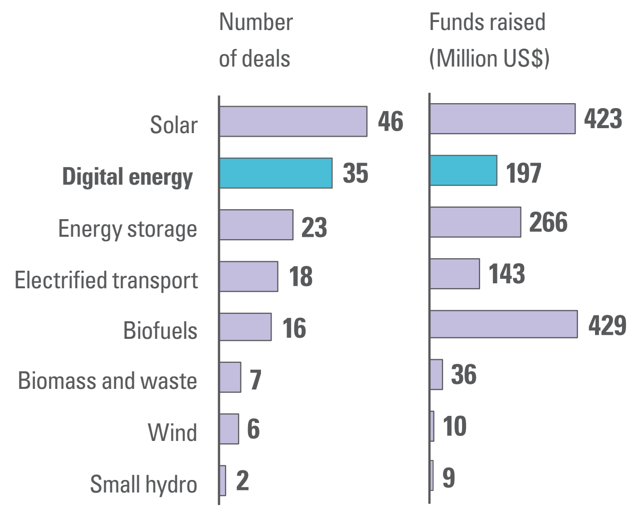
Figure 8. Annual investments in electricity grids

Billion US$



Note: Digital energy excludes capital-intensive power infrastructure for transmission-network enhancements, such as new HVDC lines and FACTS, etc..).
Source: Navigant Research (2014), "Executive Summary: Smart Grid Technologies" BNEF (2015), "Q1 2015 Global Digital Energy Outlook"; NRG Expert (2013), "Electricity T&D White Paper" for T&D Investments.

Figure 9. New energy venture capitalists deals in 2014



Source: BNEF (2015), database extraction

Conclusion

Electrons are the fastest-growing energy carrier and a pivotal element of the transformation of the energy system. Economies will become increasingly dependent on electricity, as renewable energy expands and environmental concerns intensify. As a result, electricity networks are being rapidly modernized through the introduction of smart-grid technologies. This is enabling growth in power-generation capacity, as well as the integration of new energy sources and shifts in consumer behavior.

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