POWER PLANT DESIGN

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Keywords: Thermal power plants, fossil fuels, steam turbine, gas turbine, cogeneration, steam generation, clean technologies, real and ideal efficiencies, heat engines, electricity generation.

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Summary

Like water and air, energy is another of the most basic needs of all humans, and is an indispensable element of any sustainable human development. Lack of energy resources is shown to be directly correlated with poverty, disease, illiteracy, and conflict. Today, roughly 1.6 billion people, or one of every four persons – all in developing countries and primarily in rural areas of South Asia and Sub-Saharan Africa — still have no access to electricity. Another 2.4 billion people rely on traditional biomass, mainly wood, agricultural residues, and even dung, for cooking and heating. To reduce hunger, ensure social stability, and promote sustainable living, it is paramount to alleviate poverty and increase economic standing; neither can be accomplished without adequate access to energy.

While, in the past two decades, electricity has been provided to many for the first time, it has, by no means, kept up with increases in population and higher per capita consumption. According to data released by the Energy Information Administration (EIA), world electricity demand will increase by 87 percent, from 18.8 trillion kilowatt-hours in 2007 to 25.0 trillion kilowatt-hours in 2020, and 35.3 trillion kilowatt-hours by 2035. This, in light of the rapidly aging electricity infrastructure, will pose challenges and also offer opportunities that must be addressed in the very near future. While today a relatively small number of power plants — owned and operated by utilities or their subsidiaries — generate all the electricity, the trend is toward decentralized schemes where electricity is generated by numerous power plants using a mix of technologies that include both traditional and renewable fuel sources.

In what follows pages, we address the main issues associated with electricity generation, give a technical overview of thermal power plant technologies (fossil fuel, nuclear, geothermal, and solar thermal), and compare them with non-thermal plants, in particular wind, photovoltaics, hydro, and ocean waves and currents.

1. Electricity Generation

1.1. Status: Generating Capacity

The current and future world electrical generating capacity is shown in Table 1. A total of 4,428 Gigawatt of electric power was available in 2007 – 40 percent higher than that of only a decade earlier The recent downturn in economical activities and the continued worldwide recession of the last few years have slowed the rate of growth; numbers are expected to rise again, climbing to over 7,000 GW by 2035, with the bulk of growth in non-OECD countries, mainly China, India, and Brazil. U.S. generating capacity is expected to increase by only a modest 0.7 percent.

Type	**Source of Power**	**2007**	**2035 (Projected)**	**Average annual % growth**
Thermal (75.5%) Steam Turbine Power Plant (66%)Gas Turbine Power Plant (7%) Direct Diesel Power Plant (2%)	Coal	1,425	2,366	1.8
	Gas	1,103	1,545	1.2
	Oil	436	346	-0.8
	Nuclear	380	593	1.6
Hydro Power Plant (18.5%)	Hydro (including Pumped storage)	822	1,414	2.0
Renewable (3%)	Wind	93	486	6.1
	Geothermal	9	22	3.2
	Solar	8	64	7.9
	Biomass,	44	107	3.2
	tidal/wave,	116	215	2.2
	waste, ocean			
	Others			
	Total	**4,428 GW**	**7,009 GW**	**1.7**

Table 1. World Installed Electrical Generation Capacity (GW) By Type

Coal will be the source of fuel for much of this expansion, from 132 EJ in 2007 to 206 EJ in 2035, with non-OECD countries accounting for 95 percent of this increase. Coal is the most common fuel for generating electricity in the United States, accounting for 45 percent of its nearly 4 trillion kilowatt-hours of electricity in 2009.

Liquid fuel consumption will remain relatively flat or may even decline as a source of fuel for electricity generation, as it is substituted with unconventional resources, such as oil sands, shale oil, biodiesel, and synthetic oil. Natural gas will remain an important part of the overall energy mix to produce electricity, although its share in providing electricity decreases somewhat from 25 percent in 2007 to 22 percent in 2035 (Figure 1).

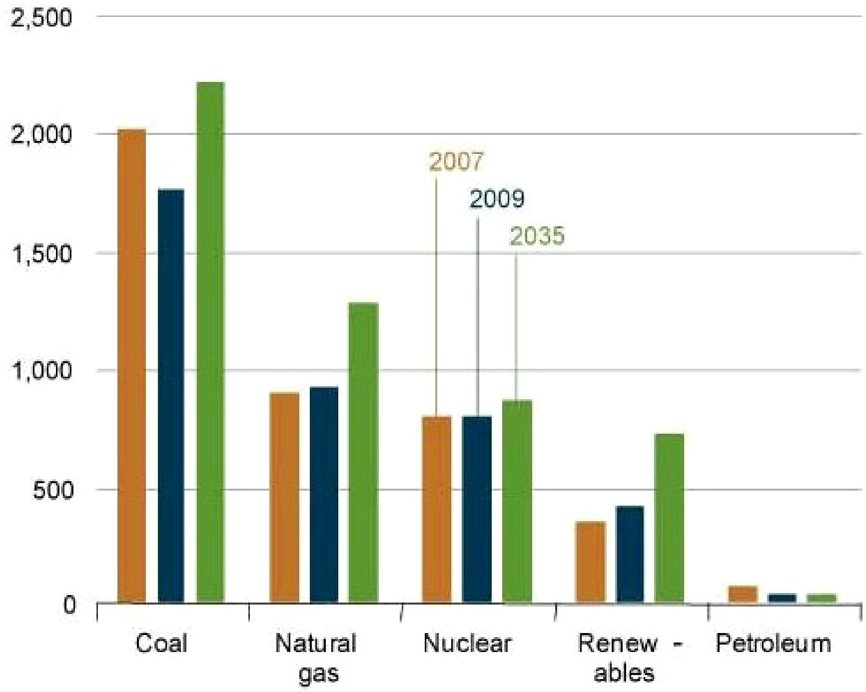

Figure 1. U.S. electricity generation (billion kWh) by fuel, 2007-2035.
Source: U.S. Energy Information Administration, State Electricity Profiles 2009, April 2011.

The fate of nuclear fission in providing a large portion of electricity is rather uncertain, and may be forced to slow its expansion. Lack of progress in finding suitable sites for disposal of radioactive waste, rising construction costs, issues associated with transport of nuclear fuel, proliferation, and safety are all impediments to large acceptance of nuclear power. The recent nuclear accident in Fukushima, once again, has flamed debate on the suitability of nuclear energy and forced many governments to reevaluate their nuclear programs.

Germany is the first country that formally announced freezing construction of new nuclear plants, and the dismantling of all nuclear reactors by 2022. Switzerland is taking similar steps to become nuclear free by 2034. Other European countries are reevaluating their nuclear policies, but are expected to phase out a large fraction of their power plants by 2050.

The fastest growth in electrical generation capacity, however, comes from renewable sources. The overall capacity still remains small, satisfying only 13 percent of the total demand. Wind and hydroelectricity will account for 80 percent of all renewable output. Solar, geothermal, biomass, waste, and tidal/wave/oceanic energy are not currently competitive, but rapid changes in technologies are expected to lower costs and help accelerate their production. China leads the world in total renewable energy consumption for electricity production because of its recent massive additions to hydroelectric production. China is followed closely by the United States, Brazil, and Canada.

1.2. Basic Elements of an Electricity Generation Plant

The procedure for generation of electricity is rather simple. A fluid such as steam, a gas, water, a refrigerant, or any other substance spins a turbine that is connected to a generator that produces electricity. The propulsive force could come from kinetic energy of the wind, current in a river or stream, the potential energy of falling water, temperature and salinity gradients in oceans, lakes and ponds, or heat released by uranium fission or burning of woods, biomass, coal, oil, natural gas, or even Earth’s geothermal resources. No matter which approach is used, there must always be a potential difference that supplies the work to run the turbine-generator.

1.3. Electricity from Wind

Like any other renewable energy source, the main concern regarding wind energy is that it is not predictable and may vary from one hour to another, or from one day to the next. Factors affecting utility of wind energy are location, type of storage system, height of the tower, and size and geometry of the rotor. When wind energy is used for electricity generation, it is best that turbines are placed in proximity to national grids, as high as economically possible and away from buildings, trees, and other obstacles. The proper selection of gearboxes and power conditioning systems assures that electricity meets the voltage and frequency requirements set by the grids.

In theory, wind turbines need only one blade to operate, although double-bladed and triple-bladed models work better. The choice depends on application, economics and the power output of the generator. Two-bladed props have higher aerodynamic efficiencies, but work only for smaller turbines; bigger turbines require higher starting torques and, therefore, three-bladed props are generally preferred. There are two kinds of wind turbines: drag types and lift types.

Drag types operate by the force of wind pushing the blades, much like a paddle that propels a canoe through the water. The tip of the rotor can never move faster than the wind, so tip-speed ratio is always smaller than 1. *Lift types* use aerodynamically shaped rotor blades. The top surface is more curved than the bottom surface, so air over the top surface passes more rapidly and the pressure drops. The difference in pressure between the top and bottom surfaces creates a lift that forces the rotor to spin. Blades move many times faster than the wind; torque is much smaller, however. Modern high-speed turbines commonly used for generating electricity are of lift types.

The energy delivered by a wind turbine is proportional to the change in kinetic energy of the mass of air that is sweeping (ingested) through its rotor. The mass flow rate increases with air density, size of the rotor, and the speed of the wind. Since kinetic energy is proportional to the mass and the square of velocity, it turns out that the total power generated by a wind turbine (P) must increase with the air density (ρ), the square of rotor diameter (d), and the cube of the wind velocity (V).

$$P = \frac{\pi}{8}\rho d^2 V^3 . \tag{1}$$

Not all the wind will pass through the blades and some will spill around the blades, and so, only a maximum of 59.3 percent of the kinetic energy of the air can be theoretically recovered (Betz Limit). The degree of slippage is not constant, however, and varies by the shape of the blades and speed at which they turn. So, it is customary that turbine performance is characterized by its power coefficient (C_P) or turbine efficiency, defined as the fraction of the wind energy in the air that is being extracted by the turbine

$$C_\mathrm{P} = \frac{P}{(1/2)\rho A_\mathrm{t} \bar{V}_1^3} \quad . \tag{2}$$

When tip-speed ratio is small, some air crosses the rotor without encountering the blades, so some air passes through without losing some of its momentum to the blades; therefore, turbine efficiency is low. For very high tip-speed ratios (low wind speed or fast rotational speed), turbine resistance prevents all air from going through, forcing some to slip and go around the rotor, again decreasing the efficiency.

The optimum efficiency occurs at intermediate tip speeds. For a given rotational speed, the wind velocity that gives the optimum tip-speed ratio is called rated velocity, and power generated at this velocity is called the rated power.

Figure 2 shows a plot of C_p versus tip-speed ratios for several types of airfoils. Vertical-axis wind turbines (VAWT) and drag-type turbines (Savonius, American Multi-Blade) have small tip-speed ratios, indicating that the blades cannot move faster than the wind that is pushing on them. Since the power coefficient drops significantly at tip-speed ratios moving away from its optimal value, it is best to allow the rotor speed to vary.

Horizontal-axis wind turbines (HAWT) and airfoil (lift) type turbines, such as Darrieus, and propeller types have much higher tip-speed ratios and are generally more efficient. The overall efficiency is generally lower because of losses in the prop itself and the generator.

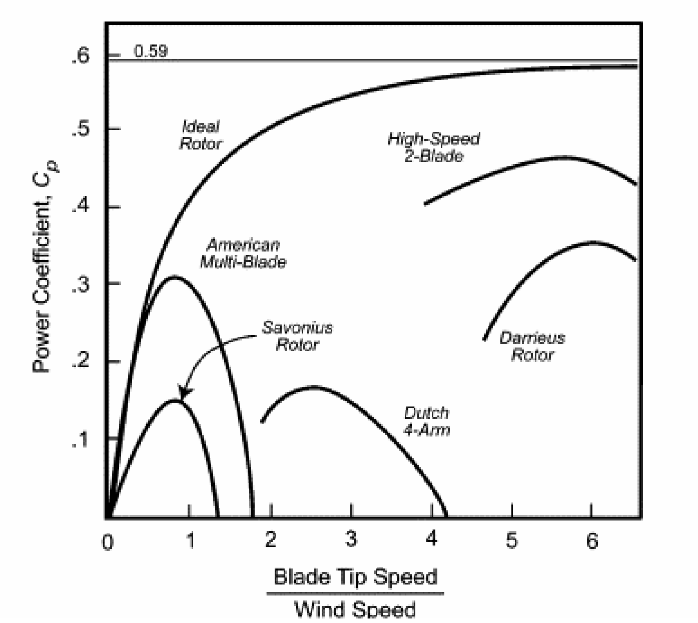

Figure 2. Power coefficients vs. tip speed ratios (tsr) for several wind turbines

The total installed wind-generated electricity was 93 GW in 2007, grew to 158 GW in 2009, to 272 GW in 2010, and is expected to double every three years. Currently, Germany is the world leader in total installed wind capacity; Britain is the leader in terms of offshore wind farms; and China holds the title of the world's largest maker of wind turbines. Other European countries, such as Denmark and Spain, are rapidly moving ahead to make wind energy a major component of their overall energy strategy. For example, wind energy is meeting 20 percent of Denmark's electricity demand, with peaks of more than 100 percent, selling the surplus to neighboring countries. The corresponding numbers for Spain are 14 percent and 50 percent. In the United States, wind energy is growing at a respectable pace, up 15 percent in the past year, with a long-term target of providing 20 percent of American electricity by 2030.

1.4. Hydro Power Plants

Hydro resources have the potential to produce 1-2 terawatts of electricity, sufficient to cover the energy demands of the world. Tapping into most of this potential is, however, not yet economically feasible. Hydro energy comes in a variety of forms, including potential energy of the water stored behind a dam, the kinetic energy of riverstreams and underwater currents, and energy locked in the tidal gravitational energy of the earth-moon-sun system.

Seawater contains enough deuterium (the main component in any fusion processes) to supply a virtually unlimited amount of energy. The latter is not expected to be technically feasible for many decades, and so is not considered a part of the energy solution at the current time.

Traditional hydroelectricity comes from the gravitational force of large waterfalls. The capacity to produce power is a function of both the flow rate and the height from which it falls. It reached 860 GW in 2006 and provided approximately 20 percent of the world's electricity and 88 percent of the electricity from renewable sources. The largest hydroelectric plant in the world is the Three Gorges in China, followed by Itaipu in Brazil, Guri in Venezuela, and Grand Coulee in the United States (See Table 2).

Rank	**Plant**	**Location**	**Max. Head (m)**	**Flow rate (m^3/s)**	**Power (MW)**	**Annual electricity generation (TWh)**
1	Three Gorges	China	185	12,000	18,300	100
2	Itaipu	Brazil-Paraguay	127	6,200	12,600	95
3	Guri	Venezuela	146	5,000	10,200	46
4	Grand Coulee	USA	108	3,100	6,800	22

Table 2. Ranking of the Largest Hydroelectric Power Stations in the World.

Tidal power generation is finding some niche markets in Canada and several European countries bordering the Atlantic Coast. The approach involves construction of a dam or barrage across an estuary (tidal lagoon), guarded by gates that allow the basin to fill during flood tides, and empty during ebb tides, producing electricity in both instances. Power generation is proportional to the amount of water discharged through the sluices; i.e., it is proportional to the surface area of the lagoon and the amplitude of the tidal swell (range).

The world’s largest tidal plant was constructed 45 years ago in Rance Estuary, in France, and produces 240 MW of electric power. Russia has the largest potential to exploit tidal power – over 1,670 billion kilowatt-hours annually. Canada and Argentina also are good candidates, but it is the United Kingdom that plans to build the largest power plant — a 10-mile-long barrage (dam) across the Bristol Channel in Severn Estuary. Once built, the Severn Tidal Plant would have the capacity to produce 8 GW of peak power (2 GW on average), producing in excess of 17 billion kWh of electricity, and at the same time, reducing carbon dioxide emissions by 16 million tons every year.

Another form of extracting power from water is through *ocean waves*. The maximum power a wave can carry over deep waters is about 100 kW per meter of wave front in the high seas, 30-60 kW/m off the Atlantic Coast of Europe, and 20-30 kW/m off the West Coast of the United States. As a wave approaches coastlines and enters shallow waters, up to 70 percent of the energy is lost by friction to the ocean floors and power is reduced to about 10-20 kW/m.

Many devices have been designed to extract power from the waves. Some, like the Oscillating Water Column and LIMPET, exploit the oscillatory motion of the waves and tides to compress air through a turbine. Others, such as Salter’s Duck the Archimedes

Wave Swing and Pelamis Wave Energy Converters, use the difference in pressure as a wave passes over these devices to swing a pendulum back and forth and generate electricity. Still others use the kinetic energy of currents to drive underwater turbines, much like air that passes through wind turbines. Although these devices eventually can play a role as part of the energy mix, they are currently at the demonstration stage of development and some time away from full-scale deployment.

1.5. Solar Photovoltaic

The solar photovoltaics (PV) industry has seen a remarkable growth in the last few years, reaching a cumulative installed capacity of roughly 40 GW and producing some 50 terawatt-hours (TWh) of electrical power every year; sales are expected to continue to grow at a rate of 60-80 percent per year for the foreseeable future. Europe is leading the way with 75 percent of the PV market; Japan and the U.S., with nine and six percent of the market, are some distance behind. China is expected to become a major player in the coming years.

The principal of operation is simple. When light photons of sufficient energy strike the p-n junction of a solar cell, they knock electrons out, forcing them through an external circuit before returning them to the other side of the solar cell to start the process all over again. Only photons of energy equal or greater than the band gap of the solar material can be used.

Today’s solar cells (single junction) are most efficient at around the red wavelength of the solar spectrum. Multi-junction cells consisting of a stack of individual single-junction cells are being developed that respond to a wide range of wavelengths. The top cell captures the high-energy photons and passes the rest of the photons on to be absorbed by lower-band-gap cells. Efficiencies as high as 41 percent have been reached under concentrated light conditions.

There are three basic types of solar cells. *Monocrystalline cells* are cut from an ingot grown from a single, large crystal of silicon, while *polycrystalline cells* use an ingot made up of many smaller crystals. Unlike monocrystalline and polycrystalline cells, *amorphous cells* lack a crystalline structure, and are fabricated by vapor-depositing silane gas directly onto a glass substrate.

Since only a small amount of raw silicon is required, amorphous cells are cheaper to produce, and, thus, have found a wide range of applications, such as calculators, call boxes, and traffic signals. Some of the advantages of their lower costs, however, are offset by their lower power density, and the additional space they require. Thin-film solar cells are becoming more widespread since they use only micrometers-thick layers of amorphous silicon, attached to a backing of glass, flexible plastic, or stainless steel. Microcells are tiny silicon cells that are much smaller in size and thickness than conventional solar cells. Because of their size, they can be built to be highly flexible. These cells could be manufactured in rolls, be placed on a substrate, or sprayed onto surfaces. Efficiencies in the range of 5 percent for amorphous silicon cells and 17 percent for monocrystalline cells are typical for commercially available silicon solar cells.

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Biographical Sketch

Reza Toossi is a professor of mechanical and aerospace engineering at California State University in Long Beach (CSULB). He received his B.S. degree from the Sharif University of Technology in Tehran, Iran, and his M.S. and Ph.D. degrees from the University of California, Berkeley. He continued his Post-Doctoral research studies in the Lawrence Berkeley Laboratory and joined the CSULB faculty in 1981. Dr. Toossi has worked both as a research scientist and a consultant on various projects related to aqueous aerosols and droplets in the atmosphere, nuclear safety, sensor design, combustion-generated soot emission, air pollution modeling, flame propagation, and fiber optics. He has successfully managed over $10 M in research contracts from various private and Government agencies, holds two patents and has published two books on energy and over 50 scholarly articles in various peer-reviewed and refereed journals. His current research interests are in hydrogen storage, sorption refrigeration, hybrid-electric vehicle design, and renewable energy systems. Dr. Toossi is a member of ASME, ASEE, SAE, SPIE, AAPT, and Tau Beta Pi, and the recipient of the 2001 CSULB Distinguished Faculty Teaching, 1995 CSULB Distinguished Faculty Scholarly and Creative Achievement, and 1994/1995 TRW Excellence in Teaching awards. He also serves as the co-chair of CSULB Sustainability Task Force.