

WIND POWER SYSTEMS

HARVESTING THE WIND

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PREFACE

“Everything on Earth belongs to princes, except the wind.”
 Victor Hugo, French author

"All animals are equal, but some animals are more equal than others."
 George Orwell Animal Farm

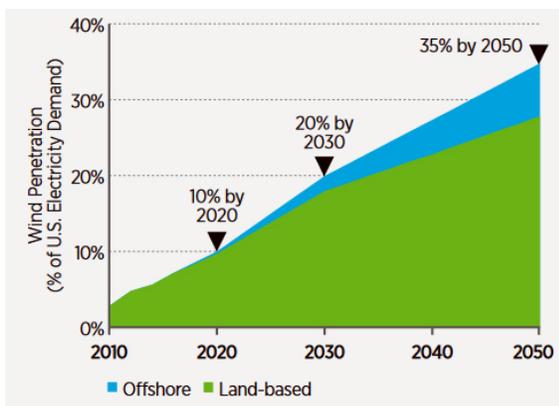
Renewable energy technologies have developed in recent years, with improved efficiency and lower cost. A barrier to their uptake is that they do not provide a constant supply of energy. Wind and solar farms only produce energy when the wind is blowing, or the sun is shining. However, electricity is needed around the clock, day and night. Humanity needs to imitate nature and develop ways to store energy on a large scale before it can make the transition to renewable sources. Note that, except for nuclear energy, we are depleting what nature has stored over millions of years in the form of hydrocarbons within a centuries time scale. In the process of releasing the hydrocarbons stored energy we are modifying the atmosphere’s and oceans’ compositions and modifying the earth’s climate.

The fundamental aspects of the science and technology of Wind Power Systems are covered from a cross-disciplinary perspective. It should be of interest to readers from the different engineering and scientific disciplines, as well as members of the public with a reasonable level of mathematical knowledge.

The Bureau of Labor Statistics (BLS) identifies wind turbines engineers and technicians as the fastest growing profession in the nation. The Department of Energy estimates that the wind energy industry could support up to 380,000 job opportunities by 2030. This is a significant increase over the 88,000 jobs existing in 2016.

Two impediments to the growth of the wind energy industry are the need to develop extra power transmission and energy storage systems for the generated power. In 2011, a Regional Transmission Operator, MISO, representing 30 transmission owner members including 13 mid-western states and parts of Canada approved a portfolio of projects designated as Multi-Value-Projects (MVPs) to increase the transmission capacity and address its reliability issues.

Wind power made up 41 percent of the new USA electrical installed capacity of 14,468 MWe in 2015. They were primarily installed in the Midwest and Great Plains region which boasts tremendous wind energy resources. These wind projects provide tax revenue and job opportunities to the local communities and royalty payments to land owners.



Cumulative Wind Capacity (GW)		2013	2020	2030	2050
<i>Baseline Scenario</i>	Land-based	61			
<i>Central Study Scenario</i>	Land-based	61	110	202	318
	Offshore	0	3	22	86
	Total	61	113	224	404

Figure 1. Wind energy projected cumulative installed capacity. Source: AWEA.

In 2012, wind energy installed capacity reached 60 GigaWatts (GWs) and ranked first in new electricity generation capacity for the first time in the USA at 43 percent of all new electric additions with \$25 billion in investments. About 13 GWs of new wind power capacity was added to the USA electric grid, about double the capacity added in 2011. Wind power capacity powers about 15 million homes in a year. Since 2000, the cumulative wind installed capacity has increased 22-fold. About 72 percent of the wind turbine equipment installed in 2011 was domestically manufactured, tripling from 25 percent in the period 2006-2007. Distributed wind reached about 69,000 units across the 50 states.

It must be recognized that renewable energy technology is called upon to replace carbon sources, yet it is still being developed supplying just about 3 percent of the current world energy demand. Its expansion is facing constraints that need to be surmounted in research and development, manufacturing, materials availability, design choices, and systems integration in the electrical grid system and the labor force. Yet, the existing fossil fuel energy sources, because of depletion and pollution, can only be considered as a bridge into a future where the renewable sources predominate, with energy storage options being developed to overcome their intermittent nature.

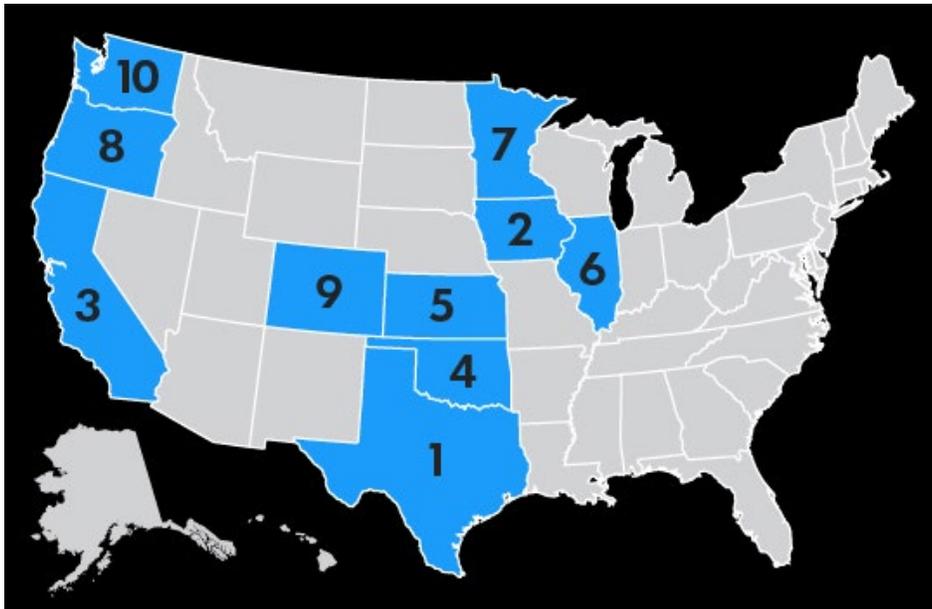


Figure 2. Top ten states in wind energy adoption. Source: USA Today.

Engineers and scientists have foregone fighting the proverbial battle of the last war, and turned their attention into fighting the first battle of the next war. They face challenges of economic growth in the USA and the developed world whose economies have substantially slowed down. Other factors hurting the world economy include depleting resources, global warming, failing infrastructures, ineffective educational systems, dearth of new jobs creation, persistent unemployment, work force shrinkage, falling households incomes, dramatic reductions

in standards of living, pay cuts, pensions and savings hair-cuts, health care triage, massive banks insolvency, monumental sovereign and private debt, large trade imbalances, budget deficits, rampant austerity measures, and global and local income inequality. In effect a new form of egregious serfdom and slavery is prevalent where the citizens of the debtor countries struggle to make a living and become de-facto debt-slaves to their lenders.

Historically, salt and its control were at a certain time a major source of power because of its ability to preserve food and consequently life. Roman legions soldiers were paid in salt, hence the names “Salaire” in French and “Salary” in English. Electricity and refrigeration replaced salt and its control and importance faded away. The control and importance of petroleum as an energy source could similarly fade away as renewable energy in different forms gradually replace it and relegate it to a lower level of importance.

The world is embarking on a third industrial revolution: the Low Carbon Age; with the use of electricity replacing the use of hydrocarbons, and wind power is being reinvented to help fill the need. It is recently blooming all over the world, particularly in the USA, the European Community and China as an answer to the problems of fossil fuels depletion, greenhouse gases emissions, global warming considerations and adherence to the Kyoto Treaty.

SUSTAINABILITY OF ELECTRICAL RESOURCES: THE ENERGY SMART GRID

For a sustainable electrical energy supply, the engineering and scientific consensus is the need for the implementation of the "Smart Grid System" in both developed and emerging economies. Using a Complex Systems description, its different components include an energy mix at its nodes with interconnected exchanges:

1. Base power stations including nuclear, coal, hydroelectric and geothermal stations. These supply continuous electric service to industries and basic infrastructures.
2. Renewable Energies. These include wind, solar thermal and photovoltaic, and essentially have a zero cost of the energy supply but suffer from their nature as intermittent sources, except for biomass.
3. To overcome the intermittency problems of the renewables, storage systems such as battery, hydrogen and pumped storage, as well complementary sources such as natural gas turbines plants are also needed.
4. Smart metering for consumers and industry would encourage conservation and the use of the produced energy when it is readily available. In this case, they pay for the actual unsubsidized price of energy which would encourage its production. To advance an analogy, consumers must be encouraged by laws and regulations to catch the fish, use some of it for their own need, and sell the surplus into the market place. This concept is implemented in Germany where farmers use part of their pastures to produce photovoltaic electricity, use part of it on their farms, store part of it, and sell the surplus to the electrical grid system. In Denmark, homeowners with small tracts of lands produce wind power for their own use and the electrical utilities are obligated to purchase their excess surplus production and feed it into the electrical grid.
5. Decentralized control of the smart grid system turning the grid system on and off depending on the demand.

Energy Internet of Things “IoT” Smart Electric Grid Configuration

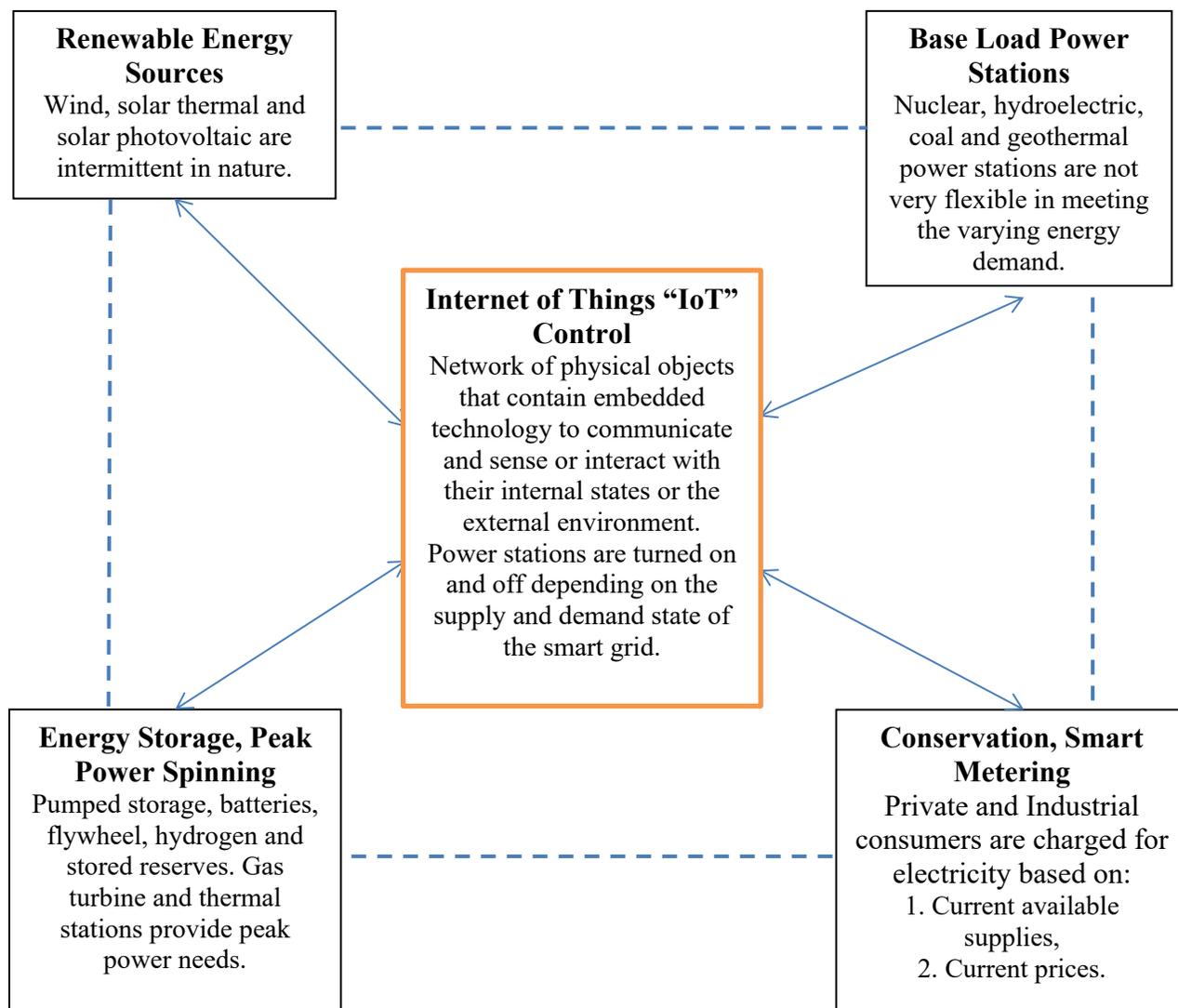


Figure 3. Smart grid configuration using the Energy Internet of Things “IoT” connecting renewables and conventional energy sources to electricity consumers through decentralized control of the power grid.

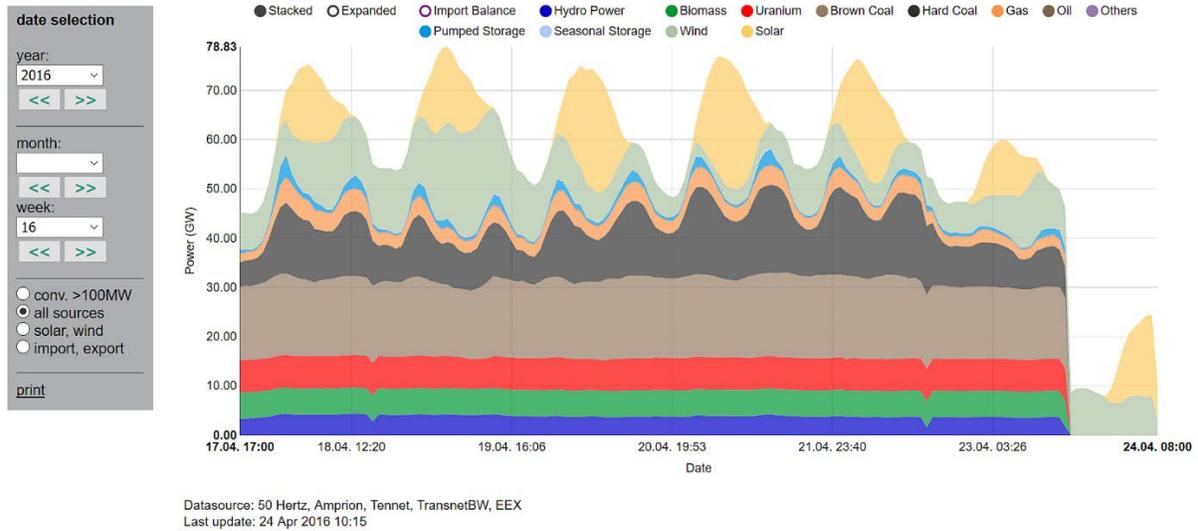


Figure 4. Electrical energy generation mix over a one-week period, Germany, 2016.

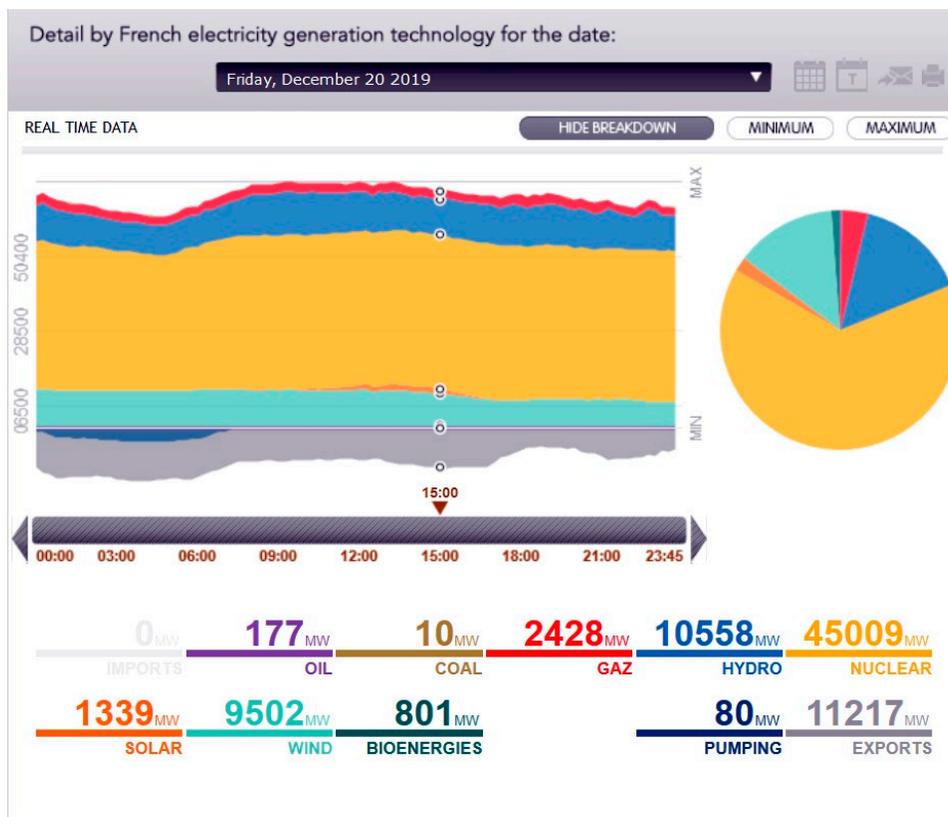


Figure 5. Electrical generation in France over a 24-hours period, January 20, 2020.

It must be noted that the renewable sources of energy are characterized by the use of a large labor supply providing job opportunities in highly populated economies. Their

implementation is rapid: it takes about 2 years in the USA for the implementation and production from wind parks since they only require local regulations, whereas nuclear power stations require 5-10 years or more because they are bound by federal bureaucratic regulations.



Figure 6. Symbiotic coupling of nuclear and wind technologies views during winter and summer. The two-units 2,309 MWe Boiling Water Reactors, BWRs LaSalle nuclear power plant near Marseilles, Illinois operated by Exelon Nuclear corporation and the Grand Ridge Wind Farm operated by Invenergy LLC in the adjacent farmland near Ransom in Illinois, USA. The nuclear reactor and the wind turbines are both manufactured by the General Electric (GE) Company. The GE 1.5 MW SLE wind turbines have a hub height of 80 m and are net recipients of electrical power from the grid on a standby basis, but then become net exporters of electricity into the electrical grid under favorable wind conditions.

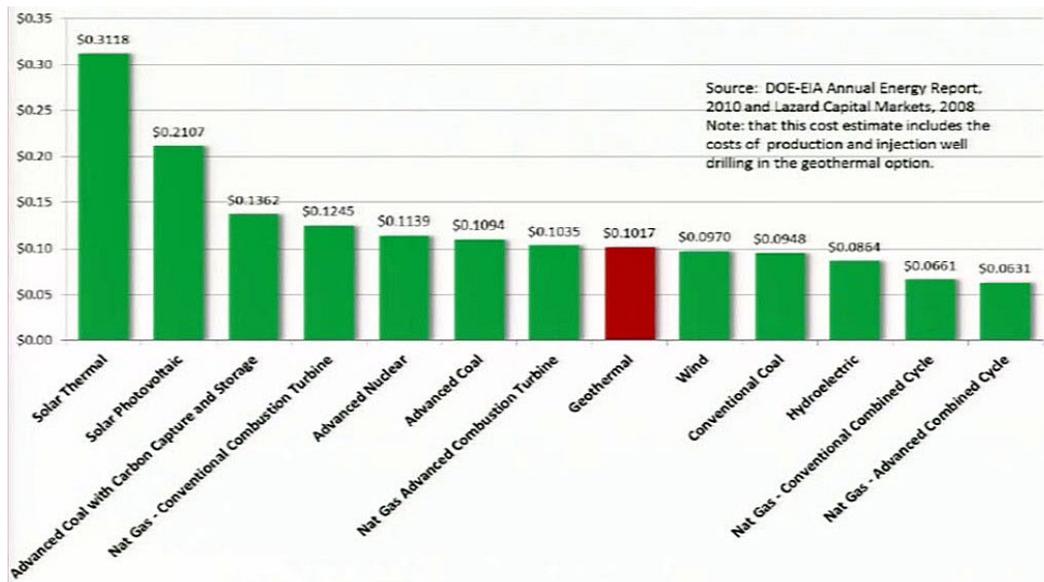


Figure 7. Total System Levelized Cost of Electricity for various methods of electricity generation. Source: DOE-EIA.

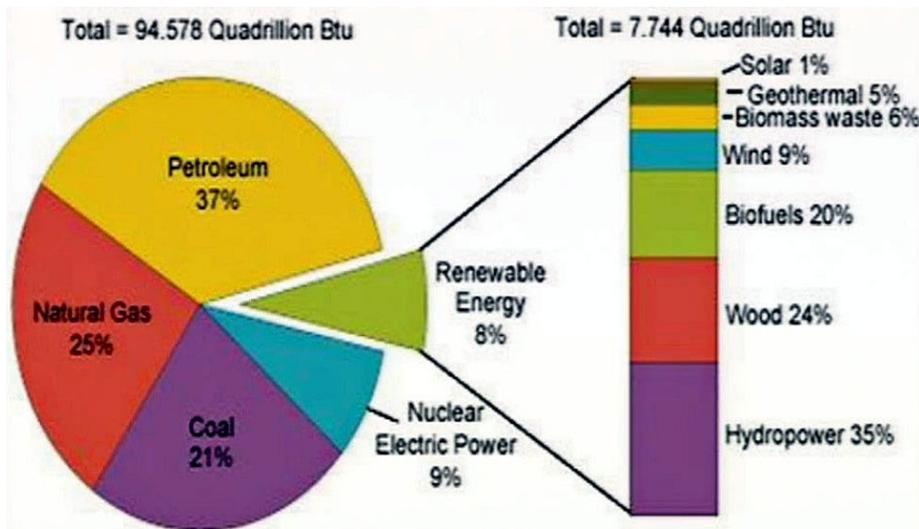


Figure 8. USA Energy consumption by energy source, 2009. Source: DOE-EIA.

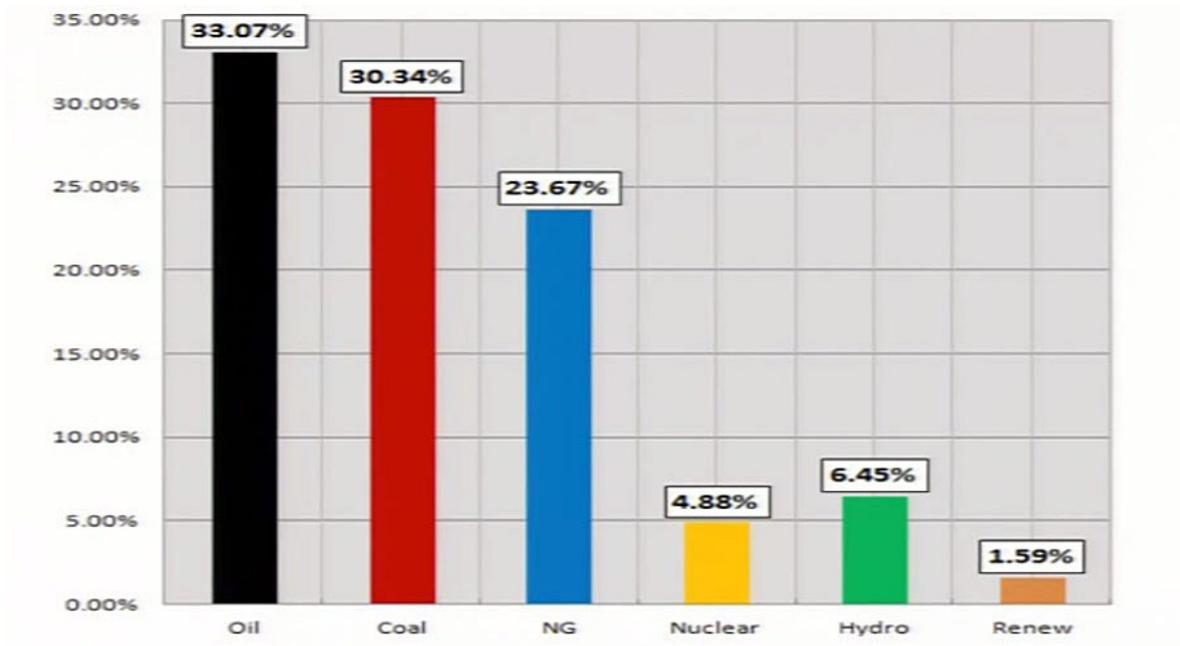


Figure 9. Global energy use according to energy source, 2011. Source: EIA.

Table 1. Cost of electricity from different energy sources, 2010.

Source	Electricity cost [¢/(kW.hr)]
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Hydroelectricity	4.6
Coal	6.6
Geothermal	6.7
Nuclear	6.7
Natural gas	6.9
Biomass	9.5
Wind	11.0
Solar	38.0

Table 2. Typical capacity factors of different energy sources, 2010.

Source	Capacity factor [percent]
Nuclear	91.1
Coal	72.2
Natural gas, combined cycle	40.7
Petroleum	9.2
Geothermal	90
Hydroelectric	37.2
Onshore wind	20-40
Offshore wind	40
Biomass	90
Photovoltaic solar	12-19
Thermal solar	15

Table 3. Sources of electricity supplied over 12 months by September 30, 2016 by the electric utility Ameren Illinois.

Source	[percent]
Biomass	0
Coal	48
Hydroelectric	1
Natural gas	23
Nuclear	16
Oil	4
Solar	0
Wind	7
Other sources	1
Total	100

The USA's goal for wind power production is from presently 2 percent up to 20 percent of electrical energy production by 2030. To accomplish this goal, the USA would need to add 1,700 Gigawatts (1 Gigawatt, GW = 1,000 Megawatts, MW) of wind power installed rated capacity per year.

The states of Iowa and South Dakota lead the nation in reaching the 20 percent goal of electrical generation by wind power in 2011. The investor-owned electrical utility Xcel Energy in Colorado through its subsidiary Public Service Company of Colorado reached on October 6, 2011, the milestone of 55.6 percent of its electricity coming from wind power.

Wind turbines prices decreased by 33 percent between 2008 and 2010. Global competition between European and Chinese manufacturers led to the drop. This is supplemented by more efficient USA manufacturing that saves on the transportation and shipping costs. Technology improvements are producing better and more efficient turbines.

The state of California established a new Renewable Energy Standard (RES) of 33 percent by 2020. This ambitious RES includes near-term and incremental targets of 20 percent by the end of 2013 and 25 percent by the end of 2016.

The USA Department of Energy (DOE) and the Department of the Interior unveiled a coordinated strategic plan to pursue the deployment of 10 GigaWatts (GWs) of offshore wind capacity by 2020 and 54 GWs by 2030. A high priority "Wind Energy Areas" program off the coasts of New Jersey, Delaware, Maryland and Virginia is established. The Cape Wind's offshore farm project was approved. A commitment of \$43 million over five years was made for technical innovations, to drive down costs, and to reduce market barriers such as supply chain development, transmission and infrastructure. A new consumer label, "Windmade" was launched for products with at least a 25 percent proportion of wind power used in their manufacturing. Fifteen companies such as Motorola Mobility, Deutsche Bank and Bloomberg have committed to obtaining the new label.

About 50 power plants totaling 7,000 MWe of capacity unexpectedly went offline in Texas due to unusually cold weather early in 2011. Wind power was available to help stabilize the system and played a critical role in limiting the severity of the blackout, providing enough electricity to keep the power on for about three million typical households. ERCOT, the Texas grid operator, confirmed that wind energy was providing between 3,500 and 4,000 MWe of electricity; about 7 percent of ERCOT demand at that time during a critical 2 hours window when the grid needed power the most.

In early 2014, the USA was subject to a cold wave, designated as a "Polar Vortex," that froze the piles of coal at coal power plants, and gas turbine and diesel fuel plants could not be started. What saved the nation from blackouts was its installed wind and nuclear capacities.

On October 3, 2008 a small wind tax credit was signed into law in the USA. It involves a 30 percent tax credit of up to \$4,000 per property, off the installed cost of a small wind turbine system.

The Renewable Energy Alternative Production Act (S. 1094) would provide a Production Tax Credit (PTC) for nonelectric renewable energy production for the first 10 years period of operation for a design lifetime of 20 years as a current PTC for wind and other renewable electrical generation systems. A four years extension was introduced in Congress as H. R. 3307, the "American Renewable Energy Production Tax Credit Extension Act." It was renewed to the end of 2013 unless extended.

Industrial companies that are active in wind power generation in the USA are General Electric (GE) Energy, Siemens Power Generation from Germany, Vestas Wind Systems from Denmark, Clipper Turbine Works from the UK, Suzlon Energy from India and Gamesa Corporation from Spain.

It is estimated that the USA could realistically have 300 GW of wind rated installed capacity by 2030 at an electrical generation cost of 6-8.5 cents / kW.hr, including the cost of transmission to access existing power lines. The cost of integrating the variable wind power into the USA power grid would be under 0.5 cents per kW.hr.

For comparison, concentrated solar thermal power, also known as Concentrated Solar Power, or CSP would provide electrical power at 14 to 15 cents per kW.hr.

It must be noted that wind turbines provide energy with an average intermittency factor of 20-40 percent. Fossil and nuclear power plants have a capacity factor that averages 90 percent. At an intermittency factor of 1/3 for wind power and a capacity factor of unity for fossil or nuclear power, this suggests that it takes 300 GW of wind rated capacity to deliver as much electricity as about 100 GWe of fossil or nuclear installed capacity, and implies the need for developing energy storage and backup options for the successful implementation of wind energy for the long term.

A symbiotic relationship could be contemplated between wind power production for peak power production and nuclear power for base production as a replacement to depleting fossil fuel supplies and reducing greenhouse gas emissions. A visionary approach for remote and arid locations wind power can be stored as compressed air to be used to increase the efficiency of open cycle gas cooled fission reactors using the thorium fuel cycle and molten salts that would not require water cooling.

The state of Illinois would contribute more than 10,000 MW (10 GW) of wind power rated installed capacity. As of December 2006, Illinois wind projects had just a 107 MW rated installed capacity.

Germany was the world leader in wind power production with 16,629 MW of rated installed capacity as of 2004. Spain was second with 8,263 MW of rated installed wind energy capacity, the USA is third with 6,740 MW and Denmark, which gets 20 percent of its electricity from the wind, was in fourth place with 3,117 MW of installed capacity. The European Union planned to increase its use of renewable energy sources to 21 percent by 2010, with much of it from wind power.

By the summer of 2008, the USA wind industry moved past the 20,000-megawatt (MW) installed rated capacity milestone. It passed Germany to become the world leader in wind generation. By the end of September 2008, the USA had over 21,000 MW of installed rated wind capacity.

However, in 2010 and 2011, China (62,363 MW) has become the leader, ahead of the USA (46,919 MW), Germany (29,060) and Spain (21,674 MW) in terms of installed rated wind capacity.

In the USA, the top five states in wind power development are: California with 2,096 MW installed rated capacity; Texas with 1,293 MW of installed rated capacity; Iowa with 632 MW installed rated capacity; Minnesota with 615 MW installed rated capacity; and Wyoming with 285 MW installed rated capacity. Vermont has one commercial 6 MW operating wind farm.

The chapters in this work are mostly self-contained and can be read in the order that the reader wishes. The work is still in progress and is evolving and is frequently being updated; or in the parlance of the World Wide Web, it is continually “under construction.” In fact, it is an ongoing effort that started sprouting and taking the present form on November 25, 2005. It has evolved as the basis of the reviewed and approved course: Wind Power Systems, NPRE 475, at the University of Illinois at Urbana-Champaign.

The hope is that this modest effort will contribute to the scientific literacy of the readers in the Wind Power Systems area of knowledge, and satisfy their intellectual curiosity about its potential contribution to the future of energy science and technology.

According to Thomas Carr:

“The word ‘energy’ incidentally equates with the Greek word for ‘challenge.’ I think there is much to learn in thinking of our federal energy problem in that light. Further, it is important for us to think of energy in terms of a gift of life.”

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