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Review Article

Reducing Carbon Dioxide Emissions from Electricity Sector Using Smart Electric Grid Applications

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Approximately 40% of global CO_2 emissions are emitted from electricity generation through the combustion of fossil fuels to generate heat needed to power steam turbines. Burning these fuels results in the production of carbon dioxide (CO_2)—the primary heat-trapping, “greenhouse gas” responsible for global warming. Applying smart electric grid technologies can potentially reduce CO_2 emissions. Electric grid comprises three major sectors: generation, transmission and distribution grid, and consumption. Smart generation includes the use of renewable energy sources (wind, solar, or hydropower). Smart transmission and distribution relies on optimizing the existing assets of overhead transmission lines, underground cables, transformers, and substations such that minimum generating capacities are required in the future. Smart consumption will depend on the use of more efficient equipment like energy-saving lighting lamps, enabling smart homes and hybrid plug-in electric vehicles technologies. A special interest is given to the Egyptian case study. Main opportunities for Egypt include generating electricity from wind and solar energy sources and its geographical location that makes it a perfect center for interconnecting electrical systems from the Nile basin, North Africa, Gulf, and Europe. Challenges include shortage of investments, absence of political will, aging of transmission and distribution infrastructure, and lack of consumer awareness for power utilization.

1. Introduction

Global CO_2 emissions in 2010 approached 30 gigatons (Gt). Approximately 12 Gt (40%) are emitted from 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. Burning these fuels results in the production of carbon dioxide (CO_2)—the primary heat-trapping, “greenhouse gas” responsible for global warming, in addition to other nitrogen and sulfur oxides responsible for various environmental impacts [1].

Over the past two centuries, mankind has increased the concentration of CO_2 in the atmosphere from 280 to more than 380 parts per million by volume, and it is growing faster every day. As the concentration of CO_2 has risen, so has the average temperature of the planet. Over the past century, the average surface temperature of Earth has increased by about 0.74°C. If we continue to emit carbon without control, temperatures are expected to rise by an additional 3.4°C by the end of this century. Climate change of that magnitude would likely have serious consequences for life on Earth. Sea level rise, droughts, floods, intense storms, forest fires, water scarcity, and cardiorespiratory diseases would be some results. Agricultural systems would be stressed—possibly declined in some parts of the world. There is also the risk that continued warming will push the planet past critical thresholds or “tipping points” —like the large-scale melting of polar ice, the collapse of the Amazon rainforest, or the warming and acidification of the oceans—that will make irreversible climate change. Despite mounting evidence of the dangers posed by climate change, efforts to limit carbon emissions remain insufficient, ineffective, and, in most countries, nonexistent. Given current trends and the best available scientific evidence, mankind probably needs to reduce total CO_2 emissions by at least 80% by 2050. Yet each day emissions continue to grow [2].

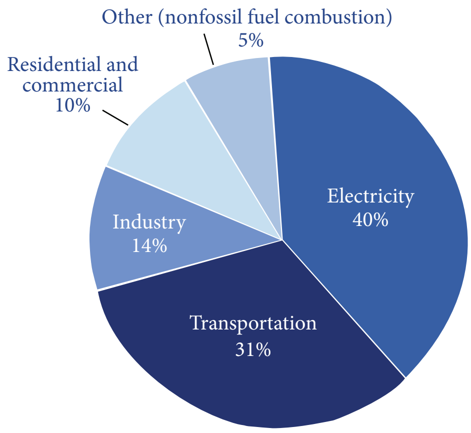

Figure 1: Sources of CO_2 emissions by sector (worldwide, 2009).

Electricity sector is the major source of the total global CO_2 emissions responsible for approximately 40% worldwide, followed by transportation, industry, and other sectors as shown in Figure 1 [3]. As a result, we will focus in this paper on how to decrease the quantities of CO_2 emitted from electricity sector using what is called the Smart Electric Grid.

2. The Smart Electric Grid versus the Existing Electric Grid

The electricity grid was once described as "the greatest engineering achievement of the 20th century." This rank was highly suspected after the famous blackout of New York city and almost Northeastern US and parts of Canada in 14 August 2003, leaving more than 50 million people without electricity, and costing more than 6 billion dollars. Today, in the early 21st century, the digital economy, the global climate change, and natural/terrorist threats have all focused attention on the pressing need for an intelligent, more reliable power grid [4].

The Smart Grid (SG) can be regarded as a vision, a concept, a framework, or an umbrella for a modernized, evolutionary, next generation step of our electrical power system. It is an integration of complementary components, subsystems, and services under the control of highly intelligent management and control systems throughout electricity power system. It is a combination of enabling technologies—hardware, software, or practices—that collectively make the electric power infrastructure environment friendly, more safe, secure, reliable, self-healing, efficient, and sustainable. Also called intelligent grid, or future grid, the concept of a SG is that of a "digital upgrade." The smartness of the SG lies in the decision intelligence layer, all the computer programs that run in relays, innovative electronic designs, substation automation systems, and control centers. SG technologies could contribute to greenhouse gas emission reductions by increasing efficiency and conservation, facilitating renewable energy integration, and enabling plug-in hybrid electric vehicles [5].

Consider how communications have changed in the latter half of the 20th century through the first decade of the 21st. We have progressed from rotary-dial telephones and expensive long-distance calling to the Internet, e-mail, cell phones, videoconferencing, and video chats. Now consider how our relationship to the electric grid has changed over that same time period. To date, the revolutions that we have seen in communications have very few analogs in the electric grid. Generally speaking, Smart Grid (SG) refers to the use of digital information and controls technology to improve the reliability, security, and overall efficiency of the electric grid. This will be accomplished by offering consumers and utilities incentives to work together to create a more responsive and less polluting system [6].

2.1. The Existing Electric Grid. For more than a century, the electrical grid consists mainly of three sectors as shown in Figure 2: generation of bulk power using generating stations, normally outside urban areas, transmission of this power through overhead transmission lines at high voltages (to decrease current and thus decrease losses and decrease the cross-sectional area of the conductors), and distribution to customers (residential, industrial, commercial, and others) at customer voltage using underground cables.

Traditional (thermal) methods are based on burning fuel (coal, oil, or natural gas) to heat water in a boiler to get steam. The steam drives a turbine that rotates conductors within a magnetic field to generate electricity. Burning of fuel in power plants releases carbon, sulfur, and nitrogen oxides, which have harmful impacts on the environment (Table 1). Emissions that result from the combustion of these fuels include carbon dioxide (CO_2), which is the major green house gas (GHG) causing global warming, sulfur oxides (SO_x), and nitrogen oxides (NO_x). These oxides cause acidic rain, respiratory illnesses and heart diseases, particulate materials (PMs), which cause lung cancer, and heavy metals such as mercury, which are hazardous to human health.

Sometimes nuclear reactors are used to create the heat necessary for boiling the water. Nuclear power plants are not a source of GHG emissions, but they do produce two kinds of radioactive problems: contamination with radioactive emissions and disposal of used nuclear fuel (uranium) that requires specially designed storage containers due to the long life time of the radioactive uranium.

2.2. The Smart Electric Grid. Power generation is likely to move towards more renewable and distributed generation (DG). Some renewables like wind farms are large-scale and interface with transmission networks, but many renewables are small-scale, and hence appropriate for interconnecting at the distribution level. This fundamentally changes the design of the grid and needs special interfaces. It incorporates distributed (or local) generation such as PV, biogas/biomass, and wind, which will be supported by battery storage and fast-starting generation sources [7].

Renewable energy sources like hydropower, solar, and wind energy are environment friendly sources. However, they are not available everywhere. Hydropower energy is stuck to dams, and solar energy requires sufficient irradiation intensities. Wind energy requires a constant unidirectional wind speed. In most cases, solar and wind energies are

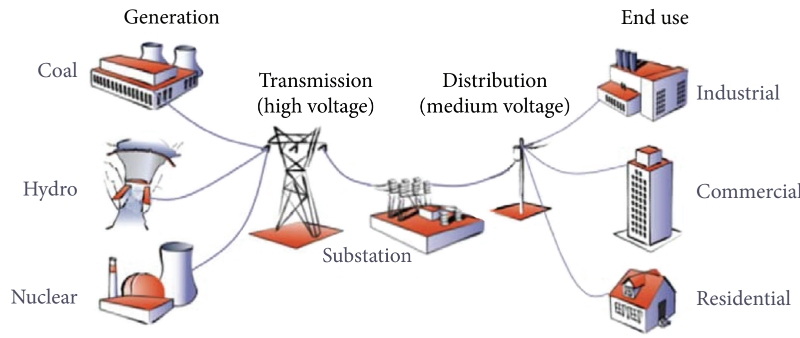

Figure 2: Elements of electrical power grid.

Table 1: Comparison of different traditional power plants (2009).

	Coal	Natural gas	Oil	Nuclear
Electricity generation (TWhr)	8,263	4,301	1,111	2,731
% of total generation	40.8%	21.2%	5.5%	13.5%
Main material	Carbon	Methane	Gasoline, kerosene	Uranium
Emissions	CO_2, SO_x, and NO_x			Radioactive
Impacts	Global warming, acid rain, respiratory diseases, and toxics			Nuclear pollution

Table 2: Comparison of different renewable power plants (2009).

	Hydroelectric	Photovoltaic	Solar-thermal	Wind farms
Electricity generation (TWhr)	3,288	12	1	219
% of total generation	16.2%	0.06%	0.005%	1.1%
Limitations	Implemented only at rivers or water falls	Low output power, depends on sun shining	Sun trackers require complex controllers	Wind speed must be >20 km/hr, noisy

coupled with a traditional diesel or gas generator to supply power when these sources are insufficient. Certain technical problems arise when plugging such sources to the grid.

Hydropower facilities convert water kinetic energy when falling from high level (potential) to a lower one into electricity. The construction and operation of hydropower dams have many impacts on natural river systems. It can flood riverside lands and destroy land habitats, it threatens the life of river populations (fish and other wildlife), and it can impede the natural flow of sediments.

There are two different approaches to generate electricity from the sun: photovoltaic (PV) and solar-thermal technologies. *Photovoltaic (PV)* cells were initially developed for the outer space program over 30 years ago. When sunlight strikes the PV cell, physical reactions release electrons, generating electric current. The small current from individual PV cells, which are installed in modules, can power individual homes. *Solar-thermal* technologies are, more or less, a thermal electricity generating technology. They use the sun to heat water and create steam to drive an electric generator. Parabolic systems use reflectors to concentrate sunlight to heat water which in turn creates steam to drive a standard turbine.

Wind power plants use large spinning blades to capture the kinetic energy in moving wind, which is then transferred to rotors that produce electricity. Regions where average wind speeds exceed 20 km/hr are the best wind power plant sites. Wind farms are comprised of large numbers of turbines each mounted atop tall towers in rural areas, requiring a large portion of land with almost no inhabitants. Two concerns always arise when designing a wind farm: oise pollution and the impact on bird populations.

Table 2 summarizes the shares of different renewable generation plants and their environmental impacts.

3. Electricity Impacts on the Environment

Figure 3 shows the world's energy mix for generating electricity (2009) [3]. Figure 4 shows a comparison among GHG emissions from the various energy sources [8]. It shows how wind and solar power emit minimum emissions. Simple calculations could show that building a power plant of capacity 1 MW fueled by gas-combined cycle would result in 400 tons of CO_2 equivalent GHG emissions. Using coal or oil

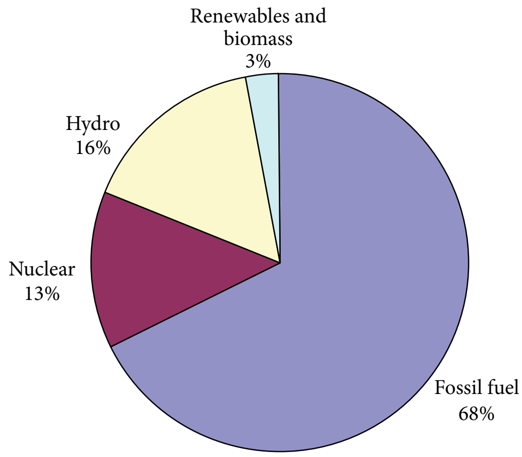

Figure 3: World's energy mix for generating electricity (2009).

Table 3: Egypt's electric data (2011).

Energy generated	147 million kWhr
Hydropower	13 million kWhr
Thermal power	119 million kWhr
Renewables	2 million kWhr
Energy purchased from private sector (BOOT)	13 million kWhr
Energy consumed	127 million kWhr
Peak instantaneous load in megawatts (MW)	23500 MW
Network losses	10%

would result in slightly more than twice that quantity. The corresponding values for renewables are less than 10% of the cleanest traditional source.

4. Smart Utilization of Electricity to Preserve the Environment

4.1. Smart Home (Building) Applications. A smart home system integrates massively deployed sensors and smart meters that can signal appliances, devices, and so forth. Each home might have dozens of nodes to be controlled, such as appliances, heating/ventilation/air conditioning (HVAC), solar panels, electric vehicles, and so forth. All these nodes are to be controlled using a single control unit with a programming feature for switching on and off where appropriate [9].

The information presented to consumers could consist of various parameters conveyed numerically, graphically, or symbolically as alerts or alarms, including: current and historical energy use, equivalent CO_2 emissions, instantaneous demand, current prices, and ambient temperature, humidity, and lighting levels. The forms of display devices under development vary, consisting of visual indicators employing data tables, charts, color codes, and flashing lights as well as audio indicators in which alarms are triggered by preset values to inform the consumer of pending price events or energy use thresholds [10].

Managing peak load through demand response instead of spinning reserves by giving consumers continuous direct feedback on electricity pricing through the day, especially during the peak interval, will make consumers adjust their usage in response to pricing [11].

Figure 5 shows an illustration of the smart home, with local generation presented in PV cells atop the roof of the home, with sensors embedded in everywhere in the home which sense people, temperature, lighting, and so forth and send these data to the control unit (a small computer) which takes preprogrammed decisions in response to the sensed data, such as switching off HVAC and lights when there is no one in the room or decreasing power consumption when there are only few persons (as programmed), operating the washing machine and charging the electric car in off-peak periods, and any other decisions.

4.2. Enabling Electric/Hybrid Electric Vehicles. Electric Vehicles run using electricity. Plug-in hybrid electric vehicles (PHEVs) can run using both electricity and gasoline. The batteries of these vehicles can be charged at home or other locations using a usual plug. Only during longer trips, gasoline will be used, as the vehicle batteries are depleted. The introduction of PHEV might also create the demand needed for companies to invest in electrical refueling stations [12].

An SG will also facilitate the market adoption and interconnection of plug-in hybrid electric vehicles (PHEVs) that can be plugged into electrical outlets for recharging. From the consumer point of view, PHEVs will save fuel costs. From a utility perspective, the ability to charge PHEVs overnight provides operational benefits through improved system load factor and utilization of base load resources. From an environmental perspective, the deployment of PHEVs will lead to CO_2 reductions. However, widespread consumer charging of PHEVs during peak periods in the day, for example, could increase peak load and increase utilities' operational costs. The development of a SG is therefore vitally important to utilities, since it entails the intelligence to send signals to consumers on when to charge their vehicles or provide differentiated rates to encourage off-peak charging.

With parallel advances in smart vehicles and the SG, PHEVs may become an integral part of the distribution system itself, providing storage, emergency supply, and grid stability. With these considerations in mind, it is reasonable to attribute some share of projected PHEV CO_2 reduction impact to the development of a SG.

Figure 6 illustrates symbolically how an electric vehicle (which runs solely using electricity) or hybrid vehicle (working using both electricity and gasoline) is *plugged in*.

5. Case Study: The Egyptian Electricity Grid

According to 2011 statistics, Table 3 presents the main data of Egypt's electric grid. Unless otherwise specified, all the data presented in this section are obtained from [13].

5.1. Generation. About 90% of the total generation plants are thermal (steam, gas, combined cycle). Nine percent

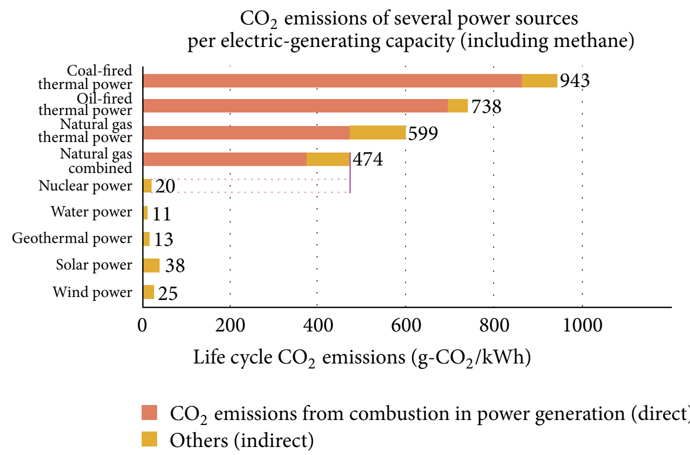

FIGURE 4: GHG emissions from various energy sources.

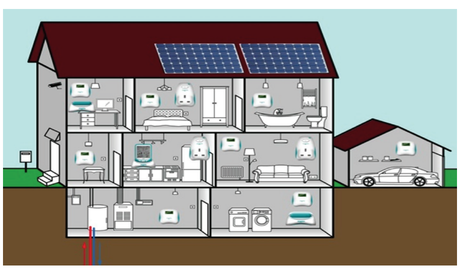

FIGURE 5: Smart home.

FIGURE 6: Plugging-in electric or hybrid vehicle.

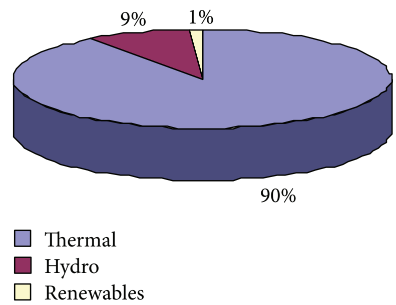

FIGURE 7: Electricity generation mix in Egypt (2011).

TABLE 4: Fuel consumption for generating electricity in Egypt.

Total fuel consumption in thermal plants	24700 ktoe
Total energy generated from thermal plants	119 TWhr
Fuel consumption rate	208 gm/kWhr gen.
CO_2 emission from thermal power plants	64 MMt
CO_2 emissions intensity	540 gm CO_2/kWhr gen.
CO_2 emissions per person (annually)	0.75 tons/person

comes from hydropower sources, and only 1% comes from renewables, as shown in Figure 7 [14].

The combustion of these fossil fuels results in emission of GHG, namely carbon dioxide, as shown in Table 4, in addition to sulfur and nitrogen oxides, causing temperature rise and contributing to the black cloud phenomena: an extreme air pollution phenomena appearing over Cairo and Delta cities.

To put Egypt in world context, the estimated CO_2 emission from the world's electrical power industry is 12 billion tonnes yearly, with approximate shares of 25% out of USA, 25% out of China, 25% out of other major industrial countries, and 25% out of the rest of the world. Egypt comes in the 30th place with approximately 64 million tons of CO_2 emissions from electrical power plants annually (approx. 0.5% of global emissions) [15].

Egypt is also working on developing nuclear power as an electrical energy source. Egypt has a 22 MW nuclear research reactor at Inshas in the Nile Delta that began operation in 1997. Egypt approved a 1.2 GW power station at *El-Dabaa* and is expected to become in operation in 2019. After the of January 25, 2011 revolution, the project seems to be on hold indefinitely.

Egypt has an ambitious plan aiming at increasing the contribution of renewables to reach 20% of total energy generated in 2020, where hydropower represents 5.8%, wind 12%, and 2.2% from solar energy.

Hydropower is considered one of the cheapest and cleanest sources of power generation. The construction of Aswan High Dam with a 2.1 GW capacity in the 1960s was a renowned engineering project of the 20th century. Currently,

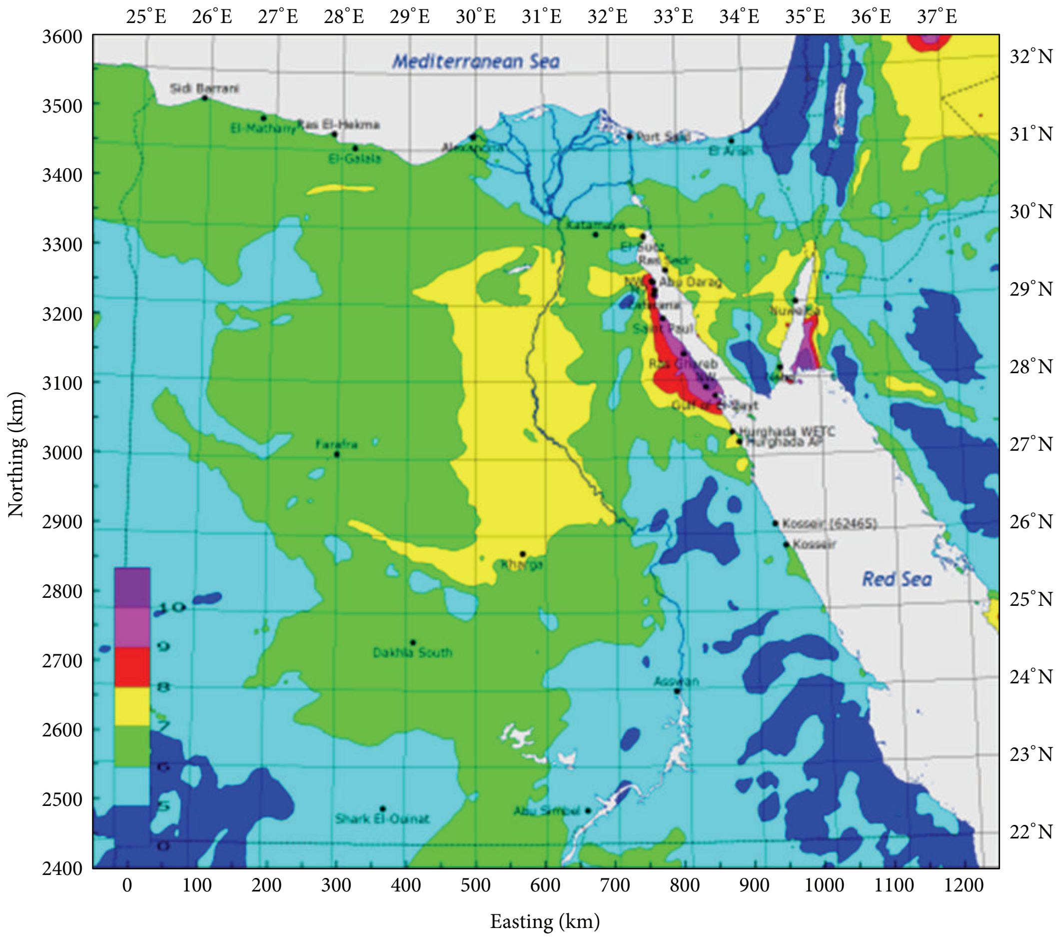

Figure 8: Wind atlas of Egypt.

over 85% of the Nile's hydro power potential has already been used.

Some of the world's best wind resources are located in Egypt, especially in the areas of the Gulf of Suez, and West and East Nile valley due to high wind speeds ranging between 8 and 10 m/s in average, and also due to the availability of large un-inhabited desert areas [16]. Figure 8 shows Egypt's wind atlas [17]. Currently, Egypt generates about 550 MW of electrical energy from *Zafarana* wind farm located on the Gulf of Suez coast, along the Red Sea coastline [18].

The high intensity of direct solar radiation (2,000–2,600 kWh/m^2) in Egypt shows great potential for solar energy development, especially in Upper Egypt. Every year, Egypt's primary locations offer 2,400 or more hours of solar operation. Egypt's first solar-thermal power plant is located in *Kuraymat*, about 90 km south of Cairo, and has the capacity to generate 140 MW and was completed and connected with the national grid at the end of June 2011. The solar power accounts for 20 MW of the plant's total generation. There is a general plan to export North African-generated solar electricity to Europe through the *Desertec* project [19].

Figure 9 shows Egypt's solar irradiation measured in possible production of kilowatt hours per square meter per day [18].

5.2. International Connections. Egypt is at the meeting point of the three continents: Africa, Asia, and Europe. Egypt activated a link to Libya's electric grid in 1999. The Five-Countries interconnection links Egypt in Africa to Jordan, Syria, and Iraq in Asia and Turkey in Europe. The interconnection has been completed in 2002.

The Gulf Cooperation Council (GCC) power grid project plans to link Egypt to the GCC through Saudi Arabia. The link is expected to be completed by 2015 and will allow the sharing of 3,000 MW of electricity between the two countries. This project will indirectly expand each country's electricity capacity by pulling from each other's supplies at different peak hours. Longer-term plans call for broader interconnections that would include Africa, the Middle East, and Europe, as shown in Figure 10.

5.3. Consumption. Most electricity customers are unaware of their electricity use: how much they use, when they use it, and how it is priced. Compared with other industries (telecommunications for instance), electricity consumers lack the service options and pricing information necessary to make informed decisions. Electricity providers estimate that benefits made possible by smart customers will constitute one-third to one-half of total SG benefits. Achieving these

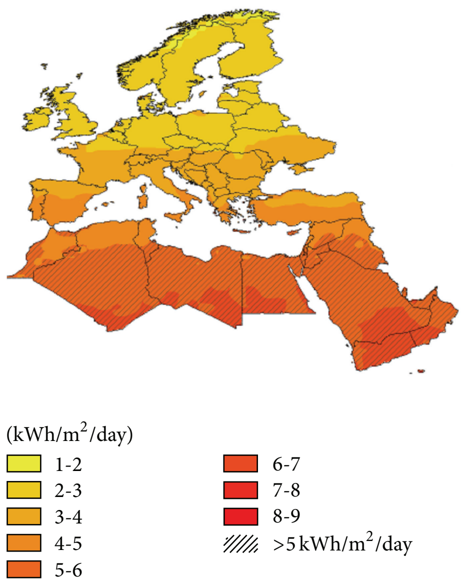

FIGURE 9: Egypt's Solar Potential.

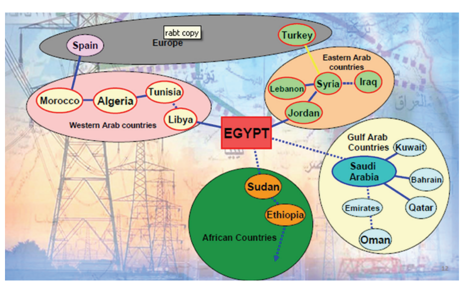

FIGURE 10: Interconnection transmission system.

benefits, however, requires large investments in new metering, communications, and customer interface technology, together with policies and service offerings that create smart customers [20].

Some of the measures that should be taken by utility companies in Egypt include.

(i) Lighting loads account for approximately 23% of country load. There is a growing interest in substituting the normal incandescent lamps with newer compact energy-efficient ones. The governmental distribution companies promote this trend by offering new lamps with half prices. Nine million lamps (20–23 W) are sold within this program. About 200,000 traditional sodium street lighting lamps (400 W) are also substituted by high efficiency (100–160 W) lamps.

(ii) Industries now begin to utilize electrical drives to control motors, aiming at increased efficiency and lower power consumption. Some industries also begin to activate projects for combined heat and power (CHP) to make use of steam with high temperatures already existing in their facilities. Industries with heavy electricity consumption such as steel and petrochemicals are subject to double tariff policy; that is these consumers have to pay 50% extra cost for their consumption for peak periods. This policy aims at load shifting to out-of-peak periods.

(iii) Some distribution companies begin the practice of prepaid electricity cards. Others apply automated meter reading by using electronic meters. This could be a step towards smart metering. Some companies allow their customers to access and pay their electricity bills through the Internet.

6. Conclusions

In this paper, the concept of Smart Electric Grid is reviewed along with its environmental benefits. This concept calls on adding smartness or intelligence to every component of the power system, from generation through transmission to distribution. The use of renewable energy sources to generate electricity instead of traditional thermal power plants will lead to fossil fuel conservation and environmental improvements as a result of reducing green house gases (especially CO_2) emitted as a result of thermal generation. As for the transmission network, smart grid optimizes the use of existing lines and substations for maximum efficiency and minimum losses. As for consumption, introducing smart meters, along with the use of smart house facilities and extended penetration of hybrid plug-in electric vehicles will lead to reducing GHG emissions, energy conservation, and preserving our environment.

Egypt can achieve many technical and environmental benefits from applying smart grid technologies, especially in the field of increased electricity generation from wind and solar energy sources as well as from activating its geographical role as an electricity center between hydroelectric Nile basin power, wind and solar power from North Africa, and its ability to interconnect with Europe across the Mediterranean. More efforts are needed to introduce the capabilities of the smart grid to the decision makers for fast funding and planning actions, as well as programs for consumer education for conserving energy and its associated benefits of preserving our environment.

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