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REVIEW

Smart Grid and nanotechnologies: a solution for clean and sustainable energy

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Abstract: Environmental sustainability remains a big trend; topics such as climate change and global warming are generating a lot of discussion. Growing world energy demand from fossil fuels plays a key role in the upward trend in CO_2 emissions and is the main source of human-induced climate changes. While energy systems around the world remain at vastly different stages of development, all countries share a common problem: they are far away from achieving sustainable energy systems. As levels of CO_2 and other greenhouse gases continue to rise in the atmosphere, with historical maximums reached lately, sustainability in energy generation and energy efficiency principles is becoming ever more important. In this paper, we describe the effects that development of new technologies, such as Smart Grid and nanotechnology will likely have on reducing carbon emissions. We discuss the main requirements and features of Smart Grids to integrate energy efficiency, the enabler technologies, and expected benefits they will bring. As findings in this review paper document, recent progress suggests that Smart Grid can become an integral part of future clean energy solutions, while nanotechnology will likely become indispensable for the Smart Grid to fully evolve in the near future.

Keywords: Smart Grid, information and communication technology, sustainability, energy efficiency, renewable energy, nanotechnology

Introduction

For the first time in recorded history, more people worldwide are living in urban areas than in rural. The urbanization trend picked up pace in the 20th century and has accelerated since. Urbanization manifests itself in two ways: expansion of existing cities and creation of new ones.[1] Cities are already the source of close to 80% of global CO_2 (carbon-dioxide) emissions and will account for an ever-higher percentage in the coming years. Too much CO_2 in the atmosphere has been linked to climate change. If humanity continued with the same solutions that have been used to address urban development needs in the past, the resulting urban ecological footprint will not be sustainable: we would need the equivalent of two planets to maintain our lifestyles by the 2030s. The challenge is to meet the demands of urbanization in an economically viable, socially inclusive, and environmentally sustainable fashion.[1,2]

According to a World Energy Council study,[3] global demand for primary energy is expected to increase by between 27% and 61% by 2050. Climate change is expected to lead to changes in a range of climatic variables, most notably temperature levels. Since electricity demand is closely influenced by temperature, there is likely to be an impact on power demand patterns. The magnitude of the potential impact of future

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climate changes on electricity demand will depend on patterns in the power use, as well as long-term socio-economic trends.

The latest assessment by Working Group I of the Intergovernmental Panel on Climate Change, released in September 2013, concluded that climate change remains one of the greatest challenges facing society. Warming of the climate system is unequivocal, human-influenced, and many unprecedented changes have been observed throughout the climate system since 1950. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions.[4]

Consumption patterns, together with aging and urbanization in some countries seem to have bigger implications for health and the reduction of carbon emissions than the total number of people in the world.[5] As developing and newly industrialized countries improve their standards of living, their use of air conditioning and other weather-dependent consumption will likely increase their sensitivity to climate change.[6] On the other hand, reducing consumption and achieving more sustainable lifestyles in rich countries will likely represent the most effective way to reduce carbon emissions.

Energy efficiency is a way of managing and restraining the growth of energy consumption. It is one of the easiest and most cost effective ways to combat climate change, improve the competitiveness of businesses, and reduce energy costs for consumers.[7]

Energy markets have a substantial amount of economic potential for improving energy efficiency, but many cost-effective energy-efficiency measures are not being deployed. Hirst and Brown[8] noted that only half of the economic potential for US energy efficiency is likely to be realized over the next 20 years.

The World Energy Council's definition of energy sustainability is based on three core dimensions: energy security, social equity, and environmental impact mitigation. Achieving these three goals will require complex linking of public and private actors, governments and regulators, economic and social factors, national resources, environmental concerns, and individual behaviors.[3]

Various strategies which can be adopted to combat global warming can be classified under the following three categories:[9]

- reducing energy consumption by employing more efficient technologies that minimize use of fossil fuels;
- adopting technologies that utilize renewable energy and energy storage technologies;
- addressing carbon management issues that involve separation, capture, sequestration and conversion to useful products.

In view of the second point, a conventional model for power systems is widely seen as untenable and Smart Grid initiatives have been launched worldwide as a response to these developments. The idea of the Smart Grid is "computerizing" the power grid. The Smart Grid of the future should act much more like an interactive web, or "energy Internet," with two-way communication, multi-directional power flow, remote-control automation technology, and real-time view of operations.

Smart grid technologies offer great potential for reduction of emissions. The emission benefits of the Smart Grid are difficult to quantify because they depend on how enabling technologies function within the system. Estimates in the literature vary both in magnitude and in source of emission abatement: electric vehicles (EVs) displacing oil consumption, price transparency stimulating conservation, enhanced energy efficiency reducing energy consumption, or renewable energy displacing conventional fuels through increased system flexibility.[10] The Climate Group study[11] suggests that the widespread adoption of Smart Grid technologies could reduce global emissions by 2.03 gigatonnes (Gt) CO_2e (carbon-dioxide equivalent is a quantity that describes, for a given mixture and amount of greenhouse gas, the amount of CO_2 that would have the same global warming potential, when measured over a specified timescale [generally, 100 years]),[1] worth €79 billion ($124.6 billion). The Information and Communications Technology (ICT) sector is uniquely placed to partner with power companies to optimize the existing electricity grid to allow more efficient power distribution and enable more renewable or green power.

Although all mentioned sources of carbon pollution can contribute to the benefits that Smart Grid technologies deliver, without careful design and well elaborated metrics for success, the risks are outweighing the benefits on the table. Failing to do so would risk forfeiting the potential benefits of Smart Grid deployment, for example through uncoordinated planning or deployment of infrastructure that lacks the capability to provide flexibility in the relevant timescales.[11]

The remainder of this paper is organized as follows: The "CO_2 emmisions" section discusses recent data on CO_2 emissions and presents possible steps that are foreseen to retain climate changes within a certain limit. The "Overview of smart power grid" section gives an overview of the Smart Grid, while the "How can Smart Grid reduce CO_2 emissions" section presents possible means by which Smart Grid can contribute to reducing pollution and increasing energy efficiency. The "How can nanotechnology reduce CO_2 emission" section is dedicated to advances in nanotechnology from the prospective of reducing CO_2 emission. We conclude with a view of recent progress which confirms that Smart Grid can become an integral part of future clean energy solutions.

CO_2 emissions

Economic development involves the increased use of highly energy intensive materials, such as steel, cement, glass, and aluminum. These materials are necessary for the construction and development of transport, energy, housing, and water management infrastructure. Coal is the most widely used source of energy in energy-intensive industries and is important in the development of modern infrastructure in growing economies.[12] According to the United States Greenhouse Gas Inventory (2006), the top five sources of CO_2 emissions are: fossil fuel (coal, oil, and natural gas) combustion, non-energy use of fuels (construction of modern infrastructure such as transport), iron and steel production, cement manufacturing, and natural gas systems.[13] Coal generates the most CO_2 emissions of any fossil fuel and yet remains the world's dominant energy source. On May 9, 2013, the Earth's atmosphere crossed an alarming threshold, when the concentration of CO_2 in the atmosphere reached 400 parts per million (ppm), up from 355 ppm in 1990,[14] Figure 1.

According to The Netherlands Environmental Assessment Agency statistics, since 2000 approximately 466 billion tons of CO_2 were cumulatively emitted due to human activities.[14]

Global CO_2 emissions in 2010 approached 30 Gt, followed by a record high of 31.6 Gt in 2011, Figure 2.[14] Approximately 45% are emitted from the electricity generation sector through the combustion of fossil fuels like coal, oil, and natural gas to generate the heat needed to power steam-driven turbines, followed by oil (35%) and natural gas (20%).[15]

Authoritative sources such as the World Resources Institute and International Energy Agency claim that atmospheric CO_2 can only be stabilized by deploying a range of measures, which include significant increases in energy efficiency and conservation, wider reliance on renewable energy, and the use of carbon capture and storage. Scientific literature suggests that limiting average global temperature rise to 2°C above pre-industrial levels – the target internationally adopted in United Nations climate negotiations – is possible if cumulative CO_2 emissions over the 2000–2050 period do not exceed 1.000 to 1.500 billion tonnes.[16]

GlobalCarbonProject.org posted data for the 2013 Global Carbon Budget with the following key findings:[17]

- global emissions due to fossil fuel alone are set to grow in 2013 at a slightly lower pace of 2.1% than the average 3.1% since 2000, reaching a level that is 61% above emissions in 1990;
- growth rates for major emitter countries in 2012 were 5.9% (People's Republic of China), –3.7% (USA), –1.3% (EU28), and 7.7% (India);

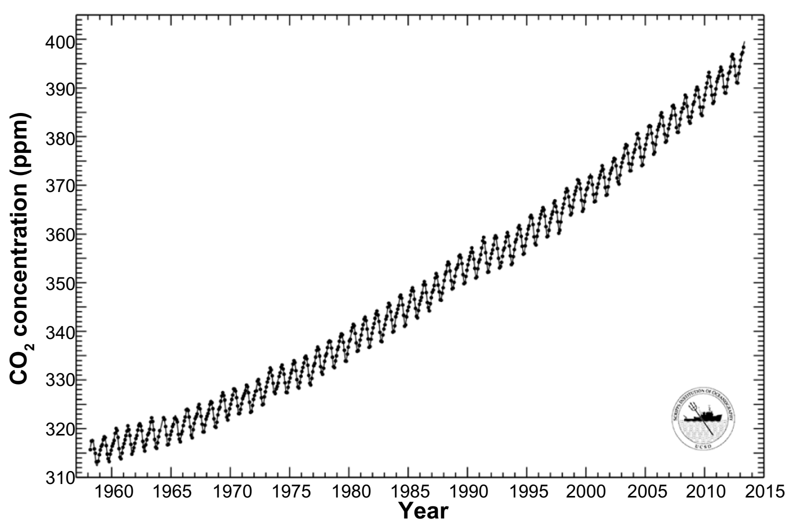

Figure 1 Monthly average carbon dioxide concentration: Mauna Loa Observatory, Hawaii.
Notes: CO_2 levels have been climbing steadily in the atmosphere for the last 55 years. Reproduced from Scripps CO_2 Program; last updated May 2013. Scripps Institution of Oceanography, University of California San Diego.[55]

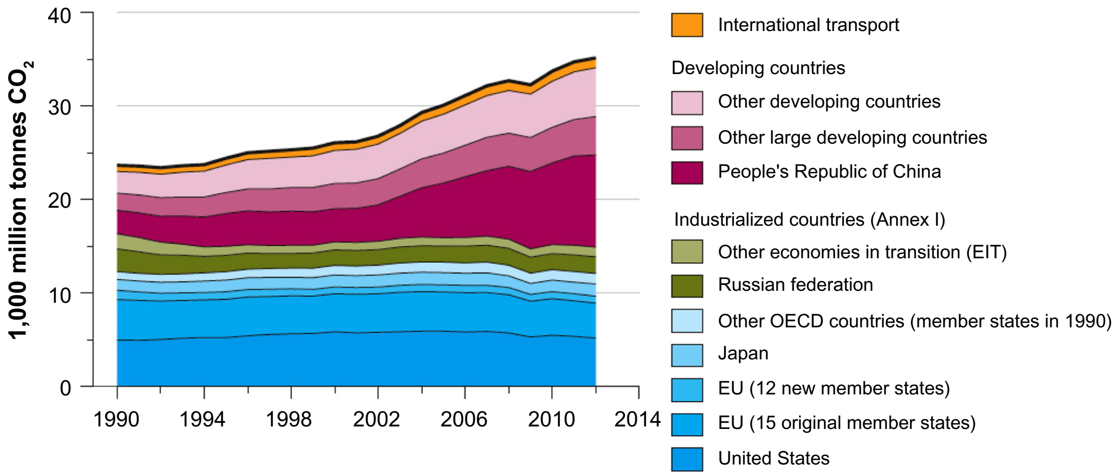

Figure 2 Global CO_2 emissions per region from fossil-fuel use and cement production.

Notes: Source data: EDGAR 4.2FT2010 (JRC/PBL, 2012); BP, 2013; NBS People's Republic of China, 2013; USGS, 2013; WSA, 2013; NOAA, 2012. http://pbl.nl/jrc.eu.europa.eu. Adapted from Global CO_2 emissions per region from fossil-fuel use and cement production. PBL Netherlands Environmental Assessment Agency. Available from: http://www.pbl.nl/en/infographic/global-co2-emissions-per-region-from-fossil-fuel-use-and-cement-production. Creative commons license available from: http://creativecommons.org/licenses/by/3.0/legalcode.[56]

Abbreviations: OECD, Organization for Economic Co-operation and Development; EDGAR, Emission Database for Global Atmospheric Research; JRC, European Commission's Joint Research Centre; PBL, the Netherlands Environmental Assessment Agency; BP, British Petroleum; NBS People's Republic of China, National Bureau of Statistics People's Republic of China; USGS, US Geological Survey; WSA, World Steel Association; NOAA, National Oceanic and Atmospheric Administration.

- the 2012 CO_2 emissions breakdown is coal (43%), oil (33%), gas (18%), cement (5.3%), and gas flaring (0.6%);
- atmospheric CO_2 levels increased in 2012 at a faster rate than the average over the past 10 years.

Regarding atmospheric CO_2 levels, some countries are witnessing a true paradox. For example, Germany, a country whose goal is to have no electricity production from fossil fuels at all by 2050, increased its electricity production from coal in 2013. As a result, Germany's CO_2 output has risen in 2013, even as power from renewable sources has reached 25% of the energy mix. Coal plants are making up for the bulk of the energy production lost due to the 2011 shutdown of eight nuclear plants, while gas plants, which emit less CO_2 but are more expensive to run, are barely profitable at present. Germany will keep pushing for growth of renewable energy; in 2014, German customers again will pay a surcharge on electricity bills that is expected to generate €23.5 billion of subsidies for renewable energies.[18]

The energy carriers in the primary energy supply all show continuous increases over the past decade, except nuclear energy, which decreased since 2012, after the Fukushima accident. However, the good news is that renewable energy has shown an accelerated increase since 2002: for example, the use of hydropower increased by 4.3% from 2011 to 2012.[14] Various technological developments are now moving from a developmental phase to a mature sustained global growth and market penetration, not only for renewable energy sources but also for oil and gas. Without the use of modern renewable energy sources, annual global CO_2 emission levels could potentially have been about 5% higher than they are today.[14]

Early indications suggest that in 2012 CO_2 emissions continued to decline in the Organization for Economic Co-operation and Development countries, more than offset by a rapid increase in non-Organization for Economic Co-operation and Development countries. According to the same indications, total energy-related CO_2 emissions increased by about 1%. For the medium term, the World Energy Outlook projects that global CO_2 emissions from fuel combustion will continue to grow unabated, albeit at a lower rate, reaching 37.2 Gt by 2035. This is an improvement over the World Energy Outlook Current Policies Scenario, but still leads to a long-term temperature increase of 3.6°C, well above the 2°C target agreed by the parties at the United Nations Framework Convention on Climate Change.[19]

Overview of smart power grid

The electric grid is traditionally divided into three stages: generation, transmission, and distribution. Generation is the stage where the electricity is created, for example, a power plant. Transmission is the stage that transfers the electricity across great distances from the generation location to an area of demand, and is comprised of high-voltage cables, step-up substations and step-down substations. The distribution stage includes transferring electricity from a substation to the end consumer. The electric grid has an interconnected mesh structure whereas major populated areas and generation plants are interconnected via more than one path, creating necessary redundancies.[20]

The four main weaknesses of the traditional grid structure are:

- limited flow control and monitoring: the current grid does not have a granular-level electricity directing, switching or monitoring capability. When a power-outage occurs, the utility has very little information regarding the nature and location of the outage, and usually does not have the capabilities to remotely repair it;
- centralized generation: the current grid structure cannot accommodate distributed generation, ie, "uploading" electricity to the grid at end- or mid-points;
- low utilization: the current grid induces waste of energy resources as a result of three main issues:
    - o many grid components are not efficient in creating and transferring electricity, for example, about 7% of the electricity generated is lost due to resistance in the transmission stage;
    - o there are currently no scalable energy storage solutions in wide use throughout the grid;
    - o Redundant energy generated at the consumer level goes to waste since there is no infrastructure to accommodate it;
- impossibility of storing: electricity cannot be economically stored using commercially available technology today, so it must be generated, delivered, and consumed at the moment that it's needed by end-use customers. Thus, maintaining a reliable electric power grid requires real-time balancing of supply and demand.

The Smart Grid conceptually consists of three main layers:[20]

- infrastructure layer includes the physical enhancements and changes that need to be installed onto the current grid to enable Smart Grid capabilities;
- communications layer includes the establishment and implementation of communication protocols and hardware that will provide the capability to monitor and control the flow and usage of electricity throughout the grid;
- applications layer refers to applications that can be installed once the Smart Grid infrastructure and communications layer is in place. Some examples of applications are demand response programs and self-healing algorithms. These allow for shifting of load during peak hours and self-maintenance of the electric grid, which provides better reliability of power.

Rather than replacing existing infrastructures, new smart capabilities are made possible by integrating new applications into transmission and distribution grids.[21] While the task of the existing energy infrastructure – to deliver energy – remains unchanged in a Smart Grid, communication between the consumer and provider will be much more efficient and effective, and therefore less expensive and more reliable.

The document Framework and Roadmap for future Smart Grids,[22] by National Institute of Standards and Technology (NIST) identifies seven domains within the Smart Grid – transmission, distribution, operations, bulk generation, markets, customer, and service provider. A Smart Grid domain is a high-level grouping of organizations, buildings, individuals, systems, devices, or other actors with similar objectives and relying on, or participating in similar types of applications. Across the seven domains, numerous actors will capture, transmit, store, edit, and process the information necessary for Smart Grid applications.

The NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0,[22] updates progress made in Smart Grid development during 2012 and 2013, and discusses the achievements during this period of transition to an industry-led organization. Some of the important changes include more focus on distributed generation, incorporating distributed energy resources and cybersecurity developments. Future developments include transactive energy and microgrids which are getting a lot more attention as a result of the deployment of coupled solar and storage solutions.[23]

In Release 3.0, Smart Grids are seen from the perspective of hybridized systems that combine computer-based communication, control, and command with physical equipment to yield improved performance, reliability, resiliency, and user and producer awareness.

The NIST Framework shows that future Smart Grids should support the following two flows:

- power (electrical) flows (generation, transmission and distribution);
- secure information processing flows (collecting, processing, and distribution).

Figure 3 shows the conceptual model with key linkages across entities that will comprise the Smart Grid.

The International Energy Agency identified eight main Smart Grid technology areas whose functions can be described as follows:[24]

- transmission enhancement applications: involve a number of technologies (such as advanced transformers) that can make transmission networks more controllable, maximize

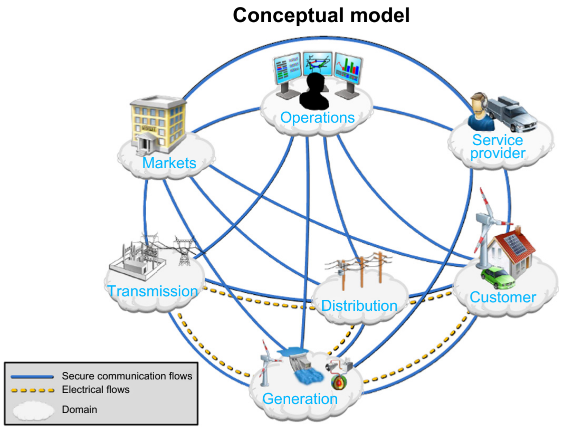

Figure 3 Interaction of roles in different Smart Grid domains through secure communication.
Notes: Adapted from National Institute of Standards and Technology. *NIST Special Publication 1108R2, NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 2.0*; 2012. Available from: http://www.nist.gov/smartgrid/upload/NIST_Framework_Release_2-0_corr.pdf. Accessed January 10, 2014.[22]
Abbreviation: NIST, National Institute of Standards and Technology.

the transfer of power, reduce transmission losses, and decrease the risk of overloads;

- distribution grid management: combines sensor technologies and automation to continuously maintain voltage levels, locate faults, reconfigure feeders, and control distributed generation so that equipment performs optimally and outages are minimized;
- wide area monitoring and control helps system operators monitor, control, and optimize the power system over large geographic areas, avoiding blackouts and facilitating the use of renewable sources. Advanced system analytics generate data used to inform decisions and make systems more reliable;
- advanced metering infrastructure: the foundation of the Smart Grid's two-way flow of data, and the key to most Smart Grid efforts to date, is the underlying infrastructure which involves a number of functions, including smart meters, the network infrastructure to transmit data from smart meters to the utility, and software to compile and manage the massive quantities of data produced;
- commercial, industrial or residential building energy management: large companies which have already had automation systems in place for years are now making these systems more integrated, using networked sensors and incorporating data from individual systems such as lighting and heating, and ventilation and air conditioning. New technologies include energy dashboards, smart appliances, local energy storage, and demand-response hardware;
- EV charging infrastructure: connecting EVs to the grid for battery recharging requires infrastructure to handle billing, scheduling and other intelligent functions. If charging stations allow power to flow both ways, EVs can serve as a source of distributed energy storage – discharging electricity back to the grid during hours when the vehicle is parked and peak power is needed;
- ICT integration: make it possible to integrate intelligence throughout the entire power system, and to achieve real time, two-way communication in order to manage energy more effectively;
- renewable and distributed generation integration: require connecting solar arrays, wind farms and other sources to power grids. This involves new products in addition to standard technologies used to connect traditional sources such as coal and nuclear.

Some of the technologies from Figure 4 are actively being deployed and are considered mature in both their development and application, while others require further development and demonstration. A fully optimized electricity system will deploy all the technology areas from Figure 4. However, not all technology areas need to be installed to increase the "smartness" of the grid.

How can Smart Grid reduce CO_2 emissions?

Pacific Northwest National Laboratory's report[25] provides an assessment of nine mechanisms by which the Smart Grid can reduce energy use and carbon impacts associated with electricity generation and delivery. The mechanisms and their impacts – a reduction in electricity use and CO_2 emissions by 2030 – are analyzed in Table 1. The impacts can be divided into direct and indirect reductions: direct reductions are Smart Grid functions that themselves produce savings in energy and/or emissions consumed or by reducing generation requirements; indirect reductions are related to Smart Grid functions producing cost savings.

Energy savings achieved through the use of Smart Grid

Smart grids are also about enabling users to improve their power usage profile and make it smarter, reducing power consumption when energy is scarcely available while allowing higher consumption when there is more on offer. Depending on the time of equipment use, energy efficiency measures can produce significant reductions in peak demand. Potential actions by which Smart Grid technology can contribute to energy savings are conservation effect of consumer information and feedback systems, deployment of diagnostics in residential and small/medium commercial buildings, support for EVs, and advanced voltage control.

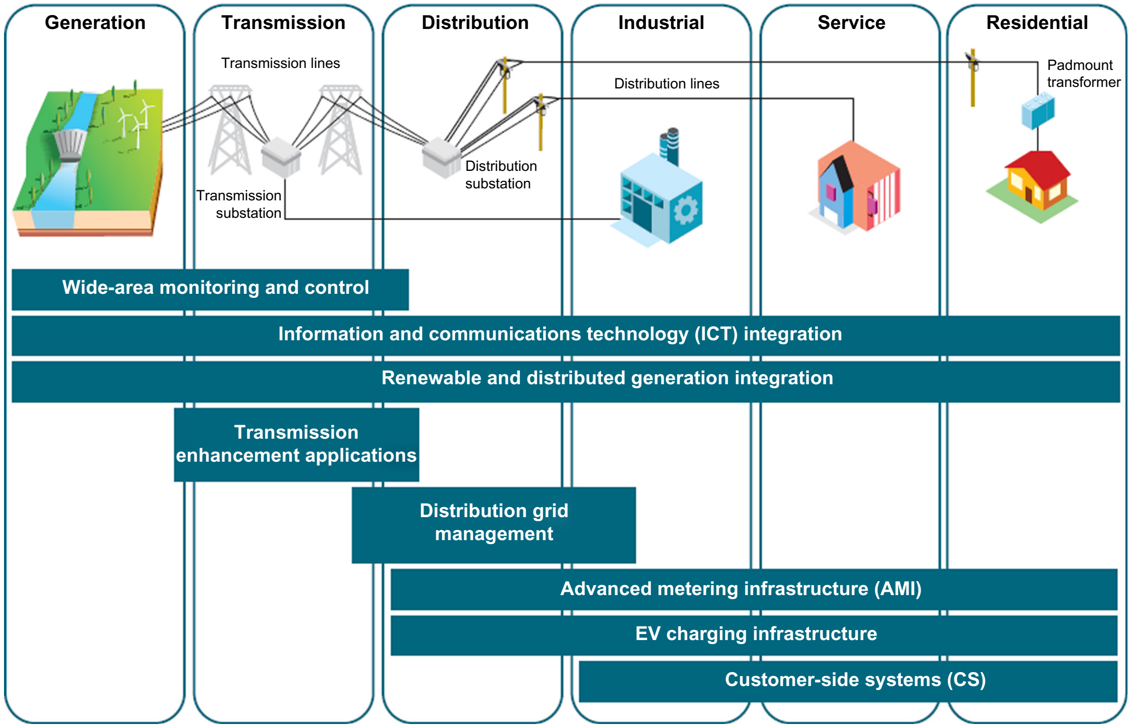

Figure 4 Smart Grid technology areas.
Notes: Smart Grid technology areas – each consisting of sets of individual technologies – span the entire grid, from generation through to transmission, and distribution, to various types of electricity consumers. Technology descriptions adapted from NETL, Understanding the Benefits of Smart Grids, 2010 and NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0, 2010. © OECD/IEA 2011, Technology Roadmap: Smart Grids, IEA Publishing. Licence: www.iea.org/t&c/termsandconditions.[22]
Abbreviations: EV, electric vehicle; NETL, US National Energy Technology Laboratory; NIST, National Institute of Standards and Technology.

Table 1 Mechanisms by which the Smart Grid can reduce energy use

Mechanism	Reduction in Electricity Sector Energy and CO_2 Emissions[a]	
	Direct (%)	Indirect (%)
Conservation Effect of Consumer Information and Feedback Systems	3	–
Joint Marketing of Energy Efficiency and Demand Response Programs	–	0
Deployment of Diagnostics in Residential and Small/Medium Commercial Buildings	3	–
Measurement and Verification (M&V) for Energy Efficiency Programs	1	0.5
Shifting Load to More Efficient Generation	<0.1	–
Support Additional Electric Vehicles and Plug-In Hybrid Electric Vehicles	3	–
Conservation Voltage Reduction and Advanced Voltage Control	2	–
Support Penetration of Renewable Wind and Solar Generation (25% renewable portfolio standard [RPS])	<0.1	5
Total Reduction	**12**	**6**

Notes: [a]Assumes 100% penetration of the Smart Grid technologies. Reproduced from Pacific Northwest National Laboratory. *The Smart Grid: An Estimation of the Energy and CO_2 Benefits Revision 1*; Jan 2010. Available from: http://energyenvironment.pnnl.gov/news/pdf/PNNL-19112_Revision_1_Final.pdf.[25]

The ability to optimize energy usage at all levels of the supply chain will become an important sustainability issue. Smart energy management systems are key enablers of the envisioned efficiencies both on the demand and supply sides of the smart energy grids.[26] The ongoing research in this area proceeds in the direction of load analysis and probabilistic energy forecasting.[27]

Load shifting from demand-response

Some organizations argue that a Smart Grid might be able to deal with the extra load without adding significant generating capacity by acting as a mediator to smooth out the peaks in consumption when there is high demand. The precise control over capacity promised by a Smart Grid will allow utilities to meet occasional peaks in demand without continuously running huge installed bases of oil, coal or gas-fired power plants.[28]

Cloud systems and machine-to-machine (M2M) communications

Energy utilities, including transmission and distribution providers, are beginning to generate massive volumes of data in Smart Grids. This data, when applied effectively with analytics, can help energy companies evaluate the returns being generated against the sizable investments in Smart Grid technologies. In addition, big data analytics can help power providers evaluate the areas within their Smart Grid networks that can be refined or improved and help assess the business benefits being achieved as a result of Smart Grid.[29]

Cloud based solutions are assisting utilities with the management and merging of Smart Grid data with other forms of data to deliver information that can help a utility save money or improve operations – ranging from grid controls to customer engagement. Cloud also provides a scalable solution, unlimited data access, computation systems to analyze raw data and cost savings, in addition to the reduced need for data storage and server configurations. Combined with an online interface, cloud computing gives utilities and customers access to accurate consumption data at any time via smart phones, tablets, desktops, and laptops. Cloud also provides computational power for complex Smart Grid projects.[30]

This commodity comes with a price: cloud-computing facilities consume megawatts of power and generate a level of greenhouse gas emissions that varies depending on factors such as local time, the utility's fuel mix for electricity generation, and the use of sophisticated power-saving techniques. Companies that host their services in the cloud need to buy sufficient capacity to meet demand, but recently the solutions appeared which allow to choose where in the world cloud servers can be located. Stratus system[31] effectively balances the load between different computer servers located across the globe and allows a company to set out how much importance to attach to cost, greenhouse gas emissions, and network delays involved in servicing Internet load.[32]

M2M communications have been considered as one of the foundation ICT solutions for implementing Smart Grid. The "Internet of Things" as M2M is sometimes called, is revolutionizing the energy industry, and helping reduce CO_2 emissions. This is because the Smart Grid's instant information flow means energy conserving decisions can be made quickly both by connected devices and the people operating them.[33]

According to a report,[34] M2M-enabled Smart Grid is a significant contributor to the reduction of greenhouse gases. M2M has the potential to enable efficiency gains throughout the global economy that could reduce greenhouse gas emissions by 9.1 Gt CO_2e by 2020. This is a remarkable figure because the International Energy Agency estimates that the world needs to reduce greenhouse gas emissions by 5–7 Gt CO_2e by 2020 in order to meet the global temperature increase goal of no more than 2°C.

EVs

Automobiles play a particular role in the transport sector because they are dominating the street traffic in most countries, and because car sales exhibit the greatest growth rates in the world. In order to meet future mobility needs, reduce climate emissions, and phase out dependence on oil, today's propulsion technologies have to be replaced by more efficient and environmentally friendly alternatives. The transition to a sustainable society, particularly efficient mobility technologies are needed worldwide. EVs have been identified as being such a technology.[35]

While the electrification of the transportation sector poses numerous challenges, it also presents utilities with a significant opportunity. Transportation electrification presents an opportunity for utilities to have greater contact with customers, creating a stronger relationship. Not only will utilities enable vehicle "fuelling" through EV charging, they will also be able to communicate greenhouse gas reductions and energy savings to customers (and regulators) through web portals and monthly bills, empowering customers as partners in energy efficiency. By planning now for EVs, utilities can maximize the utilization of their infrastructure and leverage EV supply equipment communications investments for other energy initiatives.[36]

In transportation, vehicles powered by batteries or other electric technologies have the potential to displace vehicles burning gasoline and diesel fuel, reducing associated emissions and demand for oil. The transportation sector is one of the major contributors to CO_2 emissions (about 28%, according to a report by the Environmental Protection Agency, USA).[37]

It is quite well understood that electric cars have the potential to reduce CO_2 emissions, but this potential is dependent on the type of electricity that charges the battery. Given that the vast majority of power generation around the world is grid-tied, where a car is charged plays a large role in determining its carbon emissions.[37]

Shades of Green report[37] compares the carbon emissions of electric cars in twenty of the world's leading countries and highlights that EVs must be used in tandem with low carbon power in order to maximize carbon emission reductions. In countries with coal dominated power supplies electric cars generate carbon emissions four times higher than in places with low-carbon electricity.

Integration of renewable energy sources

Energy storage will play a key role in enabling the community to develop a low-carbon electricity system. Energy storage can supply more flexibility and balancing to the grid, providing a back-up to intermittent renewable energy. In this way, it can ease the introduction of renewable sources into the electricity market, accelerate the decarbonization of the electricity grid, improve the security and efficiency of electricity transmission and distribution (reduce unplanned loop flows, grid congestion, voltage and frequency variations), stabilize market prices for electricity, while also ensuring a higher security of energy supply.[38]

Solar photovoltaic power is a commercially available and reliable technology with a significant potential for long-term growth in nearly all world regions. The roadmap[39] estimates that by 2050, photovoltaic cells will provide around 11% of global electricity production and avoid 2.3 Gt of CO_2 emissions per year.

Wind power is also very effective at cutting CO_2 emissions, as demonstrated by researchers from Universidad Politecnica de Madrid, Spain, in the report.[40] This study generated the first comprehensive analysis of the interaction between wind parks and thermal power plants in Spain and has concluded that global balance of CO_2 reduction is significant.

The roadmap[41] targets 15% to 18% share of global electricity from wind power by 2050, a notable increase from the 12% aim for 2009. The new target of 2,300 GW to 2,800 GW of installed wind capacity will avoid the emission of up to 4.8 Gt of CO_2 annually.

When considering wind sources, it is important to acknowledge that emissions in electrical systems are not proportional to the generation of intermittent sources due to the "cycling" of thermal plants that provide the balance to the network. Cycling is related to the changes produced by gas or carbon plants for diverse reasons, including renewable generation resulting in spending more fuel per MWh. Therefore, intermittence of wind energy can negatively affect the expected reduction of emissions because of the so-called "cycling" problem. When the intermittent wind energy source becomes unavailable, energy must be provided by traditional energy sources, and therefore the reduction of CO_2 emission becomes questionable and the cost of MWh rises.[42]

Power electronics and Smart Grid

Power electronics (PE) can be broadly defined as solid-state energy conversion technology that enables efficient and fully controllable conversion of electrical power.[43] Existing silicon (Si)-based PE enable conversion from direct current to alternating current and the movement of electricity from higher voltage transmission to lower voltage distribution. However, Si-based semiconductor technology cannot handle the power levels and switching frequencies anticipated by next generation utility applications.[44]

The generated power output from renewable energy is often difficult to control, and if adopted in large quantities, may cause frequency fluctuations throughout the entire power system and local voltage fluctuations may occur. With a Smart Grid, a compensating high-speed high-accuracy power supply system must be used to connect renewable energy, for which the generated output power is difficult to control, to the power system, and PE technology play an important role in the realization of such a system. In particular, many types of distributed power sources generate direct current power, and PE technology for performing power conversion is one of the most important technologies for Smart Grids.[45]

From a green angle, the use of advanced PE not only enables the effective integration of renewable resources through generation, but it also eliminates the need for building conventional generation in reactive power deficient load pockets – a net positive impact on reducing carbon emissions.[46]

PE based on wide bandgap (WBG) semiconductor materials, such as Si-carbide, gallium nitride, and diamond, could increase the reliability and efficiency of the next generation electric grid. These materials are capable of routing power more quickly and handling higher voltages. A number of barriers and challenges exist in utilizing WBG semiconductor based PE to their full potential, including identifying and designing new types of devices that best exploit WBG semiconductor properties and creating cost-effective high-volume manufacturing processes for those devices.[44]

The PE devices used in Smart Grids are required to have a function that is capable of accommodating fluctuations in frequency or voltage, as well as a function for safely interconnecting with a power system.[45] PE could potentially reduce overall electricity consumption by more than 30%.[47]

By taking advantage of technological innovations in semiconductor materials, and microprocessor (or digital-based) control systems, PE is creating devices that enhance energy generation and delivery systems. The versatility and reliability of lower cost devices combined with advances in circuit topologies and controls has resulted in technologies that replaced what has been traditionally done by electromagnetic and electromechanical systems. With the development of solid-state-based packages, PE devices can now convert almost any form of electrical energy to a more desirable and usable form. Another benefit of PE is their extremely fast-response times. PE interfaces can respond to power quality events or fault conditions within the subcycle range.[48]

Transmission owners have already begun implementing advanced power electronic technologies for a variety of applications. These applications include dynamic reactive power support to ensure satisfactory voltage profiles during system events, and series compensation to effectively increase line capacity without incurring large capital expenditures typically associated with this. Transmission owners are taking it one step further: they are implementing coordinated schemes using static and dynamic sources of reactive power to strengthen their systems and account for variable power flows that result from wind and solar penetration.[46]

How can nanotechnology reduce CO_2 emission?

Nanotechnology is a platform whereby matter is manipulated at the atomic level. There are various ways that nanotechnology can be applied along the Smart Grid to help reduce CO_2 emissions.

The major impact of nanotechnology on the energy sector is likely to improve the efficiency of current technologies to minimize use of fossil fuels. Any effort to reduce emissions in vehicles by reducing their weight and, in turn, decreasing fuel consumption can have an immediate and significant global impact. It is estimated that a 10% reduction in weight of the vehicle corresponds to a 10% reduction in fuel consumption, leading to a proportionate fall in emissions. In recognition of the above, there is growing interest worldwide in exploring means of achieving weight reduction in automobiles through use of novel materials. For example, use of lighter, stronger, and stiffer nano-composite materials is considered to have the potential to significantly reduce vehicle weight.[9,49]

Nanotechnology is applied in aircraft coatings, which protect the materials from the special conditions of the environment where they are used (instead of the conventional bulk metals such as steel). Since the amount of CO_2 emitted by an aircraft engine is directly related to the amount of fuel burned, CO_2 can be reduced by making the airplane lighter. Nanocoatings are one of the options for aerospace developers, but also for automotive, defense, marine, and plastics industries.[49] Lufthansa Cargo uses the most advanced technologies and innovative processes including efficient jet engines, nanotechnology in aircraft coatings, new composites or regular jet engine cleaning – and of course monitoring overall aircraft weight. It is often a matter of only a few grams. However, given 15,000 to 16,000 flights a year and an average flight time of about 6 hours, the cumulative effect of a number of grams can quickly add up to tons. The removal of a 350 gram phone handset resulted in jet fuel savings of 3.5 tons in a year.[50]

Nanotechnology is already applied to improve fuel efficiency by incorporation of nanocatalysts. Enercat, a third generation nanocatalyst developed by Energenics, uses the oxygen storing cerium oxide nanoparticles to promote complete fuel combustion, which helps in reducing fuel consumption. Recently, the company has demonstrated fuel savings of 8%–10% on a mixed fleet of diesel vehicles in Italy.[51]

Reducing friction and improving wear resistance in engine and drive train components is of vital importance in the automotive sector. Based on the estimates made by a Swedish company Applied Nano Surfaces, reducing friction can lower the fuel consumption by about 2% and result in cutting down CO_2 emissions by 500 million tons per year from trucks and other heavy vehicles in Sweden alone.[9] Thanks to nanomaterials like silica, many tires will in the future be capable of attaining the best rating, the green category A. Cars equipped with category A tires consume approximately 7.5% less fuel than those with tires of the minimum standard (category G).[52]

Residential and commercial buildings contribute to 11% of total greenhouse gas emissions. Space heating and cooling of residential buildings account for 40% of the total residential energy use. Nanostructured materials, such as aerogels, have the potential to greatly reduce heat transfer through building elements and assist in reducing heating loads placed on air-conditioning/heating systems. Aerogel is a nanoporous super-insulating material with extremely low density; silica aerogel is the lightest solid material known with excellent thermal insulating properties, high temperature stability, very low dielectric constant and high surface area.[51]

Nanotechnology is positioned to create significant change across several domains, especially in energy where it may bring large and possibly sudden performance gains to renewable sources and Smart Grids. Nanotech enhancements may also increase battery power by orders of magnitude, allowing intermittent sources such as solar and wind to provide a larger share of overall electricity supply without sacrificing stability. Nanotech sensors will also enable Smart Grids and foster more flexible and decentralized electricity management.[53]

Nanotechnology may accelerate the technology behind renewables in various ways:

- experts are discovering means to apply nanotechnology to photovoltaics, which would produce solar panels with double or triple the output by 2020;
- wind turbines stand to be improved from high-performance nano-materials like graphene, a nano-engineered one-atom thick layer of mineral graphite that is 100 times stronger than steel. Nanotechnology will enable light and stiff wind blades that spin at lower wind speeds than regular blades;

- nanotechnology could play a major role in the next generation of batteries. For example, coating the surface of an electrode with nanoparticles increases the surface area, thereby allowing more current to flow between the electrode and the chemicals inside the battery. Such techniques could increase the efficiency of electric and hybrid vehicles by significantly reducing the weight of the batteries. Moreover, superior batteries would complement renewables by storing energy economically, thus offsetting the whole issue of intermittent generation.

In a somewhat more distant future, we may see electricity systems apply nanotechnology in transmission lines. Research indicates that it is possible to develop electrical wires using carbon nanotubes that can carry higher loads and transmit without power losses even over hundreds of kilometers. The implications are significant, as it would increase the efficiency of generating power where the source is easiest to harness.[53]

Semiconductor devices, transistors, and sensors will benefit from nanotechnology especially in size and speed. Nanotech sensors could be used for the Smart Grid to detect issues ahead of time, ie, to measure degrading of underground cables or to bring down the price of chemical sensors already available for transformers. Nanotechnology will likely become indispensable for the Smart Grid to fully evolve in the near future.[54]

Conclusion

This review demonstrates the potential for reduction of CO_2 emissions that Smart Grids can potentially achieve. Power grid modernization is an evolution that will continue for years or decades, and providing a robust foundation for new applications and technologies is imperative.

The electric power industry is facing tremendous opportunities and becoming increasingly important in the emerging low-carbon economy. Governments are still dominant players in high-cost smart-grid investments. This suggests the need for a policy framework that attracts private capital investment, especially from renewable project developers, and communication and ICT companies.

The challenge we face is neither a technical nor policy one – it is political: the current pace of action is simply insufficient. The technologies to reduce emission levels to a level consistent with the 2°C target are available and we know which policies we can use to deploy them. However, the political will to do so remains weak. This lack of political will comes with a price: we will have to undertake steeper and more costly actions to potentially bridge the emissions gap by 2020.[4] However, technical possibilities aside, the key to reducing emission levels will be the tough but unavoidable decision that reducing carbon pollution must be of the highest priority.

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