RENEWABLE ENERGY SYSTEMS

Lecture Notes

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1. Introduction

Energy is the most important problem of the world, because of two reasons: First; the sources are limited. Considering the relationship between the standard of living and the energy usage, the situation is being worse year by year. Secondly; the processes to convert the fossil fuels are deeply hazardous for the environment.

Fortunately, the energy flows that occur naturally and repeatedly in the environment can be harnessed for human benefit. The ultimate sources of most of this energy are the sun, gravity and earth's rotation.

In renewable energy literature, the words ”alternative” and “sustainable” are being used to emphasize the possibility of using sources other than the fossil ones which will finish never. Whatever they are called, “renewable”, “alternative” and “sustainable”, these energy systems are planned as the parts of the solution to the energy problem by substituting the fossil sources with the replenished ones.

Renewable energy is the energy obtained from the continuous or repetitive currents of energy recurring in the natural environment. To assume any energy flow as “renewable” it should be replenished at least at the same rate as it is used. A renewable energy system is an “alternative” one, if it is able to provide some or whole part of the energy needs which is met by the fossil ones. Such a system is also sustainable because the energy supply will sustain continuously, as the sun continues to shine, gravity to apply on the objects and the earth to rotate. Fossil fuels, on the other hand, like coal, petroleum and gas are the conventional ones having no sustainability. Nuclear energy is another alternative to the sustainable usage but it is out of scope of this lecture, for its being a controversial issue for more than a generation.

Table 1.1 includes a summary of the energy sources. As it is seen in this table, an alternative and renewable source is always sustainable while a conventional source, even if it is renewable cannot be assumed as sustainable. Hydroelectricity, classical biomass and wood for example are used to be through the ages. However, no one can guarantee that the river will have the necessary head continuously, the animals and the forests which are the sources of the classical biomass and the wood will live forever.

Table 1.1. Classification of the energy sources (excluding nuclear energy).

	PRIMARY FOSSIL SOURCES	PRIMARY RENEWABLE SOURCES	SECONDARY FOSSIL BASED SOURCES	SECONDARY RENEWABLE BASED SOURCES
Conventional	Coal Petroleum Gas	Hydroelectricity Classical Biomass Wood	Electricity from coal or gas. Petroleum Products Hydrogen Energy generated by thermal energy of the fossil fuels.	Electricity from renewable Hydrogen energy generated by using the renewable energy sources.
Non-conventional (alternative)		Geothermal Energy Wind Energy Direct Solar Energy Indirect Solar Energy Sea-Wave Energy Ocean Thermal Gradients Energy Modern Biomass Energy Energy Cropping Energy Forest Tidal Energy		

2. A Basic Approach to "Sustainability"

There are too many definitions for sustainability.

One of them is that *the ability of humanity to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs* [1].

Another definition is that *sustainability is the preservation of the productive capacity for the foreseeable future* [2].

For the biophysical aspect sustainability *means maintaining or improving the integrity of the life support system of the earth* [3].

Based on these definitions, it is obvious that conventional-renewable energy systems or applications are not sustainable. Especially for hydroelectricity, the third definition including the *integrity of the life support system* is notable.

Fig. 2.1 is explanatory in discussion of the first definition. With such a steep change in population it is not possible to sustain the future generations' needs.

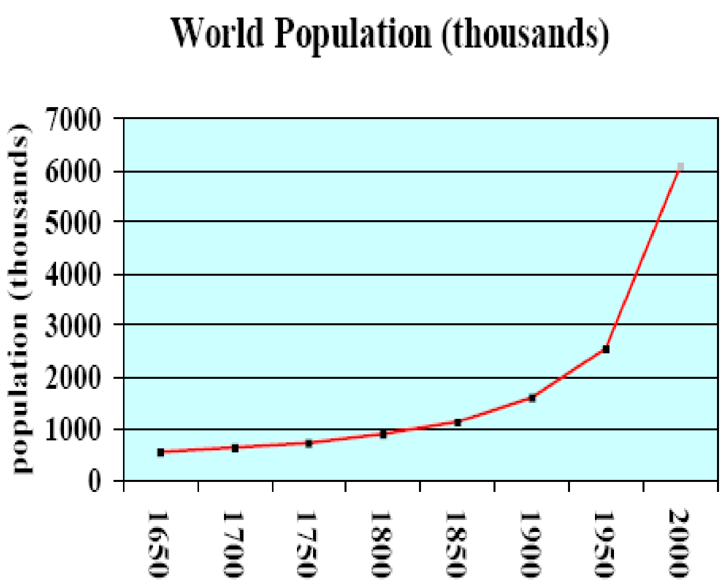


Fig. 2.1 Growth in the world population [4].

World energy consumption is rising faster than the population (Fig. 2.2) indicating that the sustainability includes elements beyond the "needs" and" supplies". For example, we might want to sustain our standard of living, health, well-being, food and water supply while population growth, unnecessary and excessive consumption, and mal-distribution of sources hinder the sustainability. The list of the things to be sustained and the events which are handicaps of the sustainability can be extended, of course.

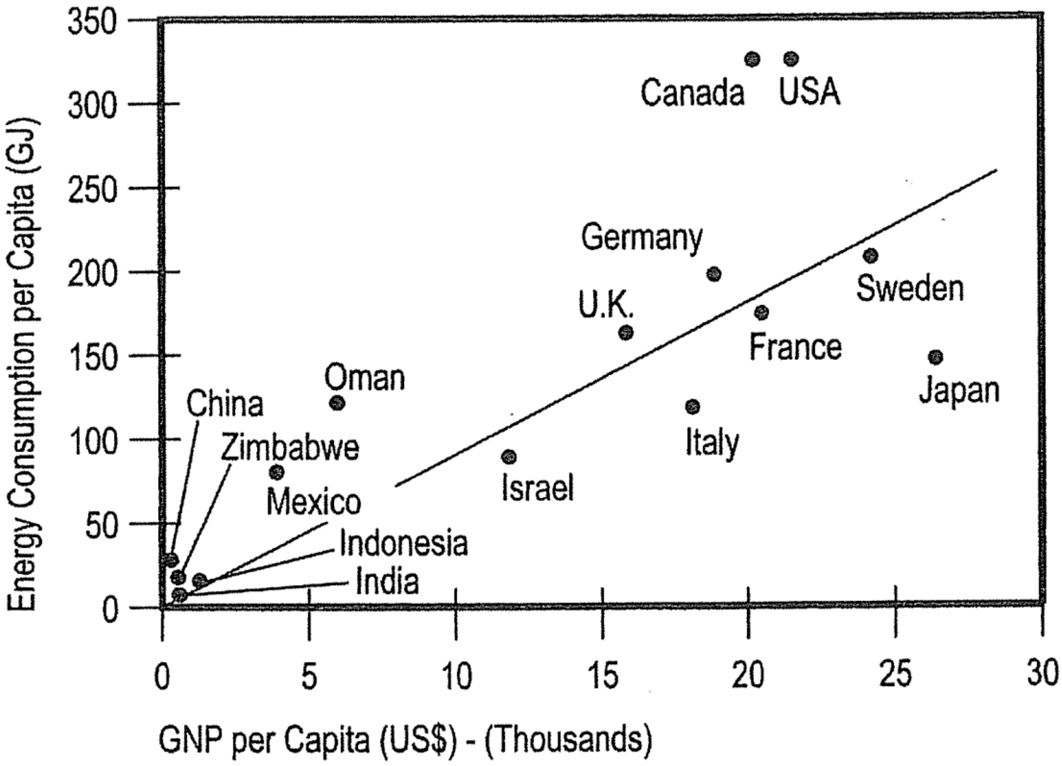


Fig. 2.2 Per capita energy consumption versus gross national product (GNP) per capita for a number of countries [5].

To be sustainable an energy conversion system must meet two conditions [6]: Endurance and cleanliness.

- Energy system must have good prospects for enduring indefinitely in terms of the type and level of energy services it provides.

- Flows of the energy systems material and energy byproducts must not exceed the ability of land, air and water to absorb and recycle them without significant negative disruption.

In fact endurance is correlated with the energy density. In Table 2.1 rough estimates for energy density are given.

Table 2.1 Energy density for the fossil fuels [6].

resource	Energy density [MJ/kg]
peat	15
wood	18
coal	20-30
natural gas	45
oil	50

The advantage of this high energy density of fossil fuels has been taken by industrialized countries. However, economic output and energy use have not been at the same rate, always. The evolution of *the ratio of the energy use to economic output is called energy intensity.* Since 1950 energy intensity has significantly declined (Fig. 2.3). In spite of this success, environmental problems of fossil fuels are still challenging. The emerging concern is the CO_2 emissions from combustion. Analysts offer three major to fossil fuels:

Energy efficiency

Nuclear Power

Renewables

Among these alternatives energy efficiency have some points which are not discussed in details. Some energy experts argue that promoting profitable energy efficiency investments will lead to higher energy use and greater environmental impacts. The following formula has greater importance form this point of the view:

E = E/GNP x GNP/POP x POP

Where E refers to energy, GNP is the gross national product and POP is the population.

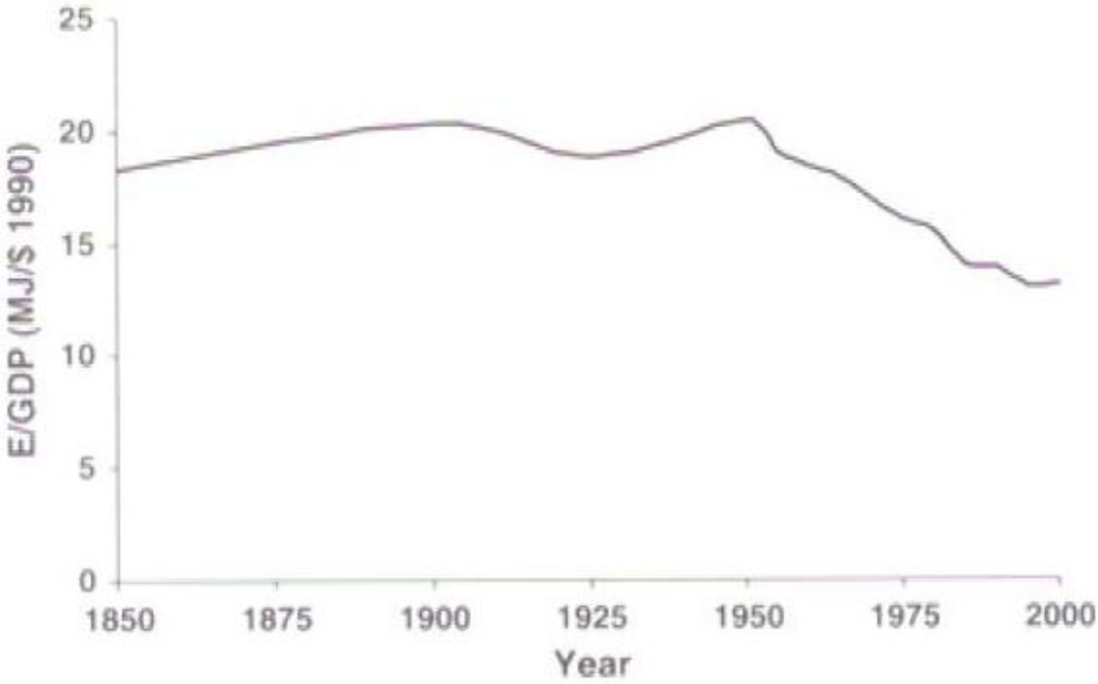


Fig. 2.3 History of the energy density (GDP refers to Gross Domestic Product) [6]

Renewable forms of energy , on the other hand are enduring and emission free, but their wide scale development must overcome low energy density (Table 2.2), intermittency and inconvenient location. These constraints can be costly and even cause significant environmental impacts.

Table 2.2 Predictions for the energy density [6].

	Unit	2000	2050	2100
POP	billions	6	9.5	10.5
GDP	$US tril.2000	32	80	230
GDP/POP	$US/capita	5,300	8,400	22,000
Energy(E)	EJ	429	770	1,390
Coal	EJ	100	220	650
Oil	EJ	163	160	110
Natural Gas	EJ	95	200	160
Nuclear	EJ	9	20	90
Hydropower	EJ	9	20	30
Traditional biomass	EJ	45	70	90
Modern biomass	EJ	7	50	120
Wind	EJ	0	20	90
Other Renewables	EJ	0	10	50
E/GDP	MJ/$US	13.6	9.6	6
E/POP	GJ/capita	71.4	81	132
Share fossil fuels	%	84	75	66
Annual growth E/GDP	%	-0.69		-0.93

3. Energy Situation for Turkey and Worldwide Energy Usage

For Turkey, both the dependency on external sources and the responsibility in the environmental pollution are problems to be solved immediately. The key and compound indicators for Turkey are listed in Table. 3.1.

Table 3.1 Energy balance and CO_2 emission for Turkey, in the year 2007 (compiled from www.ies.org)

Primary energy consumption (quadrillion Btu)	4.32
Primary energy production (quadrillion Btu)	1.15
Total Carbon Dioxide Emissions from the Consumption of Energy (Million Metric Tons)	271.5

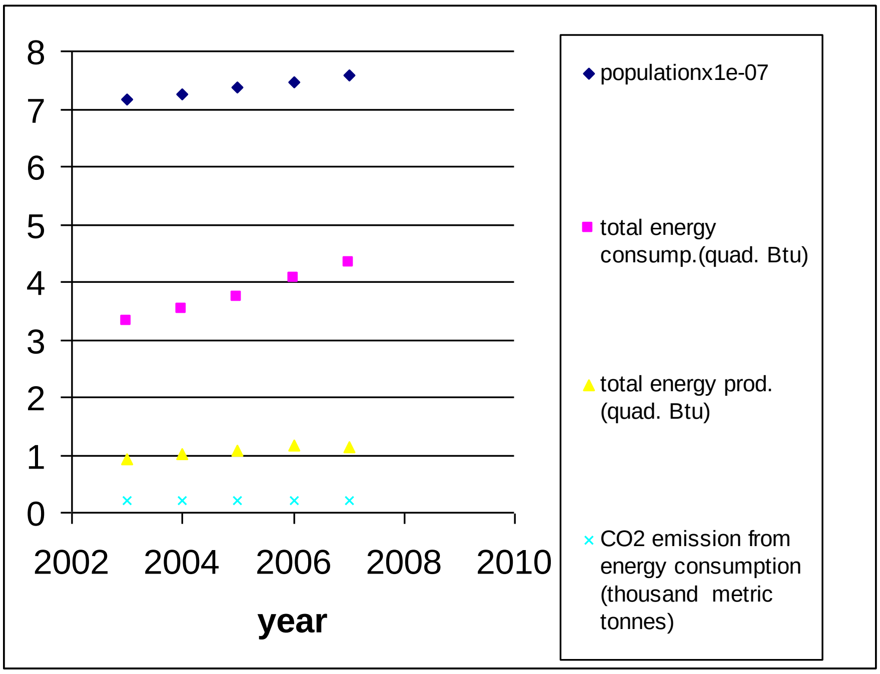


Fig. 3.1 Changes in population, energy consumption, energy production and CO_2 emission within the last years for Turkey (compiled from www.ies.org).

The slight change in energy production corresponding to the increasing one in consumption results from the lack of fossil energy sources. The majority of Turkey's electricity comes from conventional thermal (coal and gas) sources and the majority of Turkey's coal production is for electricity generation. Turkey's per GDP (gross domestic product, See the glossary) carbon emissions remain well below the regional average (Table 3.2), although emissions levels are on the rise (Fig. 3.1).

Table 3.2 Carbon Intensity using Market Exchange Rates (Metric Tons of Carbon Dioxide per Thousand Year 2005 U.S. Dollars)

Turkey	Europe	World
0.236	0.29	0.607

The increasing standard of living increases the energy consumption in our country. Total electricity consumption in 2007 is 164 TWh [4]. However, the electricity prices are very high comparing to GDP per capita (around 9,000 US dollars). The electricity prices for households and for the industry, in the year 2008 are 0.165 and 0.139 U.S. Dollars per Kilowatt hour [7]. These values are around 0.1 U.S. Dollars per Kilowatt hour for the US (where GDP per capita is around 45,000 US dollars) and 0.28 U.S. Dollars per Kilowatt hour for EU countries (where GDP per capita is around 35,000 US dollars) [7].

This situation makes the impact of the energy problem faced by Turkey, which includes too many risks for the sustainability.

On the other hand Turkey has a plenty of natural sources, especially, solar, wind and geothermal (Figs. 3.2-3.4) .

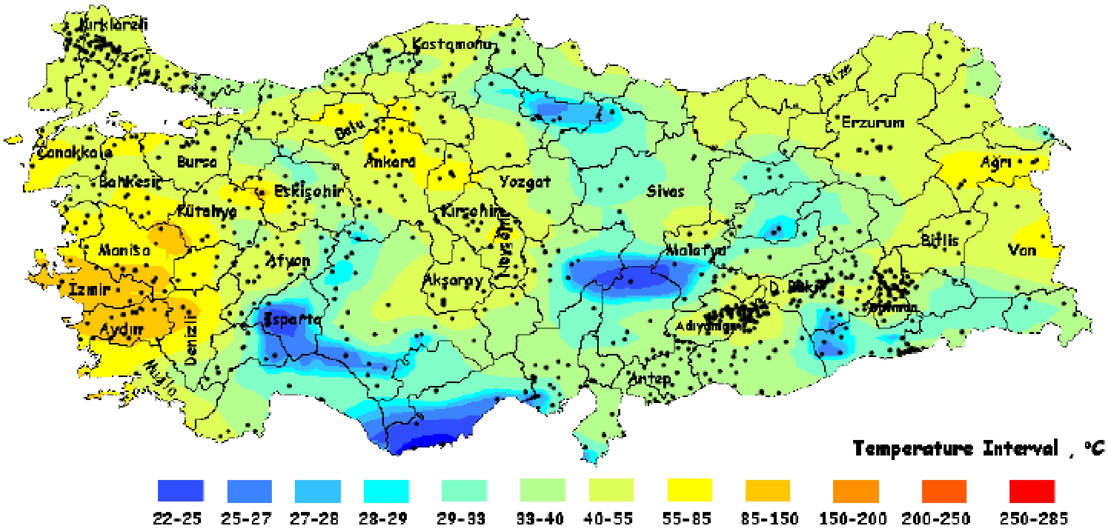


Fig. 3.2 Turkey's 1000 m depth temperature distribution map [8].

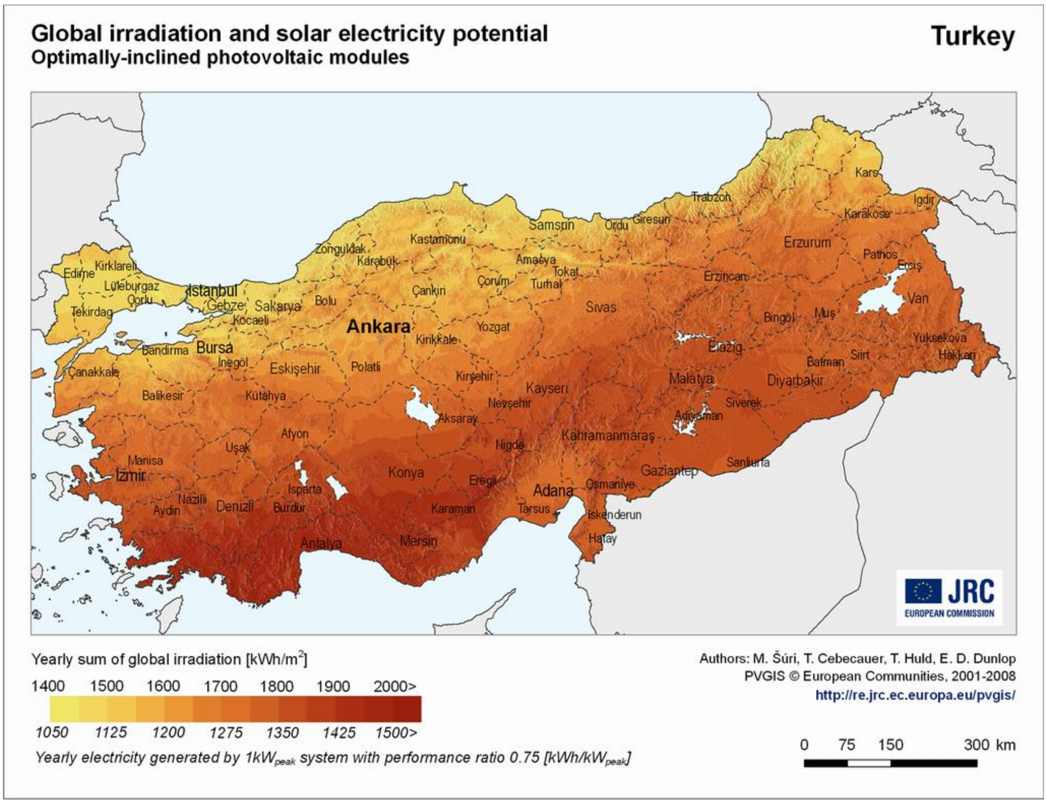
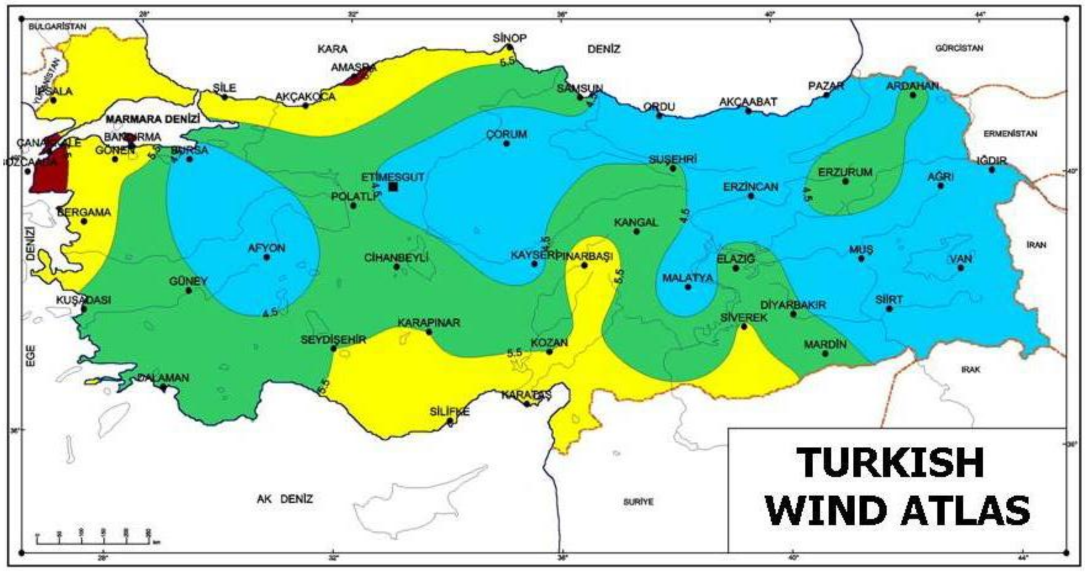


Fig. 3.3 Global irradiation and solar electricity potential for Turkey. [9]



v (m/s)	> 7.5	6.5 – 7.5	5.5 – 6.5	4.5 – 5.5	< 4.5
P (W/m²)	> 500	300 - 500	200 - 300	100 - 200	< 100

Fig. 3.4 Wind resources at 50 m above ground level for open planes in Turkey [10]

In spite of such a large potential geothermal and wind electricity net generation in Turkey are 0.148 and 0.757 Billion Kilowatt hours, respectively. [14].

The current lecture aims to address the geothermal, wind and solar source (photovoltaic only) usages which may partly be solutions to Turkey's energy problem. Because of increased interest in fuel cells, hydrogen energy as a secondary energy source and combustion applications have also been included at an introductory level.

Despite many people in engineering and political communities are interested in all "renewable energy" concerns, the scope of this lecture is mostly the "engineering" side of the procedures and systems. The person who passes this class should be able to design the system illustrated in Fig. 3.5, for example. Here, the solar energy is repetitive; the waste energy (municipal waste or organic wastes) is replenished almost at the same rate as it is used. The conversions can performed via the Collectors, both flat and concentrated, Absorbers, Fuel Cells, Gas Turbines, Photovoltaic, Chillers, and Internal Combustion Engines, so on. The engineer should know every basic law and applicable assumptions in all these conversions.

At this point, the following questions rise, and of course they cannot be answered only from the engineering point of the view:

1-If we have to change our energy technologies within a very short time period what would be the best alternatives?

2-How should we invest to develop better alternatives?

3-What are the drivers that will encourage these alternatives?

4-Do we also change our behaviors?

Then, the further readings and social analyses will be necessary to consider the global situation (Fig. 3.6).

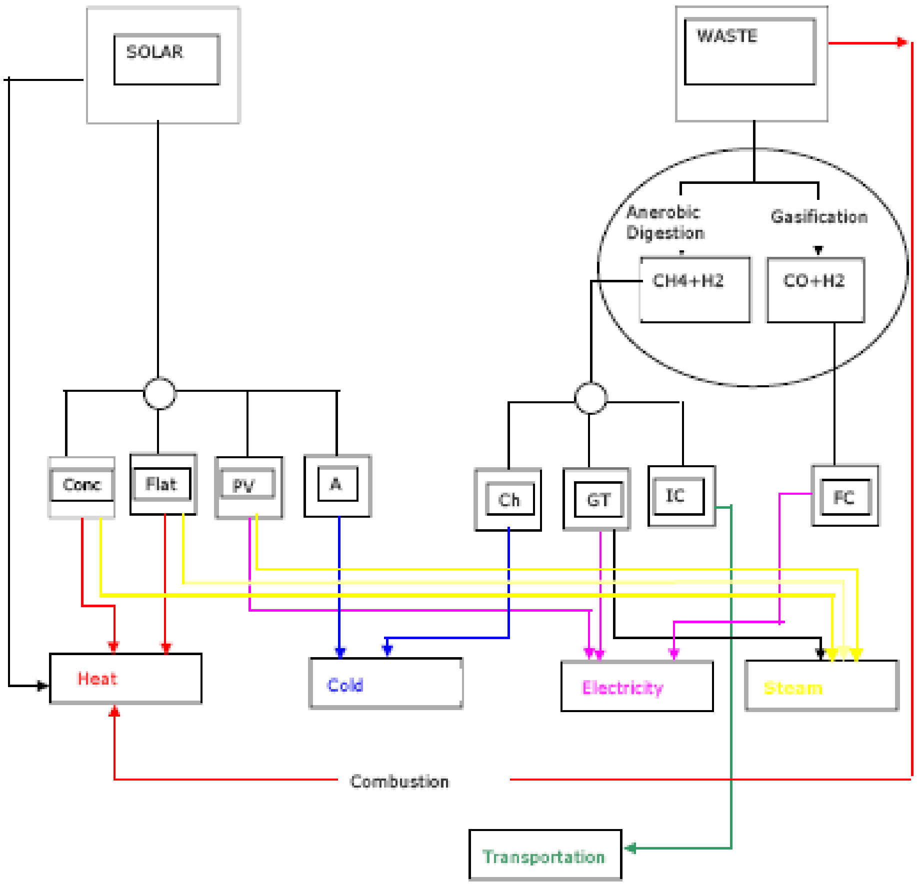


Fig. 3.5 Sample system: Utilization of solar and waste energy to meet the heat cold, steam, electricity and transportation needs.

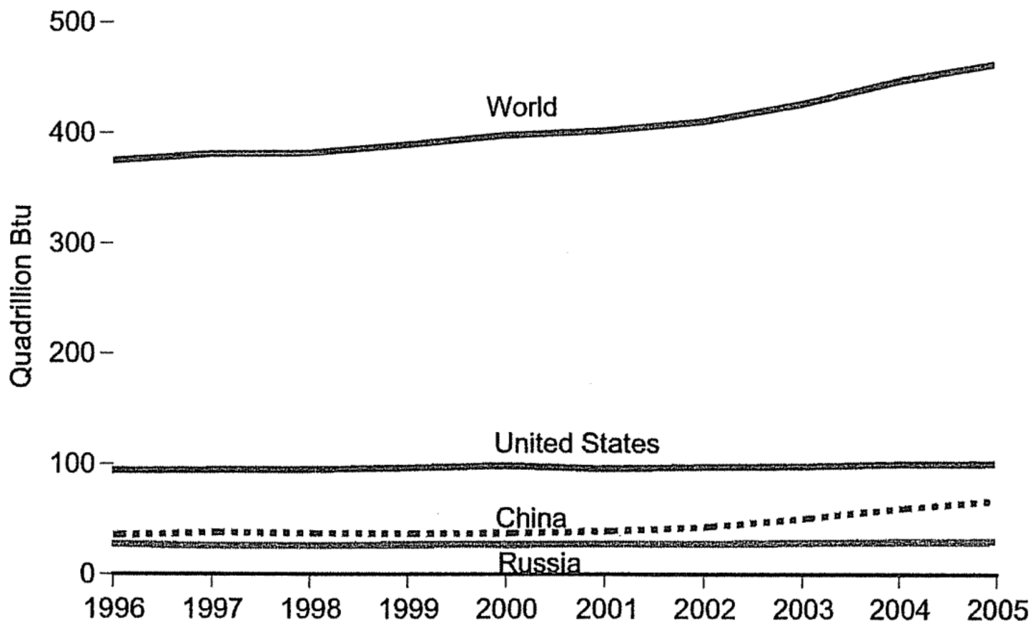


Fig. 3.6 World energy utilization [4].

In contrast to fossil fuels, the availability of the most renewable energy sources fluctuates, especially for the wind and solar energy. A fully renewable energy supply must not only convert renewable energy sources into useful energy types, such as electricity or heat, but must also guarantee their availability. This can be done through large energy storage systems, global energy transport or adaptation of the demand to the available energy [11].

Also the difference between the *reserve* and *resource* should be taken into consideration. Resource is the total energy which is technically accessible while reserve is the economically recoverable portion of the resource.

4. Efficiency and Effectiveness

Conversion efficiency does not have a single conclusion and for all energy conversions, laws provide limits and the concepts for "efficiency" are defined. In the simplest approximation efficiency is equal to output/input. The energy conversion paths (c for chemical, e for electrical, m for mechanical, r for radiant and for thermal) and the efficiencies of the selected products are present in literature (Table 4.1) .

Table 4.1 Efficiencies of selected components [5]

Component	Energy Conversion Path	Efficiency (percent
Large electric generators	m → e	98–99
Large power plant boilers	c → t	90–98
Large electric motors	e → m	90–97
Home natural gas furnaces	c → t	90–96
Drycell batteries	c → e	85–95
Waterwheels (overshot)	m → m	60–85
Small electric motors	e → m	60–75
Large steam turbines	t → m	40–45
Wood stoves	c → t	25–45
Large gas turbines	c → m	35–40
Diesel engines	c → m	30–35
Photovoltaic cells	r → e	20–30
Large steam engines	c → m	20–25
Internal combustion engines	c → m	15–25
Steam locomotives	c → m	3–6
Light Sources		
High-pressure sodium lamps	e → r	15–20
Fluorescent lights	e → r	10–12
Incandescent light bulbs	e → r	2–5
Paraffin candles	c → r	1–2

Originating from the facts that all real processes are irreversible and losses always occur, the effectiveness values are used to measure the conversion processes. However, usually these concepts, namely efficiency and effectiveness have been confused and used in misleading ways.

Simply to explain, the First Law of Thermodynamics is an energy balance equation, while the Second Law is an inequality for entropy change. Entropy is a property of the substance which is hard to explain from the practice of engineering but it is critical in decision making of the energy conversions. Inevitably, as the total entropy (summation of the entropy changes of the system and the environment) increases, the potential for the conversion once more, decreases. This means that the some part of the availability (or exergy) is destroyed. Thus; the conversion is within two extremes: From a conversion of complete destruction of the availability (maximum irreversibility occurs) to the zero destruction of the availability (reversible processes).

Imagine a cold room (volume of V in m^3, specific heat at constant volume c_v in kJ/kg-K) at temperature T_i [^{0}C] initially and an amount of wood (mass, m [kg], calorific value h [kJ]). When one burns the wood, its total energy (m x h) will be used to increase the temperature of the room air (density in kg/m^3) to the final temperature (T_f) :

$$(m \times h)_{wood}=(\rho V c_v)_{air}(T_f-T_i) \tag{4.1}$$

Since there is no possibility of recovering the converted energy to the calorific value of the wood at the initial time, the whole availability of the wood has been destroyed and there is nothing to do with the final room air.

Effectiveness (or second law analysis) is defined as

availability recovered/availability supplied = ε (4.2a)

or

1-(availability destroyed/availability supplied) = ε (4.2b)

Effectiveness is equal to zero in this case.

If any thermal source (fossil or renewable) is utilized to generate work for example the second law efficiency is defined as

the generated work/decrease in the availability of the thermal source= $\boldsymbol{\varepsilon_{\text{heat engine}}}$ (4.3)

For the wind energy utilization:

$\boldsymbol{\varepsilon_{\text{wind turbine}}}$ **= the generated work/kinetic energy of the wind** (4.4)

For all energy conversions there are three types of metrics (Table 4.2):

i- Ideal efficiency defined as (output/input),

ii- Actual efficiency limited by the laws of thermodynamics and fluid mechanics,

iii- Theoretical efficiency for which the effectiveness is equal to one (no availability destruction).

Table 4.2 Examples of conversion metrics.

Utilization System	**Conversion type**	**Ideal**	**Actual**	**Theoretical**
Geothermal power plant	Heat source to electrical work	Carnot efficiency	Thermal efficiency, $\eta_{thermal}$ (about 10%)	Electrical work/decrease in geothermal brine availability
Wind Energy Conversion System	Kinetic energy to electrical work	Betz limit*	Power coefficient, C_p (around 30%)	Electrical work/kinetic energy of the wind
Steam Power Plant	Chemical energy to electrical work	Carnot Efficiency	Thermal efficiency, $\eta_{thermal}$ (around 40 %)	Electrical work/decrease in supplied heat availability
Photovoltaic Cell	Radiant energy to electrical energy	Fill factor x V_{oc}xI_{sc}/(intensity x cell area)*	Cell efficiency, η_{cell} (around 25 %)	(Electrical work+availability gained due to the thermal potential)/decrease in the availability of the solar intensity

- Discussed to be later on.

Another, important metric is the heat rate. “Heat rate” is defined as the input energy per kWh output. The smaller the heat rate is better:

$$Heat\ \mathrm{rate} = \frac{\text{energy in}}{\text{energy out}} = \frac{1}{\eta_{thermal}} \tag{4.5}$$

$$Heat\ \mathrm{rate} = \frac{1}{\eta_{thermal}} x 3412 x \frac{Btu}{kWh} \tag{4.6}$$

In Eqns. (4) and (5) generator efficiency is considered as unity. 1 kWh = 3412 Btu.

Especially for large scale investments another criteria should be life cycle assessment (LCA). The life cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials usage and environmental releases, to assess the impact of those and to evaluate and implement opportunities to effect environmental improvements [11].

During LCA,

i-energy and raw material requirements, emissions, effluents, solid waste and costs and mass and energy balance of each process in system should be quantified. (Inventory)

ii- environmental burden through process design changes, material substition, recycle etc. should be reduced. (Improvement)

iii-values should be assigned to each effect. (Impact)

An example of LCA is illustrated for hydrogen production via steam reforming in Fig. 4.1.

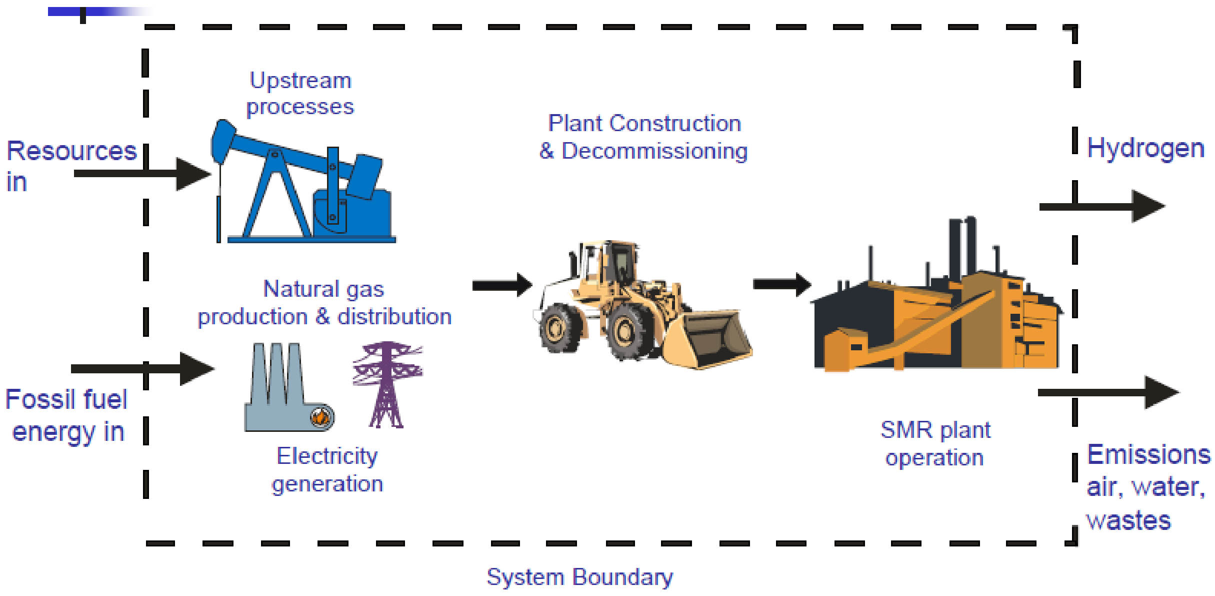
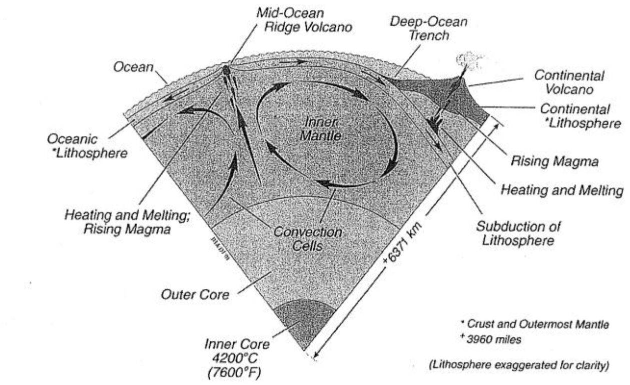


Fig. 4.1 Inputs and outputs of the hydrogen production by steam reforming.

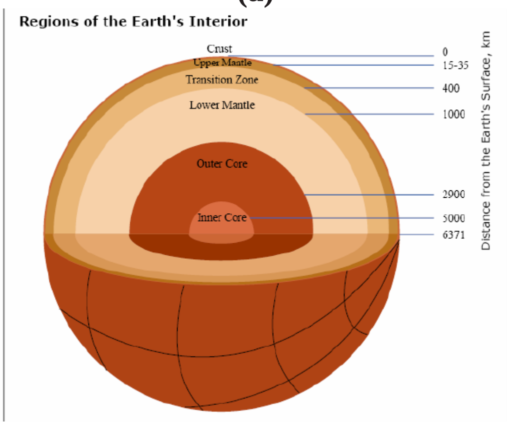
5. Geothermal Energy

5.1 Geothermal Background

Geothermal energy is energy from the earth. It lies deep within the Earth. The respective available annual energy globally is 996,000 PJ/year [12]. Currently, especially in our country, the use of ground-source heat pumps using the soil as a reservoir is common. Since 99% of our planet is hotter than 1000^{0}C, it should be a pervasive renewable energy source. However, the problem is to access to this source. The technology of drilling is an important part of utilizing geothermal energy. Fig. 5.1 illustrates the cut away view of the Earth's composition.



(a)



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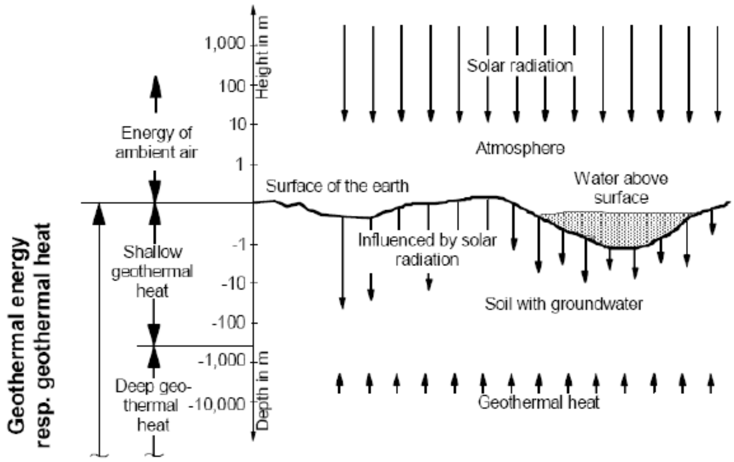


(c)

Fig. 5.1 a) Schematic of the structure of the Earth b) Distance details. c) Utilization.

Much of the geothermal energy is inaccessible because of its great depths, but along the plate boundaries, geothermal activity is close enough to the surface to be accessible. The active geothermal zones are the zones with the most earthquake activity.

Example 5.1 Calculate the geothermal power potential of a site that covers 50 km^2 with a thermal crust of 2 km, where the temperature gradient is 240^{0}C. At this depth the specific heat of rock is determined to be 2.5 J/cm^3, and the mean surface temperature is measured at 15^{0}C.

Heat content:

Q_h=50 x 2 x 10^{15} x (240-15) = 5.625 x 10^{19} J

Assuming that the only 2 percent of the available thermal energy of the geothermal mass could be used to provide power fro electricity generation, how many years would it take to produce 1000 MW/yr of power?

Total capacity to generate this power is 50 x 1000 = 50,000MW/yr

50,000 x 10^6 (W) x 3.15 x 10^7(s/yr) = 1.58 x 10^{18} j/yr

Lifetime production = 5.625 x 10^{19} / 1.58 x 10^{18} = 35 years

Geothermal resources are characterized by their thermal and compositional characteristics:

i-Hydrothermal or geohydrothermal,

ii-Geopressurized,

iii-Magma,

iv-Enhanced geothermal systems (hot, dry rock)

i- Hydrothermal resources are the most limited category among the four classes. However they are easiest to harvest. In hydrothermal resources, water is heated and/or evaporated by direct contact with hot porous rock. The porous or permeable rock is bounded with rock of low permeability. Water trickles through the porous rock and is heated (and perhaps evaporated) and discharged to the surface. Hydrothermal systems producing steam are called *vapor dominated*, and if they produce mixture of hot water and steam they are called *liquid dominated.*

ii-Geopressurized resources include sediment-filled reservoirs and hot water confined under pressures. The fluid temperature is range is 150-180^{0}C. The pressure value is up to 600 bars. In many of these systems the fluid contains methane up to 100,000 ppm. This is why the fluid is called "geothermal brine" and it is highly corrosive.

iii-Magma or molten rock is under active volcanoes at accessible depths. Temperatures excess 650 ^{0}C.

iv-Hot dry rock (HDR) has the temperature in the excess of 200^{0}C. However, as the name implies, contain little amount of liquid. The method for harvesting this resource is to send the water under the rock and reject the heat. This method is also called EGS (enhanced geothermal system). Table 5.1 gives the estimates for the geothermal resource in the World.

Table 5.1 Geothermal resource estimate [5] (1 quad = 10^{15}Btu)

Resource	United States (1000 quad)	World (1000 quad)
Hydrothermal	10	130
Geopressurized	170	540
Magma	1,000	5,000
Hot, dry rock	30,000	105,000

Table 5.2 lists the results of a very recent study [7] related to Turkey's geothermal source.

Table 5.2 Turkey's geothermal resource base (in 10^{23}J) between 3 to 10 km depth for different temperature classes [8]

Depth, km	Temperature, °C				Total
	T<100	100<T<150	150<T<250	T>250	
	Stored Heat, x 10^{23} J				
3	1.72	1.30	0.65	0.30	3.97
4	1.77	2.31	1.97	1.01	7.06
5	1.77	2.61	4.22	2.41	11.01
6	1.77	2.70	6.55	4.85	15.87
7	1.77	2.70	7.94	9.19	21.60
8	1.77	2.70	8.54	15.2	28.21
9	1.77	2.70	8.86	22.4	35.73
10	1.77	2.70	9.01	30.6	44.08

Comparing Tables 5.1 and 5.2, the average stored heat within 3 km below the earth for Turkey which has an average of 4 x 10^{23} J is approximately 0.4 % of the world's total resource.

5.2 Geothermal Power Production

38 years after the invention of the electric power generator by Werner von Siemens and 22 years after the start of the first power station by Thomas A. Edison in New York in1882, geothermal power production was invented by Prince P. G. Conti in Lardarello, Italy in 1904.

Geothermal power production in Tuscany has continued since then and amounted to 128 MW of installed electrical power in 1942 and to about 790 MW in 2003. In 1958, a small geothermal power plant began operating in New Zealand, in 1959 another in Mexico, and in 1960 commercial production of geothermal power began in the USA within the Geysers Field in California [13].

Today, the worldwide geothermal electricity net generation has increased to about 57 billion kWh in the year 2007 which corresponds to 0.3% of the total electricity net generation whole over the world (www.eia.org). For Turkey this figure is 0.093 billion kWh which is corresponding to 0.16% of the world's total geothermal electricity generation. The installed geothermal electric generation capacity has reached to 10.2 GW, worldwide (Table 5.3). One of the main reasons for this success is the base load ability of geothermal power generation. However, for Turkey, the installed electricity capacity by utilization of the geothermal sources is around 95 MW, only [14].

Table 5.3 Installed geothermal electric generation capacity (top 10 countries and world total, 2008) [13]

Country	Installed capacity [GW]
US	2.9
Philippines	2.0
Indonesia	1.9
Mexico	1.0
Italy	0.8
Japan	0.5
New Zealand	0.5
Iceland	0.5
El Salvador	0.2
Costa Rica	0.2
Worldwide	10.2

Today, geothermal power production is economic viable only when high temperatures are found at relatively shallow depth. In regions with a normal or a slightly above normal geothermal gradient of about 3 K / 100 m, one has to drill more than 5,000 m deep in order to achieve temperatures above 150 °C. Such deep wells are expensive and there is a high risk of failure. For this reason under economic considerations geothermal power production is mainly restricted to geothermal fields with extremely high temperature gradients and high heat flows.

5.2.1 Hydrothermal (geo-hydrothermal) sources

Fig. 5.2 illustrates the schematic of a vapor dominated geothermal system.

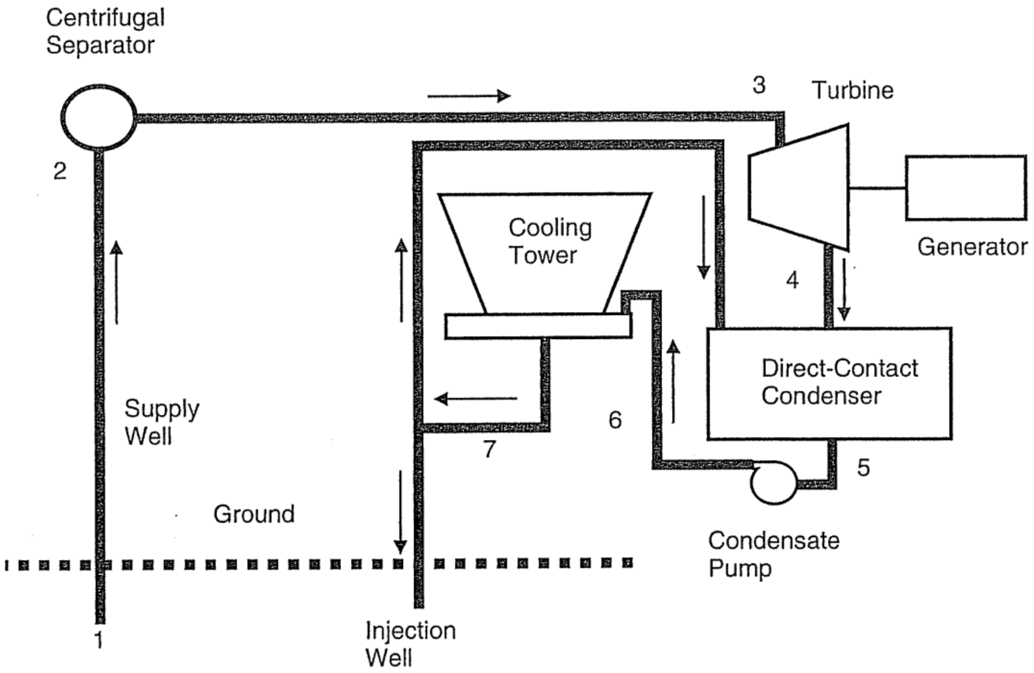


Fig.5.2 Vapor dominated hydrothermal system.

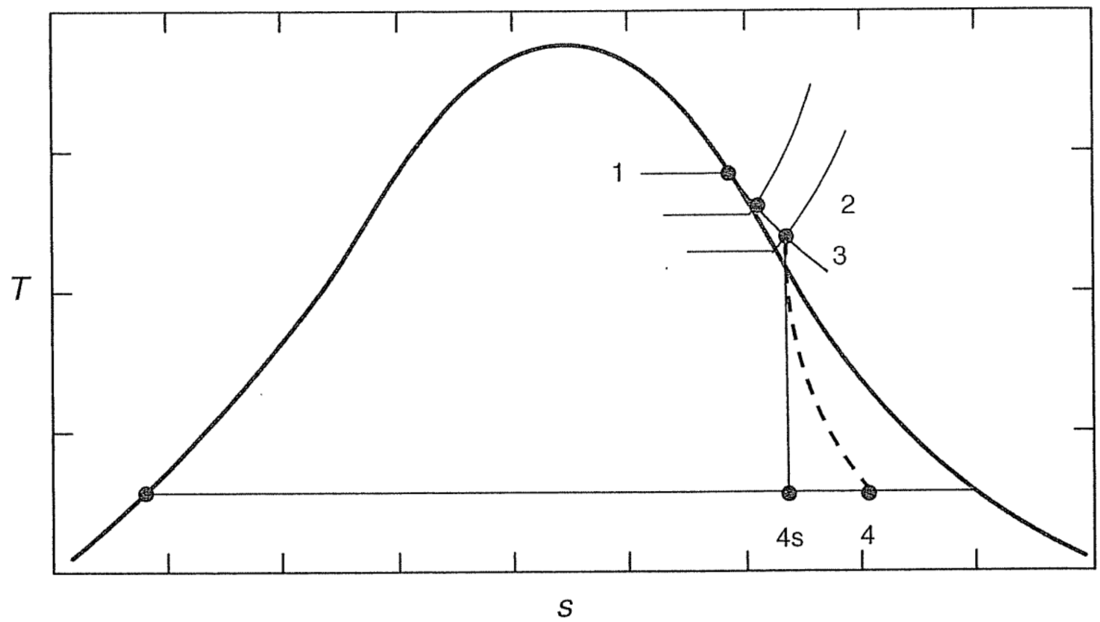


Fig. 5.3 T-s diagram for the vapor dominated hydrothermal system.

The main problem is the solid contents of the brine. The solid particles are separated by the means of the centrifugal separator and filtered. The vapor dominated systems require steam

>175^{0}C. T-s diagram is given Fig. 5.3.

Problem 5.1 [15]

A vapor-dominated geothermal system is supplied with saturated steam at 3 MPa. The steam enters the turbine at 0.5 MPa and exits at 15 kPa. The turbine isentropic efficiency is 82 percent, and the electrical generator is 90 percent efficient. If re-injection occurs at the cooling tower, analyze the system performance (thermal efficiency and heat rate). What flow rate of steam is required for a power generation of 10 MW?

Liquid dominated hydrothermal systems are more abundant than the vapor dominated ones. In these systems water is available at 150-315^{0}C. When the pressure is reduced, the water is flashed into a two phase mixture. Three systems are possible in liquid dominated systems:

I-flash (Figs. 5.4-5.5)

ii-total (Figs. 5.6-5.7)

iii-binary (Figs.

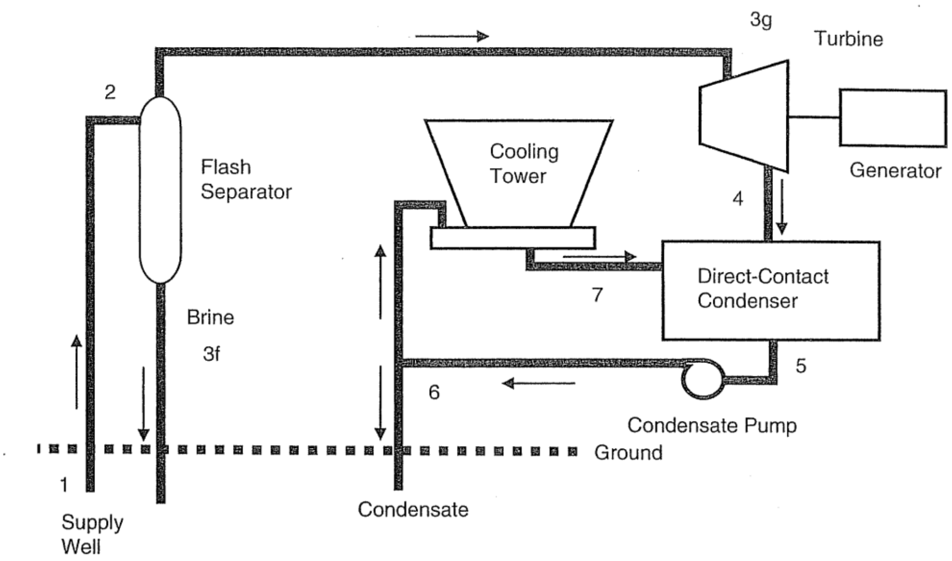


Fig. 5.4 Schematic of the flash liquid dominated geothermal systems.

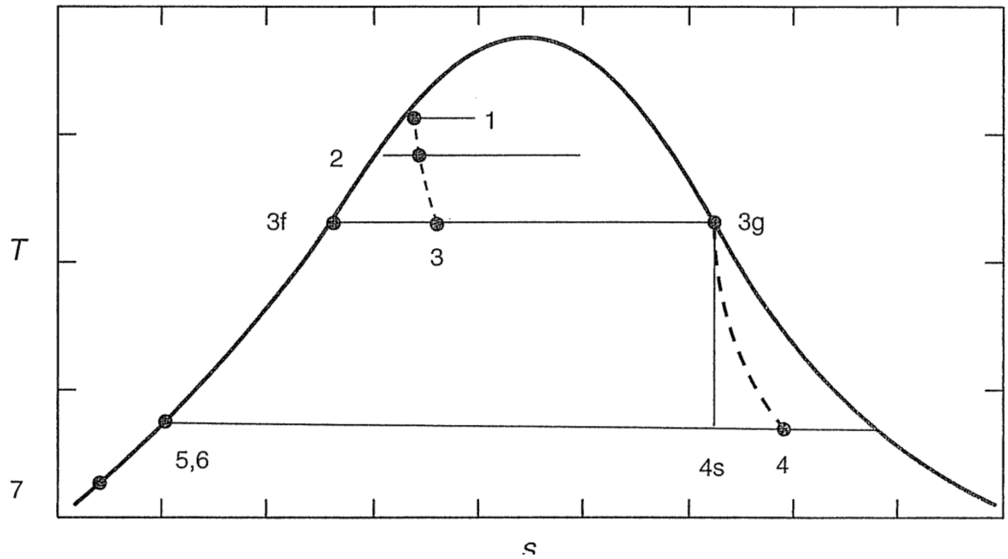


Fig. 5.5 T-s diagram for flash liquid dominated systems.

One of the disadvantages of the flash system is that the brine with significant energy (at point 3 f) is re-injected to the well. Energy is extracted from the vapor phase, only.

Problem 5.2 [13]

A geothermal power plant is supplied with water at a well bottom temperature of 225° C and a pressure of 8 MPa. The fluid flows into a flash separator maintained at 40 kPa. The turbine exit pressure is 10 kPa. The overall efficiency of the turbine is 0.83. Calculate the thermal efficiency, the heat rate, and the steam and water mass flow rates required for an output of 10 MW.

Since re-injection of too much energy results in low efficiency in flash systems, a solution is proposed: In total –flow concept design, the turbine is replaced by a mix-flow expander that extracts energy from the vapor liquid mixture (Figs. 5.6-5.7). The mix-flow expander is a type of biphase turbine.

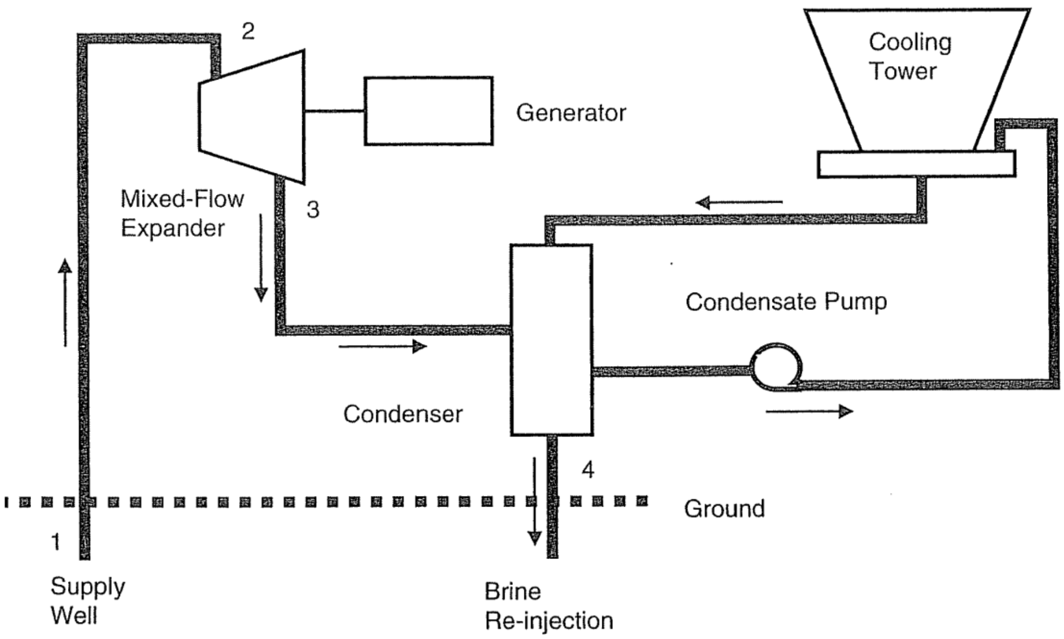


Fig. 5.6 Schematic of total flow liquid dominated geothermal system.

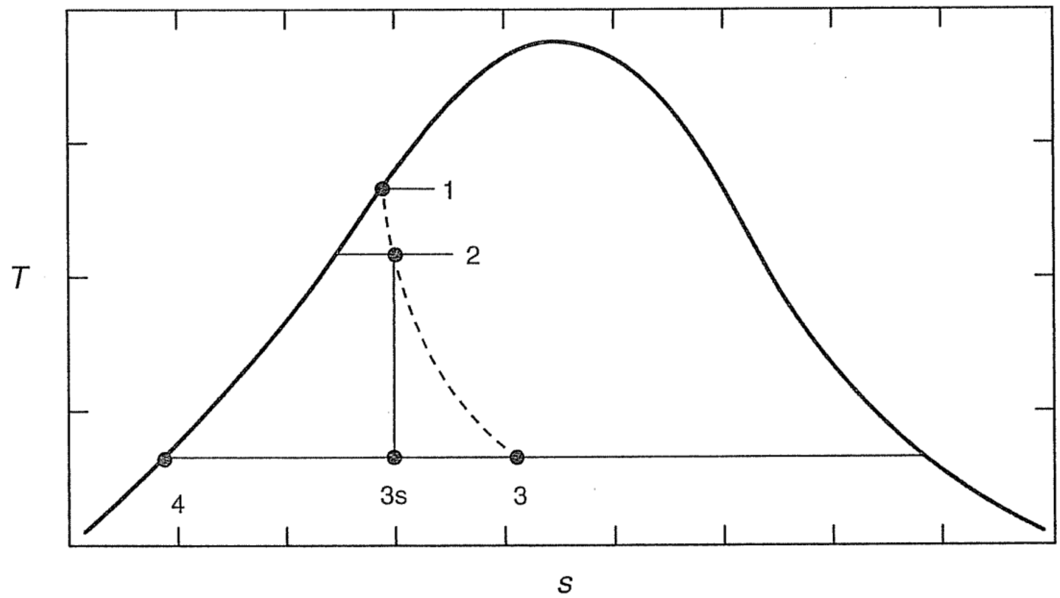


Fig. 5.7 T-s diagram of total flow liquid dominated geothermal system.

Problem 5.3 [15]

Consider a total-flow geothermal system using the same well bottom conditions as Problem 5.2. The fluid enters the expander as a saturated liquid and discharged at 10 kPa. Determine the thermal efficiency, the heat rate, and the flow rate for a 10 MW system if the mixed-flow expander possesses an isentropic efficiency of 0.50.

The biphase rotary separator was developed to extract power from a two phase , steam/water mixture as indicated in Figs.5.6 and 5.7. The unit is made up of three main components, as shown in Fig. 5.8, a series of two phase, a rotary separator and a liquid turbine. The two phase nozzle converts part of the enthalpy of the two phase mixture into fluid kinetic energy. Passing through the nozzle, the mixture is expanded from high inlet pressure to the low exit pressure with steam and water droplets intimately mixed. The expanding gas accelerates, entraining liquid droplets with it, therefore increasing the kinetic energy of the water and the steam. The result is a two phase jet.

The two phase jet has been directed tangentially onto the inner surface of a drum-shaped rotary separator rotating at a speed close to that of the two phase jet. The high centrifugal acceleration forces the heavier liquid towards the wall. Thus the liquid is separated from the steam. The separated liquid rotates with the drum, while the steam flows inwardly to an exit port.

In the bi phase turbine the rotational speed of the liquid turbine (N_U) is about 60 % of that of the rotary separator (N_s) [16]. The spent liquid is collected by the stationary diffuser.

The usual arrangement for the bi phase plant is the topping arrangement (Fig. 5.9). The remaining steam from the separation is sent to the conventional condensing turbine . In the bottoming arrangement on the other hand, the discharge water from a conventional flash separation is passed through a biphase plant, instead of being directly injected (Fig. 5.10).

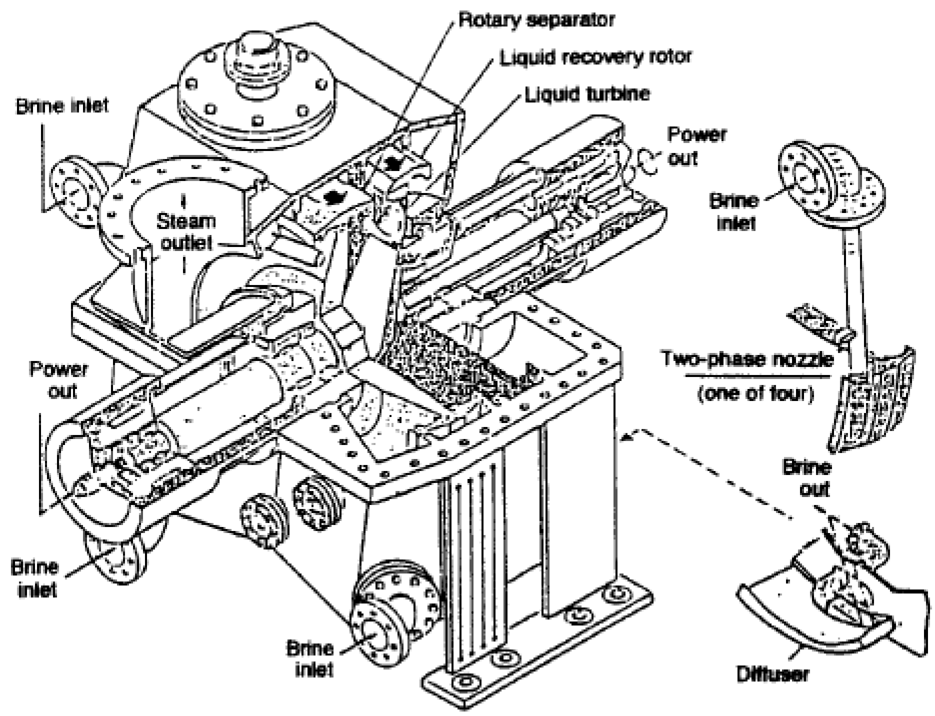


Fig. 5.8 View of a biphase turbine [16]

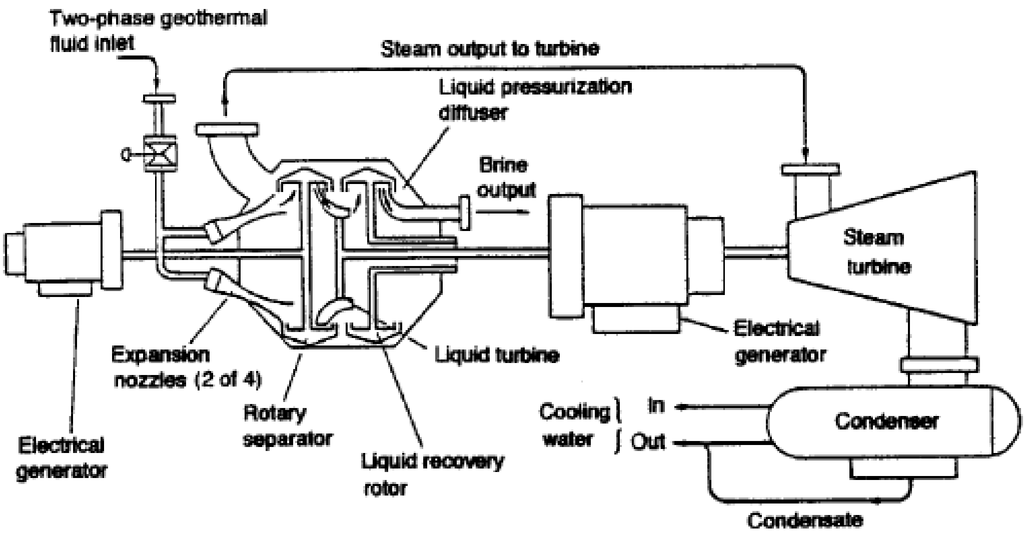


Fig. 5.9 Schematic of topping arrangement [16]

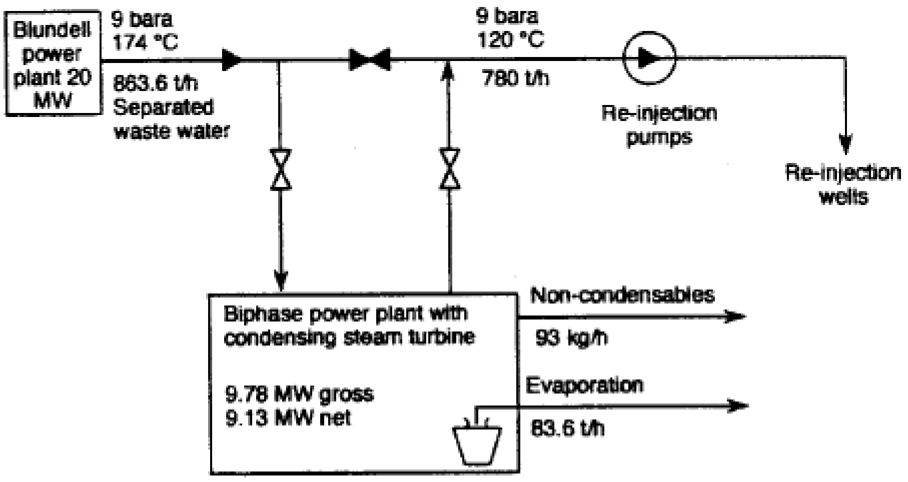


Fig. 5.10 An example of bottoming arrangement [16]

Another common system being utilized by a number of existing geothermal systems is the binary system (Fig. 5.11). In flash systems, when a steam phase separates from boiling water, $CO_2$is the dominant (over 90% by weight) non condensable gas. In most geothermal systems, non-condensable gases make up less than 5 % by weight of the steam phase. For each megawatt-hour of geothermal electricity produced in USA, for example, the average emission of CO_2 is about 18% of that emitted when natural gas is burned to produce electricity [17]. In binary systems since all of the produced fluid is injected back into the reservoir there is no emission.

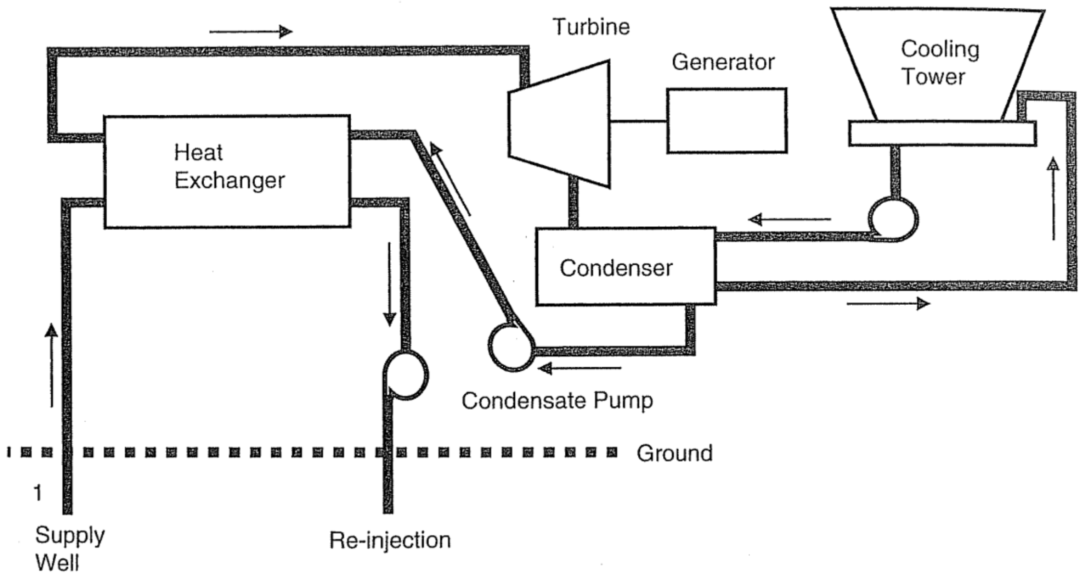


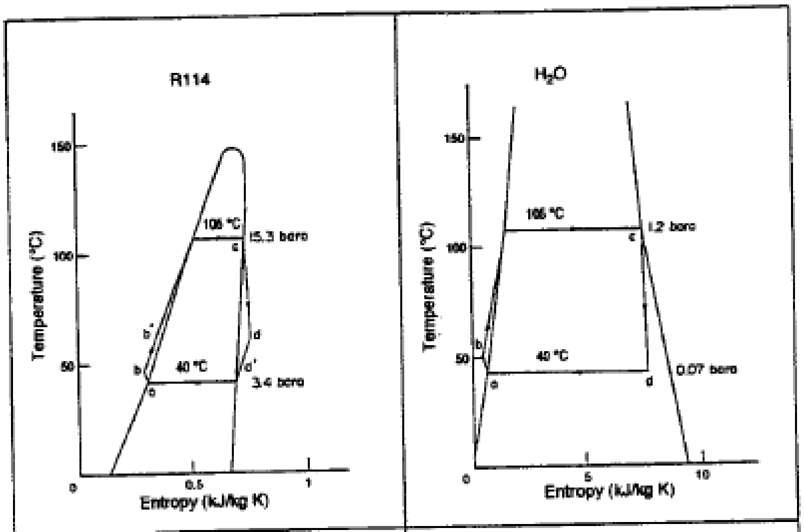
Fig. 5.11 Schematic for the binary liquid dominated geothermal system.

In these systems, two fluids are involved: the hot brine and a working fluid (generally a hydrocarbon). The working fluid circulates in the closed portion of the system. The working fluids include propane, isobutene, isopentane, and water ammonia. The boiling points of these fluids are lower than that of the water. The special attention in these systems should be given to the heat exchanger design. Only the heat exchanger and hot brine transport components are exposed to the harsh and corrosive brine conditions.

It should be noted that the Rankine cycle efficiency for the organic fluids used is little different to that for water/steam between the same two top and bottom cycle temperatures. The cycle efficiency is slightly low for the organic fluids.Even though the cycle efficiency is about the same value, in the two cases, the overall efficiency , which is proportional to the generated electrical energy, is considerable higher for the organic fluid.

Overall efficiency = Cycle efficiency x (thermal power extracted/thermal power available from the source) (5.1)

Fig. 5.12 shows two cycles one using R114 in one case and water in the other. As a consequence of organic fluid having a lower ratio of latent heat of vaporization versus specific heat capacity than that of water results in some limitations in heat exchange process (Fig. 5.13).



	R114	H_2O
Hot source temperature (°C)	140	140
Top cycle temperature (°C)	105	105
Carnot efficiency between 140 and 40 °C (%)	24.2	24.2
Maximum obtainable efficiency between 140 and 40 °C (%)	13.2	13.2
Rankine cycle efficiency (%)	10.1	10.9
Overall efficiency (%)	5.5	3.6

Fig. 5.12 Comparison of two cycles one using R114 as the secondary fluid, and the other is using water [16].

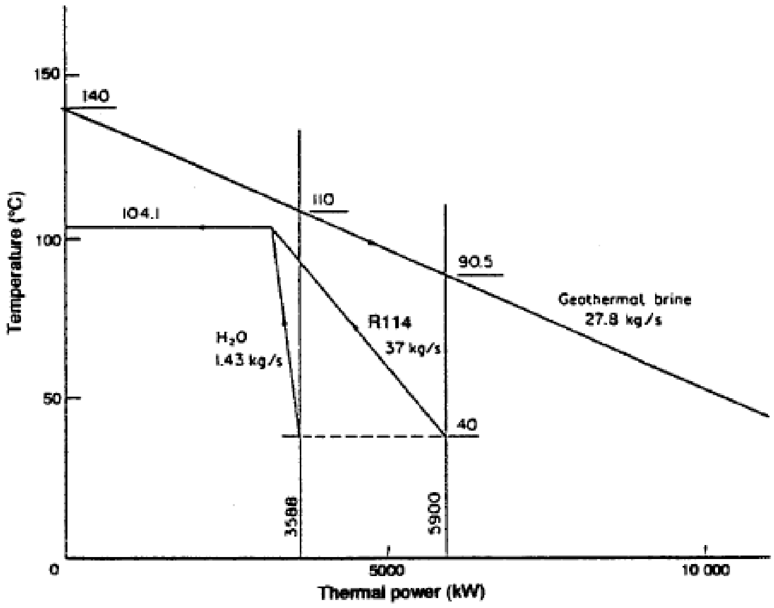


Fig. 5.14 Extraction of energy from the geothermal brine [16].

5.2.2 Geopressurized sources

These resources may have pressures up to 1000 bar and temperatures between 150-180^{0}C. They are 2000-9000 m in depth. They have high content of dissolved methane and dissolved solids typically30-80 ft^3/barrel (approximately 16%). These brine solutions are corrosive and difficult to handle. Technical problems and high costs have precluded only pilot studies. A major enhanced geopressure electrical generating project has been initiated in US the first stage of the project calls for developing a total of 200 geopressurized wells in the States of Mississippi and Texas. The project is expected to ultimately generate base load electrical power of at least 400 megawatts. Total capital cost is estimated to be $280 million [18].

5.2.3 Magma

Magma is the molten rock, under the volcanoes (temperature exceeding 650^{0}C). Methods for harvesting magma are speculative only. In case of reaching this source magma pools also would produce hydrogen because at 600^{0}C iron oxide reacts with water and produce hydrogen:

$$2FeO+H_2O\rightarrow 2FeO_{1.5}+H_2 \qquad (5.2)$$

Although the potential is great, magma based plants are years away (See www. Magma-power.com).

5.2.4 Enhanced geothermal systems (EGS)

These systems involve injecting water into the source and circulating it through the dry rocks. Because of the low thermal conductivity of the rocks large surface areas are necessary. The rocks can be fractured by sending pressurized water (at 200 atm. for example). An example of such an application is present in (Fig. 5.15).

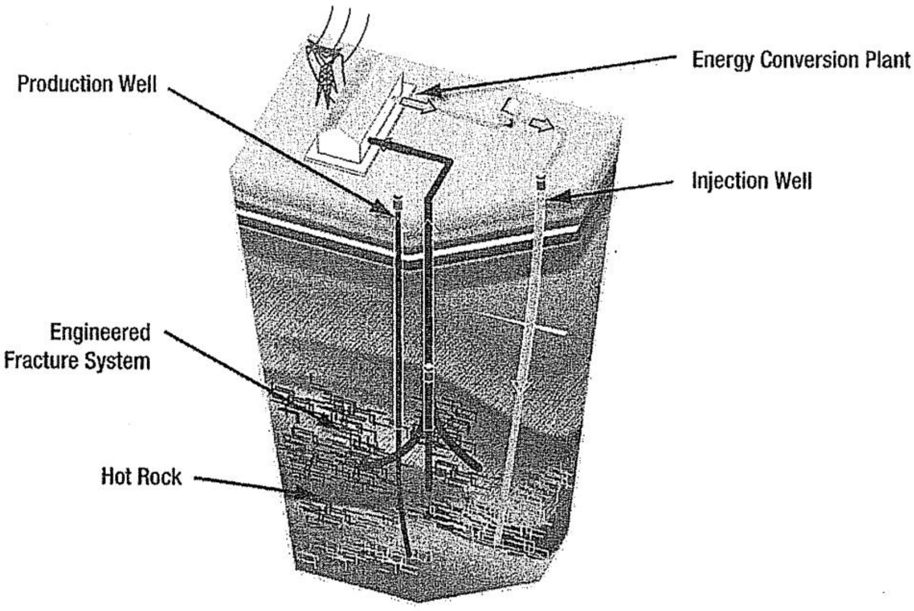


Fig. 5.15 Schematic of an EGS power plant [19].

5.2.5 Geothermal electricity applications in Turkey

Table 5.4 illustrates the update data about the geothermal power plants in Turkey. This data is changing according to the bidding for transferring the consents of some of these fields from the state to the private sector.

It is reported that in 2011 another 17.5 MWe power plant in Hidirbeyli would be commissioned [20]. All these activities have indicated that power generation capacity in the last 4 years has increased fourfold.

Table 5.4 Geothermal power plants in Turkey (updated from [14]).

Power Plant Name	Start-Up Date	Installed Power [MW_e]	Resource Temperature[^0C]
Dora-I	2006	7.35	172
Dora-II	2010	11.1	174
OmerBeyli	2009	47.4	231
Bereket	2007	7.5	145
Tuzla-Çanakkale	2010	7.5	171
Kızıldere-Denizli	1984	17.8	243
Total		97.85	

5.3 Direct Use of Geothermal Energy (Ground Source Heat Pumps)

The heat pump is a "device which absorbs heat at a certain specific temperature (cold side) and releases it again at a higher temperature level (warm side) after adding drive work”.

Hence a heat pump can withdraw thermal energy from a heat source at a low temperature level (e.g. ambient air).

A few meters below the surface, the ground temperature remains nearly constant. Using the ground as a heat source/sink allows improved performance over a heat pump using the atmosphere as heat source/sink (conventional heat pumps).

Conventional heat pumps possess COP values of around 3, while GSHPs (geothermal source heat pumps) have COP values approaching 4. However, GSHP systems cost twice that the conventional heat pump systems [15].

The general configuration of a GSHP has been shown in Fig. 5.16.

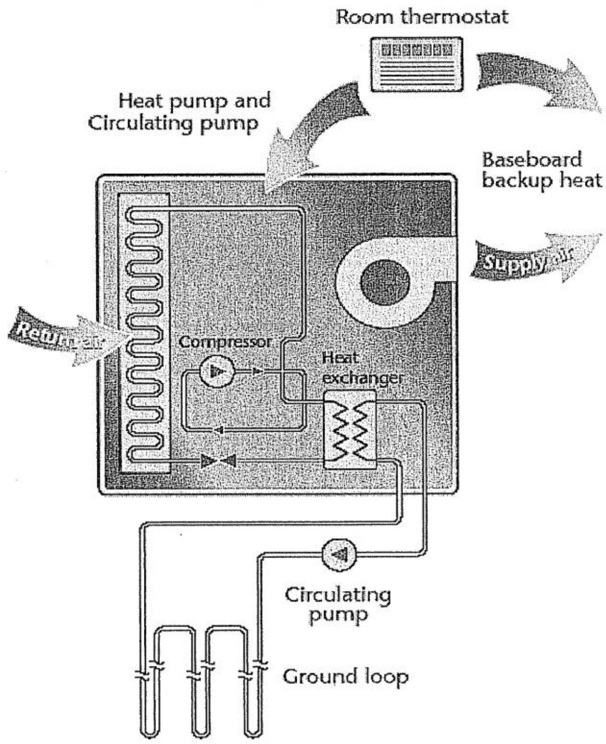
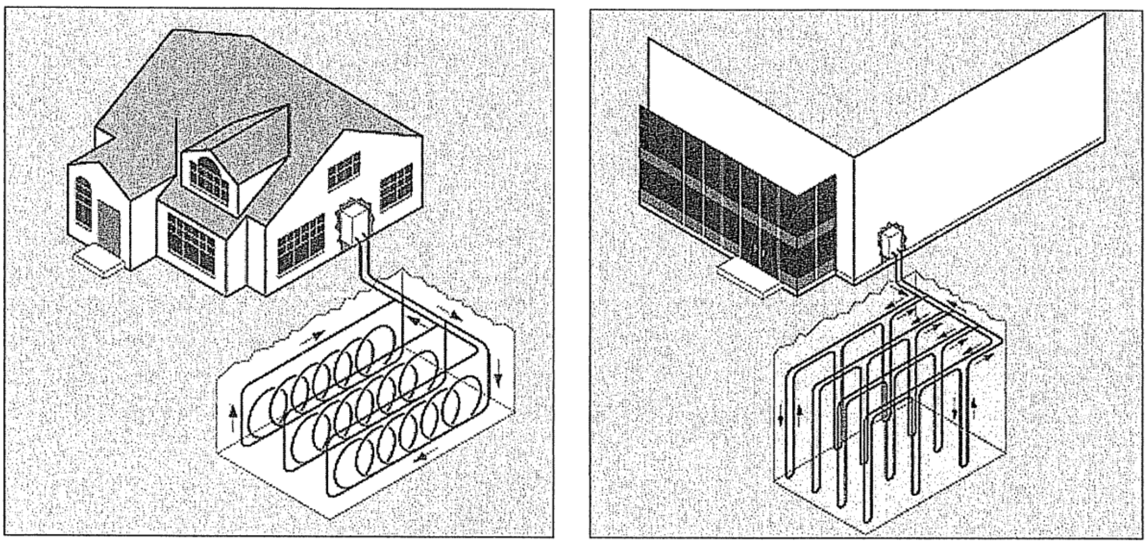
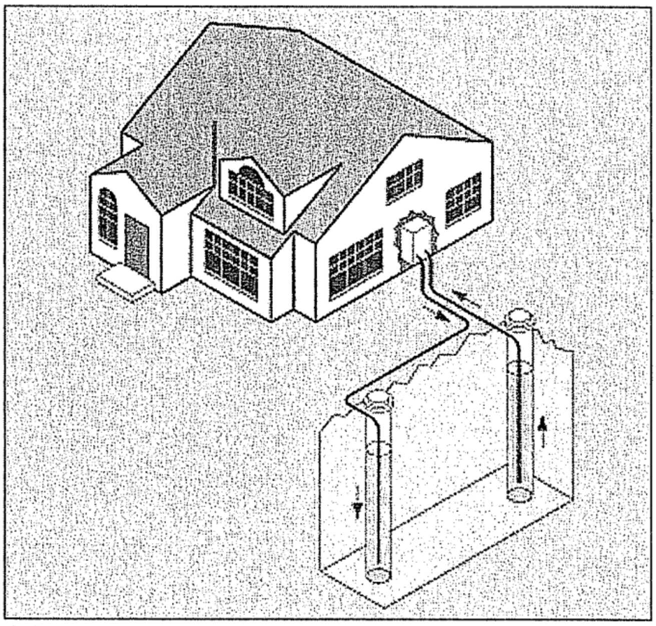


Fig. 5.16 Schematic of a GSHP system [15].

The heat exchanger transfers energy between the compressor refrigerant and the ground via a circulating pump in the ground loop. The utilization of the ground as a heat source/sink is in several ways as shown in Fig. 5.17.



(a) (b)



(c)

Fig. 5.17 GSHP ground loop configurations a) Closed loop horizontal, b) closed loop vertical, c) Open loop [15].

In a closed loop system, a loop is buried in the earth around the home. Virtually all loops built today use high-density polyethylene (HDPE) pipe. This type of pipe is specifically designed to be buried in the ground and is marked “geothermal” or “geo”. Joints are made by fusing or melting the pipe and fittings together, which makes a nearly leak-proof connection. Mechanical joints are not used in the ground. A loop made out of HDPE can last 50 years or more.

A mixture of antifreeze and water is circulated continuously through the loop and heat pump, transferring heat from or to the soil respectively, as heating or air conditioning is needed. In a closed-loop system, the fluid never comes in contact with the soil. It is sealed inside the loop and heat pump.

In an open-loop system, ground water is drawn up from a well and through the heat pump, then typically pumped back into a return well. New water is always being pumped through the system when it is in operation. It is called an open-loop system because the ground water is open to the environment.

Over the years the industry has developed standards for GXS (Geothermal Heat exchanger Systems) installation. The best known standard is CSA C448.2-02 Design and Installation of GeoExchange Systems for Residential and Other Small Buildings.

Open loops, or ground water GXS, take heat from well water that is pumped directly through the heat exchanger in a heat pump. The required flow of well water is determined by the capacity of the heat pump. In the coldest part of the winter, heating a typical 150-m^2 new home takes 20 000–30 000 L of water per day, or a flow rate of 0.4–0.5 L per second. A larger home will need proportionally more water [21].

To utilize the low temperature geothermal source, absorption heat pumps are applicable. The absorption cycle is a process by which refrigeration effect is produced through the use of two fluids and some quantity of heat input, rather than electrical input as in the more familiar vapor compression cycle (Fig. 5.18).

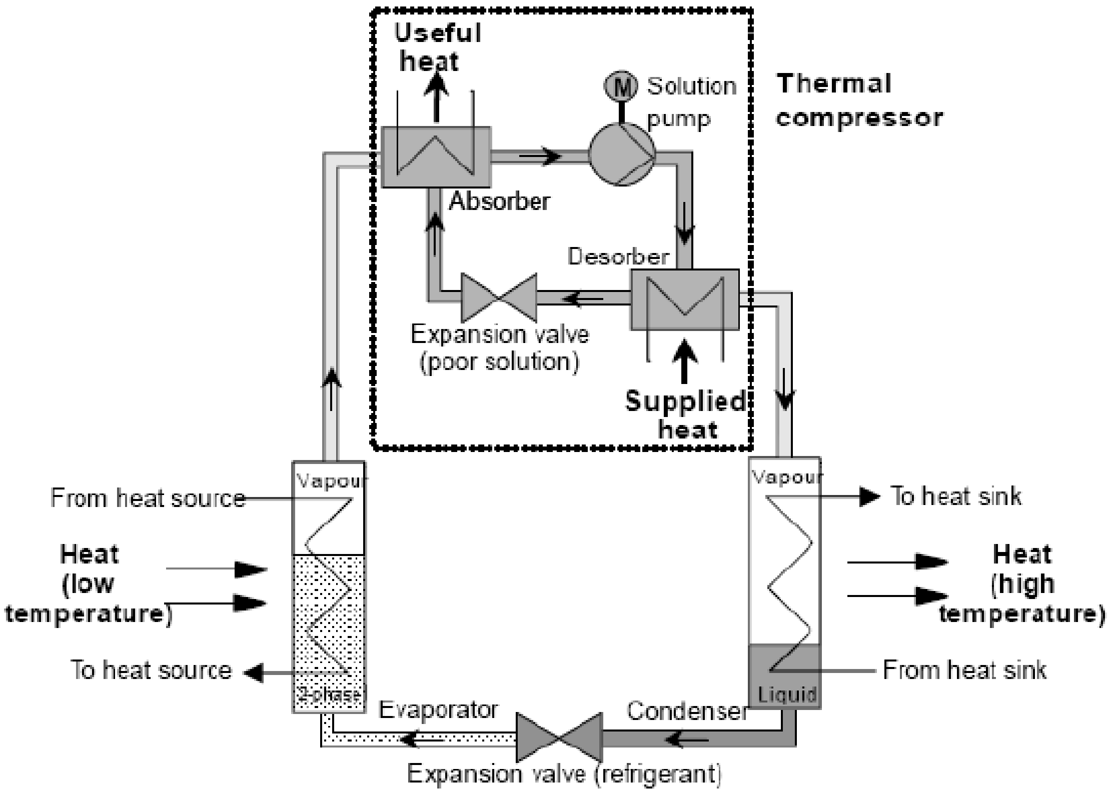


Fig. 5.18 Thermal compressor in a heat pump.

In the absorption system, a secondary fluid or absorbent is used to circulate the refrigerant. Because the temperature requirements for the cycle fall into the low-to-moderate temperature range, and there is significant potential for electrical energy savings, absorption would seem to be a good prospect for geothermal application.

Absorption machines are commercially available today in two basic configurations. For applications above 0^0C (primarily air conditioning), the cycle uses lithium bromide as the absorbent and water as the refrigerant. For applications below 0^0C, an ammonia/water cycle is employed with ammonia as the refrigerant and water as the absorbent.

Problem 5.4 *The cooling load for a computer room near to a geothermal power plant is 12,000 Btu/h. The room temperature should be kept constant at 22^0C. If the well temperature is 80^0 , calculate the COP of the system for 40% LiBr and 60% LiBr for the rich and the poor solutions, respectively.*

The high pressure in the system is 7 kPa. The mass flow rate of the rich solution to the mass flow rate of the pure refrigerant is 10.

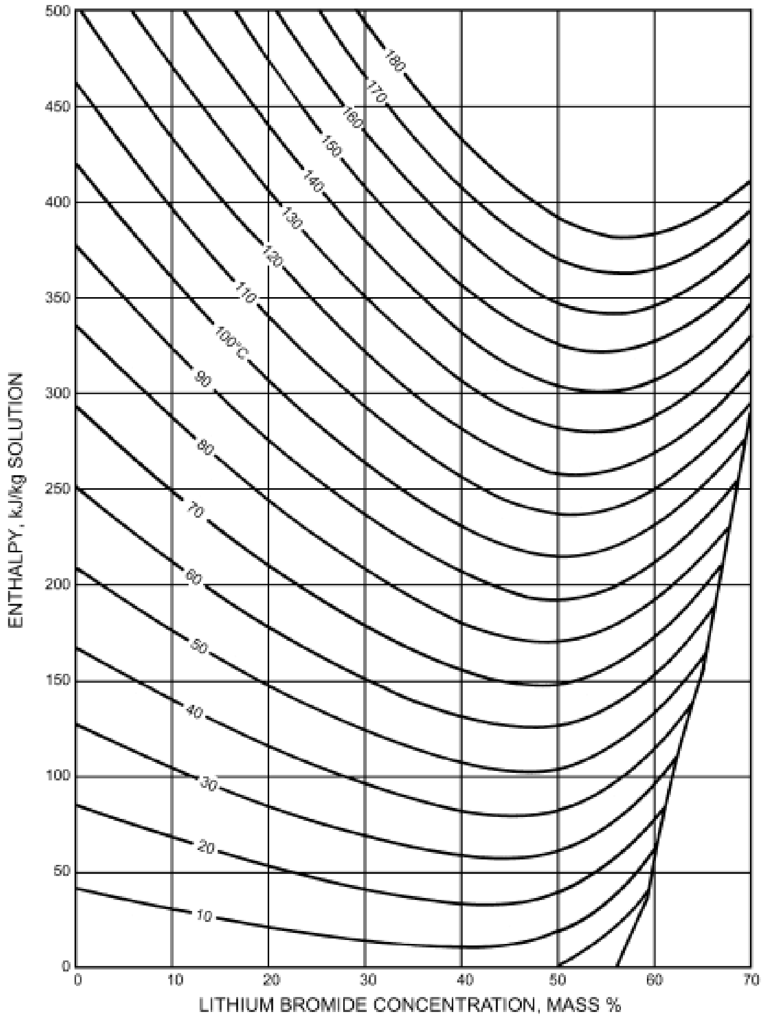


Fig. for Problem 5.4 Enthalpy versus concentration for LiBr-water solution.

5.3.1 Use of geothermal energy in district heating in Turkey

District heating in Turkey started in 1987 heating 1500 households [22]. Later the system was expanded to 2500 subscribers. As seen in Table5.5, by 2007, Turkey had 20 district heating systems working with geothermal energy. Of these district heating systems, one in Saraykoy is heated by the waste heat coming from bottoming binary power plant in Kızıldere. Table 5.5 shows that low temperature geothermal resources are mostly used in district heating with the exception of Balçova and Simav, which have medium grade resources that could also have been used for power generation purpose. About 6 million square meter space are heated by district heating with a capacity of 395 MWt.

According to Serpen et al. [22], district heating projects has been stalled in Turkey for the following reasons: (1) no geothermal resource close to towns available anymore, (2) hard competition from natural gas industry despite high natural gas costs, (3) disappointments with geothermal district heating systems because of lack of heat supply in some of them and (4) weak economics of such projects due to high heating costs.

Table 5.4 Turkey's district heating systems [22].

District Heating	Year	$T_{in,}$ °C	T_{out} °C	Q_{max} kg/s	Capacity MW_t	Equivalent Area, 100 m^2
Gönen-Balikesir	1987	67	45	200	18.4	2500
Simav-Kütahya	1991	100	50	175	36.6	6000
Kirsehir	1994	54	49	270	5.6	1800
Kizilcahamam-Ankara	1995	70	42	150	17.6	2600
Balçova-Izmir	1996	118	60	320	77.7	21500
Afyon	1996	90	45	180	33.9	5000
Kozaklı-Nevsehir	1996	98	52	100	19.2	1500
Sandikli-Afyon	1998	70	42	250	29.3	4000
Diyadin-Ağrı	1998	65	55	200	8.4	400
Salihli-Manisa	2002	80	40	150	25.1	4000
Dikili-Izmir	2008	120	60	40	10.0	150
Sarayköy-Denizli	2002	125	60	100	27.2	2500
Edremit-Çanakkale	2004	60	45	270	16.9	2740
Bigadiç-Balikesir	2006	80	50	80	10.0	1000
Bergama-Izmir	2006	62	40	100	10.0	200
Kuzuluk-Sakarya	1994	80	40	25	11.2	500
Armutlu-Yalova	2000	78	40	30	4.8	250
Güre-Balikesir	2006	62	52	200	8.5	300
Sorgun-Yozgat	2007	75	50	200	20.9	1500
Yerköy-Yozgat	2007	60	40	40	3.3	500
Total					394.6	58940

6. Wind Energy and Wind Energy Conversion Systems

Wind power has obvious benefits in that it causes no air or water pollution, its small size and quick installation reduces the risks from market uncertainty, and its rapidly declining cost has been the great success story of renewable energy. It has exhibited the most rapid growth among all renewable energy sources (Fig. 6.1).

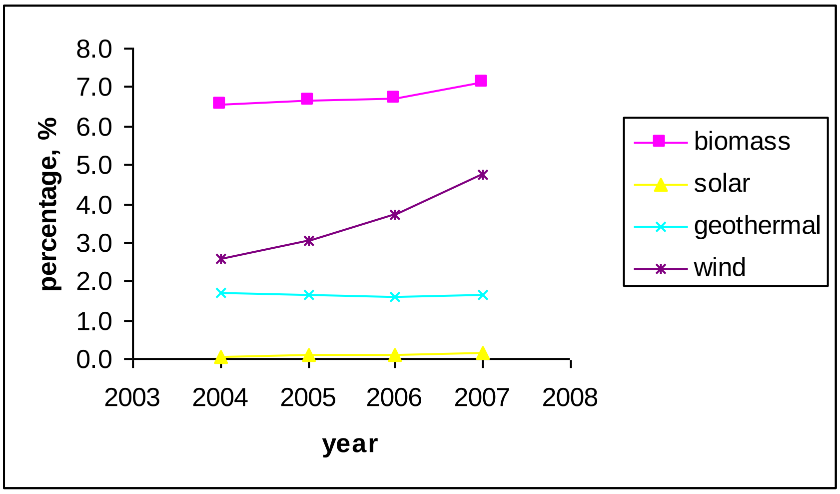


Fig. 6.1 Contribution of non-hydroelectric renewables to the world's total electric generation from the renewables (compiled from [14]).

The contribution of the non-hydroelectric sources to the total(renewable + fossil based) electric generation is illustrated in Fig. 6.2.

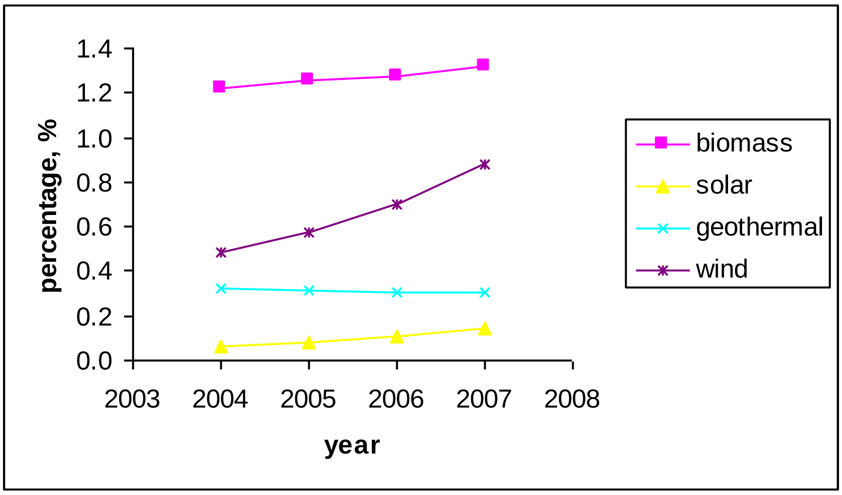


Fig. 6.2 Contribution of non-hydroelectric renewables to the world's total (renewable + fossil based) electric generation (compiled from [14]).

The growing trend is valid for also Turkey, as well as US and European countries (Fig. 6.3).

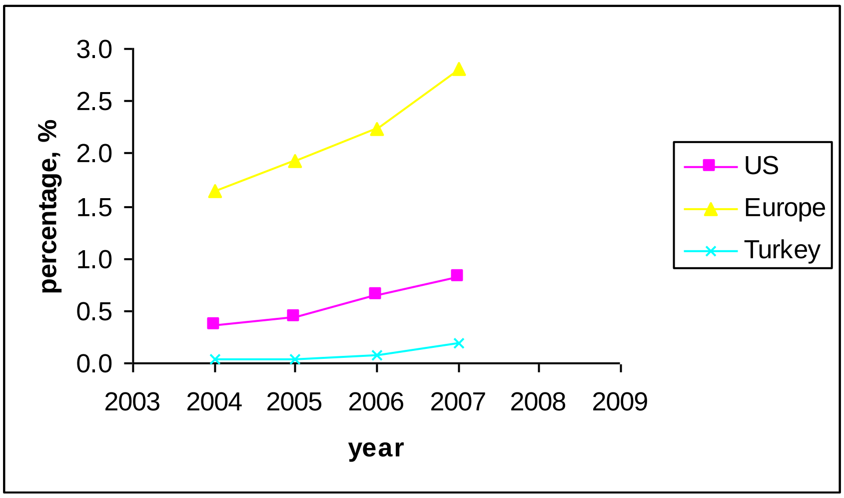


Fig. 6.3 Contribution of wind energy to the total (renewable + fossil based) electric generation for US, Europe and Turkey (compiled from [14]).

Electricity produced from the wind produces no CO2 emissions and therefore does not contribute to the greenhouse effect. Wind energy is relatively labour intensive and thus creates many jobs. In remote areas or areas with a weak grid, wind energy can be used for charging batteries or can be combined with a diesel engine to save fuel whenever wind is available. Moreover, wind turbines can be used for the desalination of water in coastal areas with little fresh water, for instance the Middle East.

At windy sites the price of electricity, measured in $/kWh, is competitive with the production price from more conventional methods, for example coal fired power plants.

One of the drawbacks of wind energy is that wind turbines create a certain amount of noise when they produce electricity. In modern wind turbines, manufacturers have managed to reduce almost all mechanical noise and are now working on reducing aerodynamic noise from the rotating blades.

Another disadvantage is that wind energy can only be produced when nature supplies sufficient wind. However, for most countries, which are connected to big grids and can therefore buy electricity from the grid in the absence of wind.

6.1 Types of Wind Turbines

There are various classifications of WTs (Wind Turbines). The classification depending on the amount of the generated power is as follows:

small (< 25 kW)

medium (25-100 kW),

large (100-1000 kW)

very large (>1000 kW)

Wind turbines are classified also depending on their rotation direction (Fig. 6.4):

-Horizontal Axis Wind Turbines (HAWT)

-Vertical Axis Wind Turbines (VAWT)

HAWTs have their axis of rotation horizontal to the ground and almost parallel to the wind stream. Most of the commercial wind turbines fall under this category but HAWTs should have a yaw control mechanism to keep them pointed into wind where the VAWTs do not need such a mechanism. Depending on the number of blades, horizontal axis wind turbines are further classified as single bladed, two bladed, three bladed and multi bladed

Fig. 6.4 HAWT on the left (three bladed) and VAWT (Darrieus) on the right.

6.1.1 Horizontal Axis Wind Turbines (HAWTs)

HAWTs have low cut-in wind speed values and they can easily be furled. (Cut-in velocity is the wind velocity value at which the wind turbine starts to produce power.) In general, they show relatively high power coefficient (See below). However, the generator and gearbox of these turbines are to be placed over the tower which makes its design more complex and expensive.

Most of the present commercial turbines used for electricity generation have three blades because they are more stable as the aerodynamic loading will be relatively uniform. Machines with more blades (6, 8, 12, 18 or even more) are also available.

The ratio between the actual blade area to the swept area of a rotor is termed as the **solidity.** Hence, multi-bladed rotors are also called high solidity rotors. These rotors can start easily as more rotor area interacts with the wind initially. Some low solidity designs may require external starting.

Consider two rotors, both of the same diameter, but different in number of blades; say one with 3 blades and the other with 12 blades. Which will produce more power at the same wind velocity? As the rotor swept area and velocity are the same, theoretically both the rotors should produce the same power. However aerodynamic losses are more for the rotor with more number of blades. Hence, for the same rotor size and wind velocity, we can expect more power from the three bladed rotor.

Some applications , on the other hand, like water pumping require high starting torque. For such systems, the torque required for starting goes up to 3-4 times the running torque. Starting torque increases with the solidity. Hence to develop high starting torque, water pumping wind mills are made with multi bladed rotors.

Based on the direction of receiving the wind, the two and three bladed HAWTs can be also classified as upwind and down wind turbines as shown in Fig. 6.5.

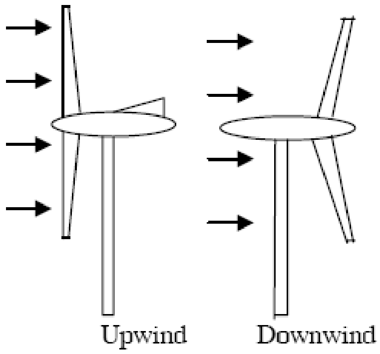


Fig. 6.5 Upwind and downwind turbines.

For the upwind turbines, which are the most common, as the wind stream passes the rotor first, they do not have the problem of tower shadow. However, yaw mechanism is essential for such designs to keep the rotor always facing the wind. For the downwind rotors, as the rotors are placed at the lee side of the tower, there may be uneven loading on the blades as it passes through the shadow of the tower. On the other hand, downwind machines are more flexible and may not require a yaw mechanism.

6.1.2 Vertical Axis Wind Turbines (VAWTs)

VAWTs are classified as drag and lift lift devices based on their operating principles.

Darrieus turbine illustrated on the right in Fig. 6.4 is a lift turbine, since the shaft torque results primarily from lift on the blades. Savonios turbine (Fig. 6.6), on the other hand is drag type VAWT, since drag of the wind on the cups generates the torque on the axis.

Lift and drag are the components of the force perpendicular and parallel to the direction of the relative wind respectively. It is easy to show theoretically that it is much more efficient to use lift rather than drag when extracting power from the wind.

Fig. 6.6 Savonious turbine

VAWTs can receive wind from any direction. Hence complicated yaw devices can be eliminated.

The generator and the gearbox of such systems can be housed at the ground level, which makes the tower design simple and more economical. Moreover the maintenance of these turbines can be done at the ground level. The major disadvantage of some VAWT is that they are usually not self starting. Even the most common types of VAWTs, The Darrieous and the Savonious turbines have not been commercialized. That is why a detailed explanation of the HAWTs will be provided in this lecture.

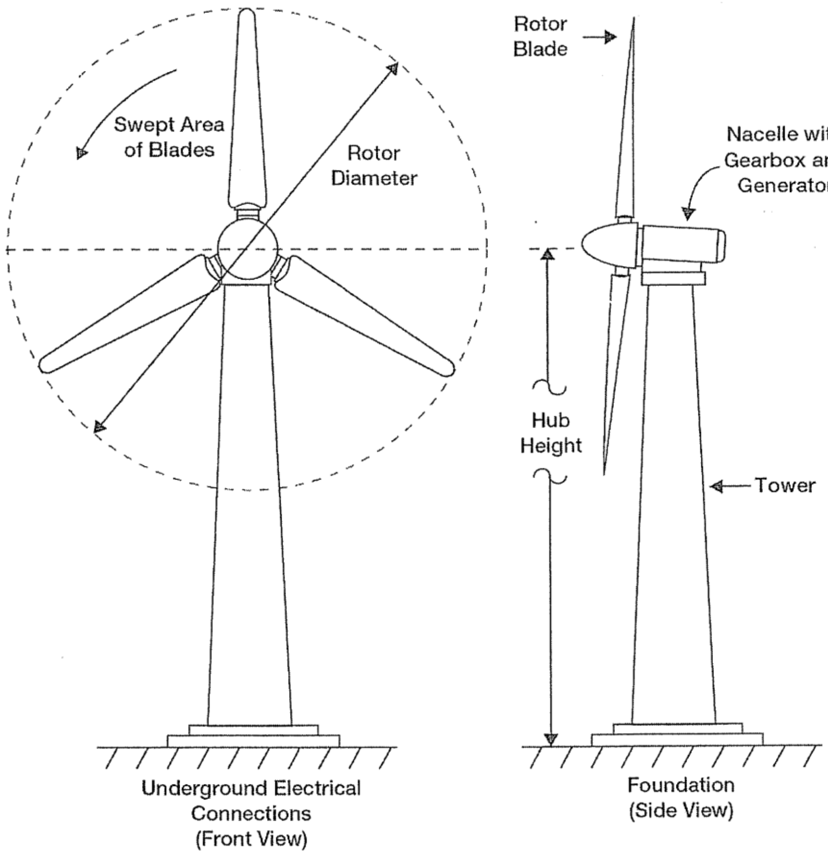


Fig. 6.7 Schematic of a HAWT and the nomenclature.

6.2 Fundamental Concepts

Wind turbines convert the kinetic energy of the air particles to the mechanical or electrical form. .Turbine blades are the main tools to realize this conversion. The efficiency of the conversion basically depends on the followings:

1-Meteoroligal data;

2-Topography of the site;

3-Blade profiles;

4-Number of blades;

5-Tower height.(See Fig.6.7)

The tower height is important since wind speed increases with height above the ground and the rotor diameter is important since this gives the area *A* in the formula for the available power. The ratio between the rotor diameter *D*

and the hub height *H* is often approximately one. The rated power is the maximum power allowed for the installed generator and the control system must ensure that this power is not exceeded in high winds.

The rotational speed of a wind turbine rotor is approximately 20 to 50 rpm and the rotational speed of most generator shafts is approximately 1000 to 3000 rpm. Therefore a gearbox must be placed between the low-speed rotor shaft and the high-speed generator shaft.

The rotor is the wind turbine component that has undergone the greatest development in recent years. The aerofoils used on the first modern wind turbine blades were developed for aircraft and were not optimized for the much higher angles of attack frequently employed by a wind turbine blade. Blade manufacturers now started to use aerofoils specifically optimized for wind turbines.

Different materials have been tried in the construction of the blades, which must be sufficiently strong and stiff, have a high fatigue endurance limit, and be as cheap as possible.

Today most blades are built of glass fibre reinforced plastic, but other materials such as laminated wood are also used.

The kinetic energy of a stream of air with mass m and moving with a velocity is

$$E = \frac{1}{2} m V^2 \tag{6.1}$$

Consider a wind rotor of cross sectional area A exposed to this wind stream as shown in Fig. 6.7 . The kinetic energy of the air stream available for the turbine can be expressed as

$$E = \frac{1}{2} \rho_a v V^2 \tag{6.2}$$

where ρ_a is the density of air and v is parcel available to the rotor.

The air parcel interacting with the rotor per unit time has a cross-sectional area equal to that of the rotor (A_T) and thickness equal to the wind velocity (V). Hence

energy per unit time, that is power, can be expressed as

$$P = \frac{1}{2} \rho_a A_T V^3 \tag{6.3}$$

From Eq. (6.3), we can see that the factors influencing the power available in the wind stream are the air density, area of the wind rotor and the wind velocity.

Effect of the wind velocity is more prominent owing to its cubic relationship with the power.

Power also depends on the elevation and temperature to a certain extent because density is a function of these parameters: $\rho_a = f(Z,T)$ where Z and T are elevation and temperature, respectively.

Fig. 6.8 illustrates the dependence of the air density on temperature and elevation.

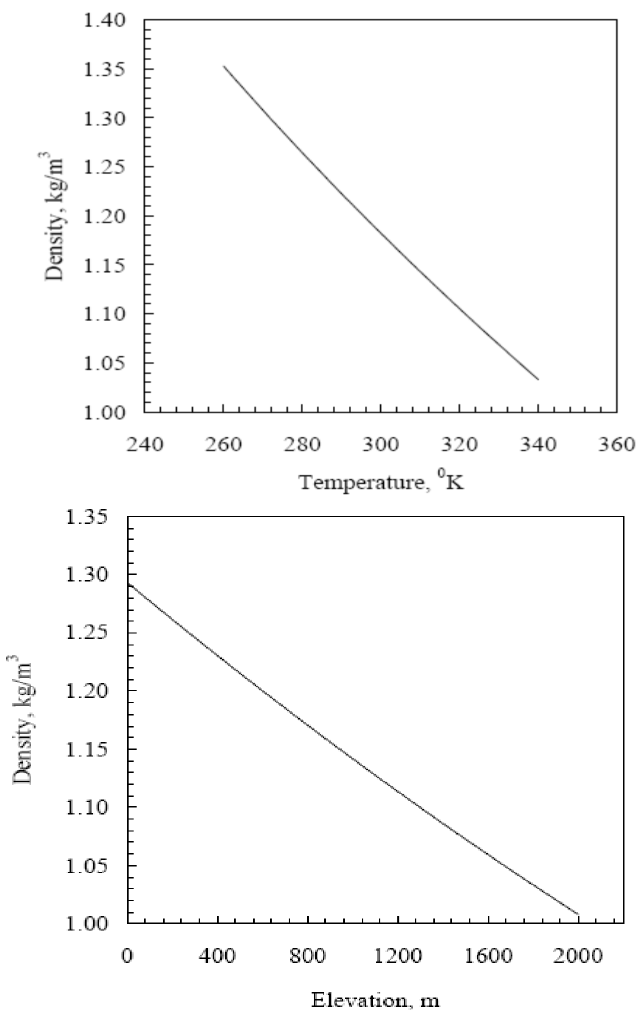


Fig. 6.8 Change of air density with respect to temperature and elevation.

It is obviously seen from Eq. (6.3) that when the wind velocity is doubled, the available power increases by 8 times. In other words, for the same power, rotor area can be reduced by a factor of 8, if the system is placed at a site with double the wind velocity. Hence, selecting the right site play a major role in the success of a wind power projects.

6.2.1 Efficiency concept in wind energy conversion systems

Definition of efficiency for wind energy conversion systems (WECS) is different than that of thermal conversion systems. There is no cost for WECS. The input is the kinetic energy of the air particles which is free of charge!. However, a wind turbine cannot extract the theoretical power (Eqn. 6.3) completely from the wind. When the wind stream passes the turbine, a part of its kinetic energy is transferred to the rotor and the air leaving the turbine carries the rest away.

Then actual power produced by a rotor would decide by the efficiency with which this energy transfer from wind to the rotor takes place.

This efficiency is usually termed as the power coefficient (Cp). Thus, the power coefficient of the rotor can be defined as the ratio of actual power developed by the rotor to the theoretical power available in the wind.

$$C_P = \frac{2P_T}{\rho_a A_T V^3} \tag{6.4}$$

where P_T is the actual power developed by the turbine rotor.

The actual power or the power coefficient which is its ratio to the theoretical power depends mainly on the profile of the rotor blades, blade arrangement and setting etc.

A designer would try to fix these parameters at its optimum level so as to attain maximum Cp at a wide range of wind velocities.

Here, the velocity range is also important because the wind velocity is not constant.

6.2.2 Rotor speed-wind velocity interaction

To go into details in the correlation of the above parameters with the power coefficient, the force balance on the rotro blades should be analyzed. The thrust, experienced by the rotor and the torque are:

$$F = \frac{1}{2}\rho_a A_T V^2 \tag{6.5}$$

$$T = \frac{1}{2}\rho_a A_T V^2 R \tag{6.6}$$

Where R is the radius of the torque. (6.6) is the maximum theoretical torque. In practice the the rotor shaft can develop only a fraction of this maximum:

$$C_T = \frac{2T_T}{\rho_a A_T V^2 R} \tag{6.7}$$

C_T is the torque coefficient and T_T is the actual torque developed by the rotor.

The profiles and the settings of the blades are effective on the efficiency of the WETC because the power developed by a rotor at a certain wind speed greatly depends on the relative velocity between the rotor tip and the wind.

These cases can be analysed:

i-Slow rotor – fast wind velocity

Consider a situation in which the rotor is rotating at a very low speed and the wind is approaching the rotor with a very high velocity. Under this condition, as the blades are moving slow, a portion of the air stream approaching the rotor may pass through it without interacting with the blades and thus without energy transfer.

ii-Fast rotor-slow wind

Similarly if the rotor is rotating fast and the wind velocity is low, the wind stream may be deflected from the turbine and the energy may be lost due to turbulence and vortex shedding.

In both of the above cases, the interaction between the rotor and the wind stream is not efficient and thus would result in poor power coefficient.

This means that the ratio of the rotor to the wind velocity is an important factor. This ratio is called tip speed ratio:

$$\lambda = \frac{R\Omega}{V} = \frac{2\pi NR}{V} \tag{6.8}$$

Where Ω is the angular velocity and N is the rotational speed of the rotor. There is an optimum λ for a given rotor at which the energy transfer is most efficient :

$$C_P = \frac{2P_T}{\rho_a A_T V^3} = \frac{2T_T\Omega}{\rho_a A_T V^3} \tag{6.9}$$

Combining Eqns. (6.7) and (6.8):

$$\frac{C_P}{C_T} = \frac{R\Omega}{V} = \lambda \tag{6.10}$$

Example 6.1

Consider a wind turbine with 5 m diameter. The rotor is rotating with 130 rpm at 10 m/s wind velocity. C_P=0.35. Calculate a)the tip-speed ratio; b) torque coefficient; c) torque available on the rotor shaft. Assume ρ=1.24 kg/m^3.

Area of the rotor is $A_t=\pi 5^2/4=19.63$ m^2

Angular velocity is

$$\Omega = \frac{2\times\pi\times 130}{60} = 13.6 \text{ rad/s}$$

Tip-speed ratio is:

$$\lambda = \frac{2.5\times 13.6}{10} = 3.4$$

Torque coefficient is:

$$C_T = \frac{0.35}{3.4} = 0.103$$

For this torque coefficient the torque available on the rotor shaft can be calculated:

$$T_T = \frac{1}{2}\times 1.24\times\frac{\pi}{4}\times 5^2\times 10^2 \times 0.103 = 313.39 \quad \text{Nm}$$

6.2.3 The Betz limit

The conventional analysis of HAWT originates from the axial momentum concept introduced by Rankine, which was further improved by Froudes for marine propellers. One can imagine a circular duct to construct this theory (Fig. 6.9).

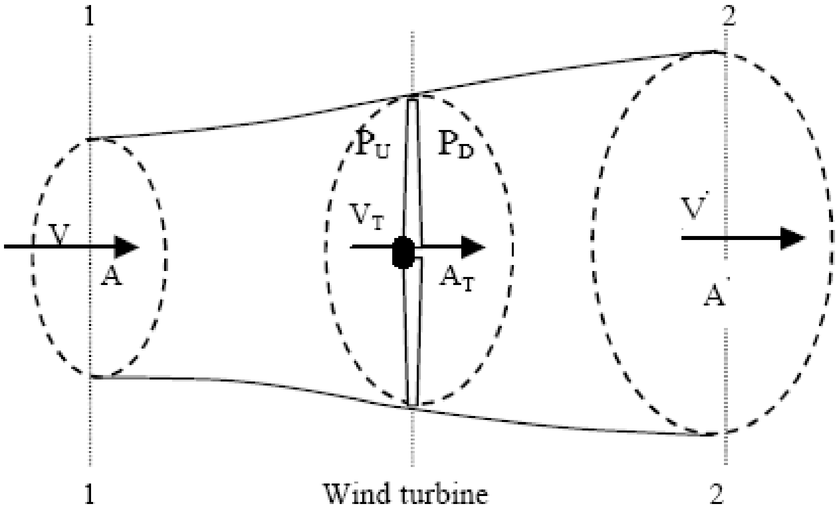


Fig. 6.9 Scheme for axial momentum theory.

Section 1 in Fig. 6.9 denotes the place where the upstream wind comes through the rotor but not disturbed by it. After the wind velocity is reduced by the rotor , it leaves the imaginary circular duct through Section 2 (downstream). Subscripts “T” , “U” and “D “refer to the rotor , upstream and downstream sections, respectively.

In this theory ideal flow conditions have been assumed. In other words, the flow is assumed to be incompressible and homogeneous. The rotor is considered to be made up of infinite number of blades. Static pressures far in front and behind the rotor are considered to be equal to the atmospheric pressure. Frictional drag over the blades and wake behind the rotor are neglected.

V_T is the velocity at the turbine section. According to the law of conservation of mass, the mass of air flowing through these sections is equal. Thus:

$$\rho_a AV = \rho_a A_T V_T = \rho_a A'V' \tag{6.11}$$

The thrust force experienced by the rotor is due to the difference in momentum of the incoming and outgoing wind, which is given by

$$F = \rho_a AV^2 - \rho_a A'V'^2 \tag{6.12}$$

Assuming that the density of the air remains constant

$$F = \rho_a A_T V_T (V - V') \tag{6.13}$$

The thrust can also be represented as the pressure difference in the upstream and downstream sides of the rotor:

$$F = (p_U - p_D)A_T \tag{6.14}$$

Applying the Bernoulli Eqn.

$$p + \frac{\rho_a V^2}{2} = p_U + \frac{\rho_a V_T^2}{2} \tag{6.15a}$$

$$p + \frac{\rho_a V'^2}{2} = p_D + \frac{\rho_a V_T^2}{2} \tag{6.15b}$$

From equations (6.15a) and (6.15b)

$$p_U - p_D = \frac{\rho_a (V^2 - V'^2)}{2} \tag{6.16}$$

Substituting the above equation in Eqn. (6.14) results in

$$F = \frac{\rho_a A_T (V^2 - V'^2)}{2} \tag{6.17}$$

Comparing Eqns. (6.13) and (6.14),

$$V_T = \frac{(V + V')}{2} \tag{6.18}$$

is obtained which means that the velocity of the wind stream at the rotor section is the average of the velocities at its upstream and downstream sides. Here, also another factor is obtained, indicating the degree with which the wind velocity at the upstream of the rotor is slowed down by the turbine:

$$a = \frac{(V - V_T)}{V} \tag{6.19}$$

The factor given in Eqn. (6.19) is called “axial induction factor”.

From Eqns. (6.18) and (6.19)

$$V_T = V(1-a) \tag{6.20}$$

and

$$V^{'} = V(1-2a) \tag{6.21}$$

As it is discussed earlier, the power imparted to the wind turbine is due to the transfer of kinetic energy from the air to the rotor. The mass flow through the rotor over a unit time is

$$m = \rho A_T V_T \tag{6.22}$$

Hence, the power developed is:

$$P_T = \frac{1}{2}\rho_a A_T V_T (V^2 - V^{'2}) \tag{6.23}$$

Substituting the the relationship between the rotor velocity and the downstream velocity,

$$P_T = \frac{1}{2}\rho_a A_T V^3 4a(1-a\ \ )^2 \tag{6.24}$$

Thus, the power coefficient can be written in terms of induction factor:

$$C_P = 4a(1-a)^2 \tag{6.25}$$

To search for the value of the induction factor generating the maximum power,

$$\frac{dC_P}{da} = 0 \tag{6.26}$$

is applied and

$$P_{TMAX} = \frac{1}{2}\rho_a A_T V^3 \frac{16}{27} \tag{6.27}$$

is obtained.

Thus; *the maximum theoretical power coefficient of a horizontal axis wind turbine is 16/27*, known as the Betz limit.

Example 6.2 [15]

A 12 m/s wind at 96 kPa and a temperature of 21^{0}C enters a two bladed wind turbine with a diameter of 12 m. Calculate a) the power of incoming wind. b) the theoretical maximum power that could be extracted. c) a reasonable value for attainable power. D) the rotor speed in RPM, requieredfor part c) and the torque for part c).

6.2.4 Performance of the wind turbines

The performance of a wind rotor is usually characterized by the variations in its power coefficient with the tip speed ratio (Fig. 6.10). As both these parameters are dimensionless, the cp-λ curve (Fig. 6.10) will represent the rotor performance irrespective of the rotor size and site parameters.

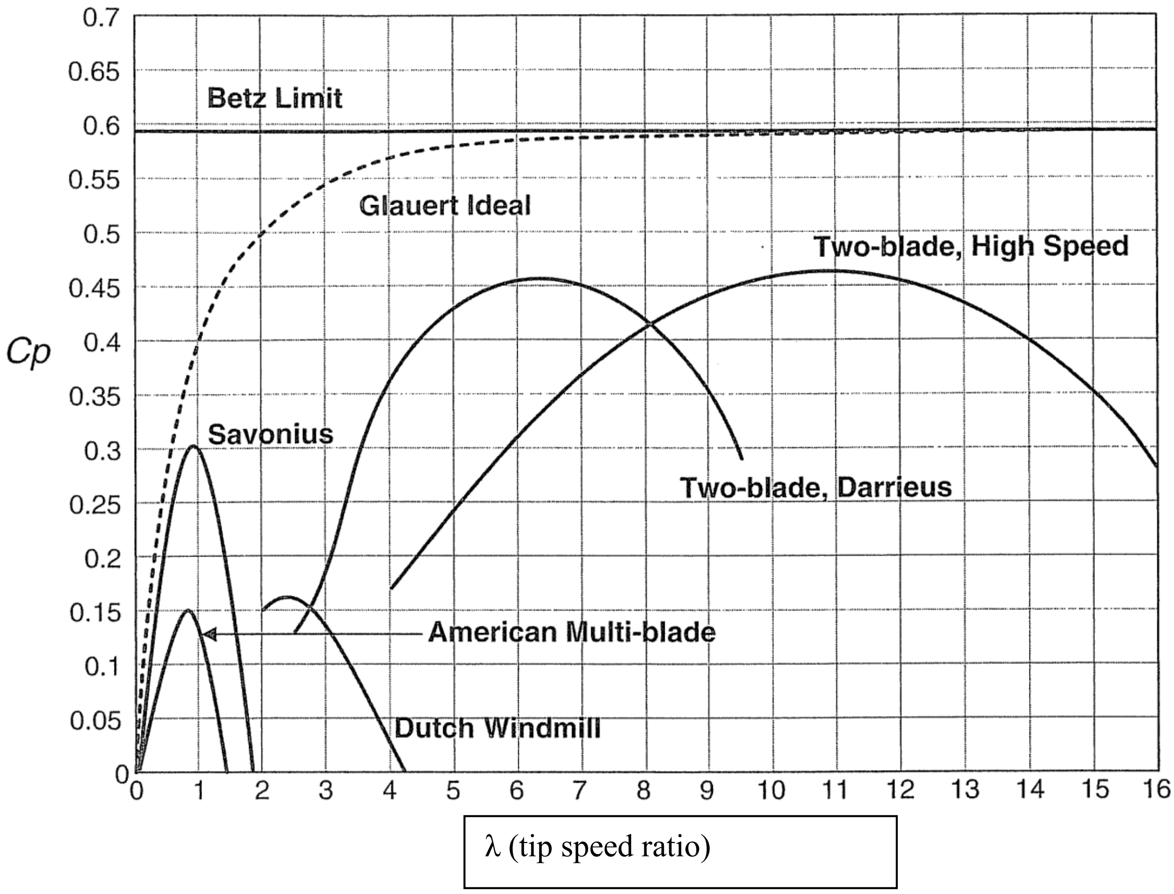


Fig. 6.10 Power coefficient versus tip speed ratio for different wind turbine configurations.

6.3 Aerodynamics of Wind Turbines [23]

Items exposed to the wind are subjected to forces in both the drag direction (parallel to the air flow) and the lift direction (perpendicular to the air flow). The old Dutch windmills utilized lift as well as drag, and because lift devices must be widely separated to generate the maximum possible amount of power, those machines evolved with a small number of blades. The high-lift, low-drag shapes, referred to as airfoils, that were developed for airplane wings and propellers in the early part of the twentieth century were quickly incorporated into wind machines to produce the first modern wind machines, usually known as wind turbines. Wind turbines use the lift generated by the blades to produce power. Because the blades must be widely separated to generate the maximum amount of lift, lift-type machines have a small number of blades.

Fig. 6.11 illustrates the flow field about a moving drag device. The drag results from the relative velocity between the wind and the device, and the power that is generated by the device (the product of the drag force and the translation or blade velocity) may be expressed as

$$P = Dlv = [1/2\rho(U-v)^2]C_D dv, \tag{6.28}$$

where P is the power extracted from the wind, D is the drag force per unit length in the span direction (into the page), l is the length of device in the span direction (into the page), v is the translation (or blade) velocity, r is the air density, U is the steady free-stream wind velocity, C_D=Drag/(1/2pclU^2) (drag coefficient, a function of device geometry), and c is the device width (perpendicular to the wind, in the plane of the page).

The translation (or blade) velocity of the device must always be less than the wind velocity or no drag is generated and no power is produced. The power extraction efficiency of the device may be expressed as the ratio of the power extracted by the device to the power available in the wind passing through the area occupied by the device (the projected area of the device), known as the power coefficient, Cp.

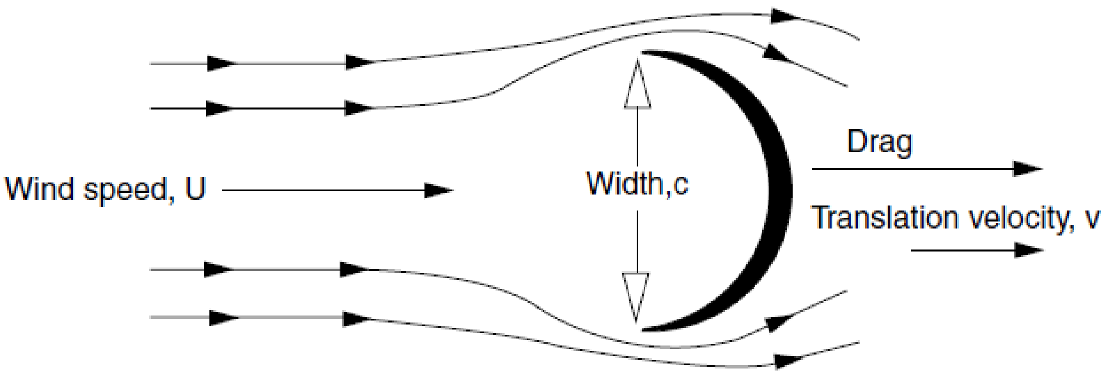


Fig. 6.11 Definition of drag

The power available is

$$P_A = \frac{1}{2}\rho U^3 A = \frac{1}{2}\rho U^3 cl, \tag{6.29}$$

where A is the area of the device projected perpendicular to the wind (cl). C_P for a drag machine is

$$C_P = \frac{P}{1/2\rho U^3 cl} = \frac{v}{U}\left[1 - \frac{v}{U}\right]^2 C_D. \tag{6.30}$$

Fig.6.12 depicts an airfoil that is moving at some angle relative to the wind and is subject to both lift and drag forces. The relative wind across the airfoil is the vector sum of the wind velocity, U, and the blade velocity,v. The angle between the direction of the relative wind and the airfoil chord (the straight line from the leading edge to the trailing edge of the airfoil) is termed the angle of attack, α. The power extracted by this device may be expressed as

$$P = 1/2\rho U^3 cl \frac{v}{U}\left[C_L - C_D \frac{v}{U}\right]\sqrt{1 + \left(\frac{v}{U}\right)^2}, \tag{6.31}$$

Where c is the chord length, and

$$C_L = \frac{\text{Lift}}{1/2\rho cl U^2} \text{(where lift is the coefficient, a function of airfoil shape and } \alpha\text{)},$$

$$C_D = \frac{\text{Drag}}{1/2\rho cl U^2} \text{(where drag is the coefficient, a function of airfoil shape and } \alpha\text{)}.$$

And power coefficient for a lift machine is

$$C_P = \frac{v}{U}\left[C_L - C_D\frac{v}{U}\right]\sqrt{1+\left(\frac{v}{U}\right)^2}. \qquad (6.32)$$

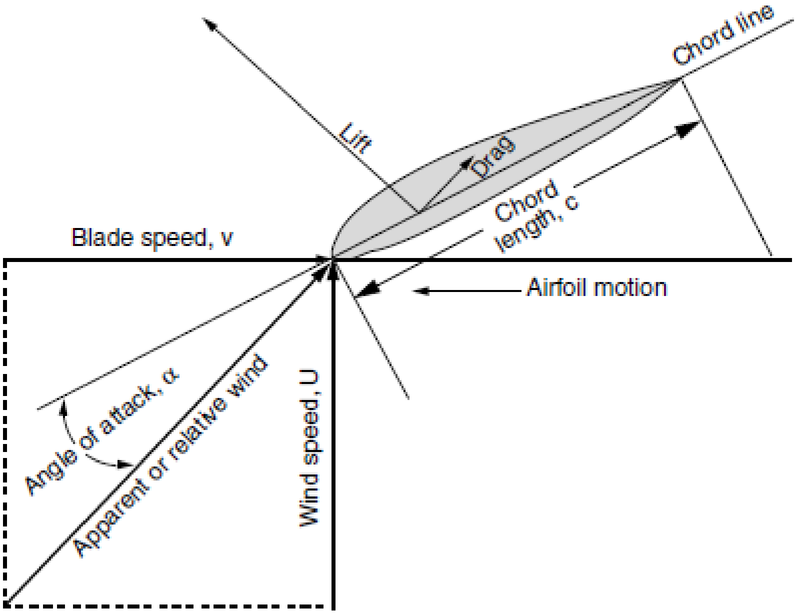


Fig. 6.12 Schematic of lift induced airfoil.

As the angle of attack increases beyond a certain value, the lift levels off and then drops slightly and the drag begins to rise rapidly. This is due to separation of the flow from the upper surface of the airfoil, a flow condition referred to as *stall*. An example, S-809 airfoil is illustrated in Fig. 6.13.

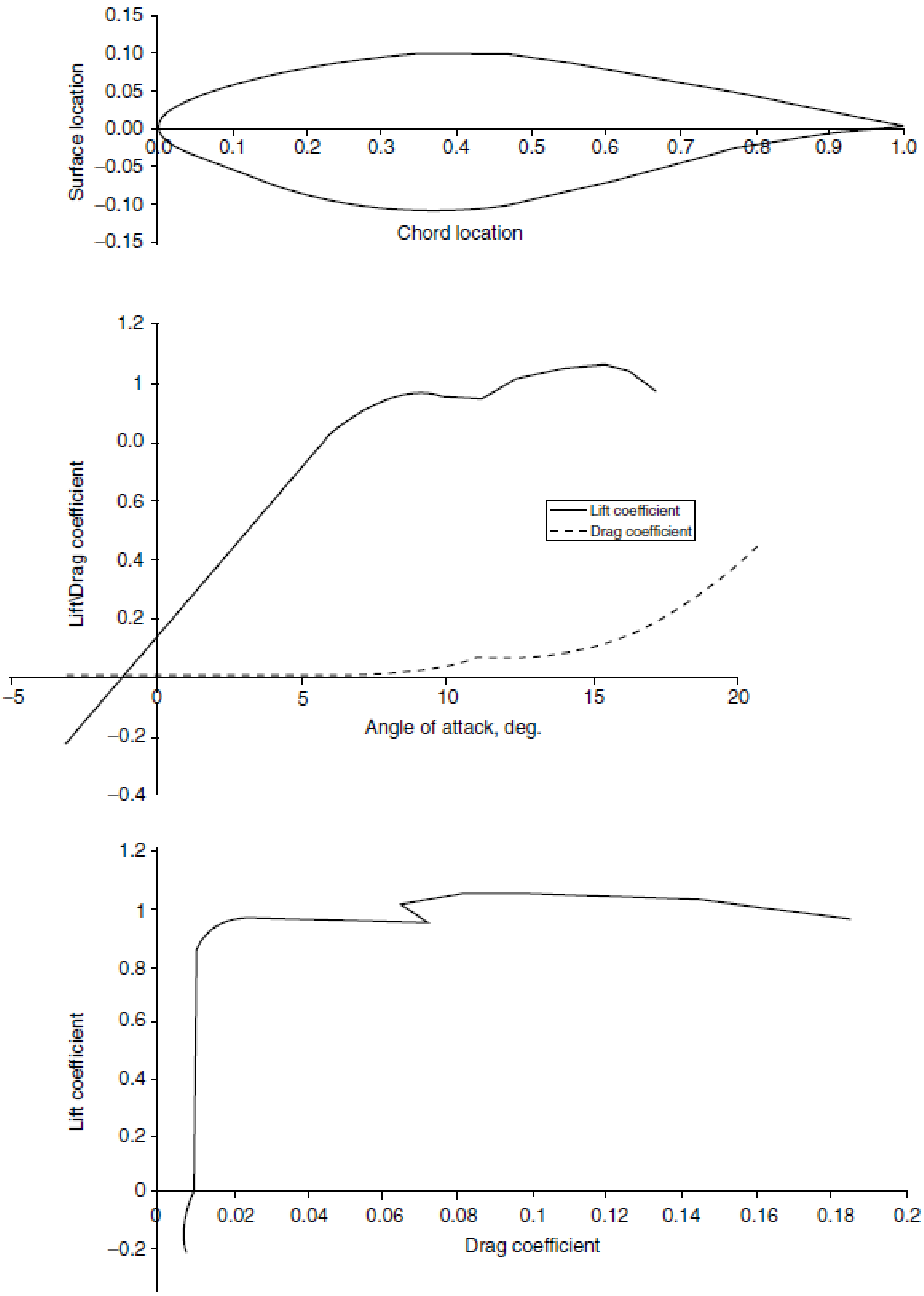


Fig. 6.13 Profile and performance characteristics of S-809 airfoil.

Lift-type machines tend to have only a few blades, while drag-type machines tend to have many blades. Thus, the difference in the turbine performance coefficient (now based on the rotor. frontal area rather than the blade or bucket frontal area) of actual wind machines is much less than might be expected from the analysis presented above. A well-designed lift-type machine may achieve a peak power coefficient (based on the area covered by the rotating turbine blades) of 0.5–0.59, while a pure drag-type machine may achieve a peak power coefficient of no more than 0.2. Some of the multi bladed drag-type windmills actually utilize a blade shape that creates some lift, and they may achieve power coefficients of 0.3 or slightly higher. The drag machines rotate slowly (the blade translation velocity cannot exceed the effective winds peed) and produce high torque, whereas the lift machines rotate quickly (to achieve a high translation velocity) and produce low torque. The slow-rotating, high-torque drag machines are very well suited for mechanical power applications such as milling grain and pumping water.

On the other hand, extensive experience has shown that fast-rotating, lift-type machines are much easier to adapt to electrical generators and can produce electricity at a significantly lower cost of energy than drag-type machines.

6.4 Regulation

All turbines incorporate some method of regulating or limiting the peak power produced. The entire turbine, including the rotor, the transmission and the generator, must be sized to handle the loads associated with peak power production. While high winds (above, for example, 25 m/s) contain large amounts of available power, they do not occur very often, and the power that can be captured is very small. This is illustrated in Fig. 6.14. In this figure, the power density is the power per unit of rotor area (normalized to yield a value under the curve of unity) that is available for capture by a wind turbine. This takes into account the amount of time that the wind actually blows at each wind speed (the probability density that is also shown on the figure).

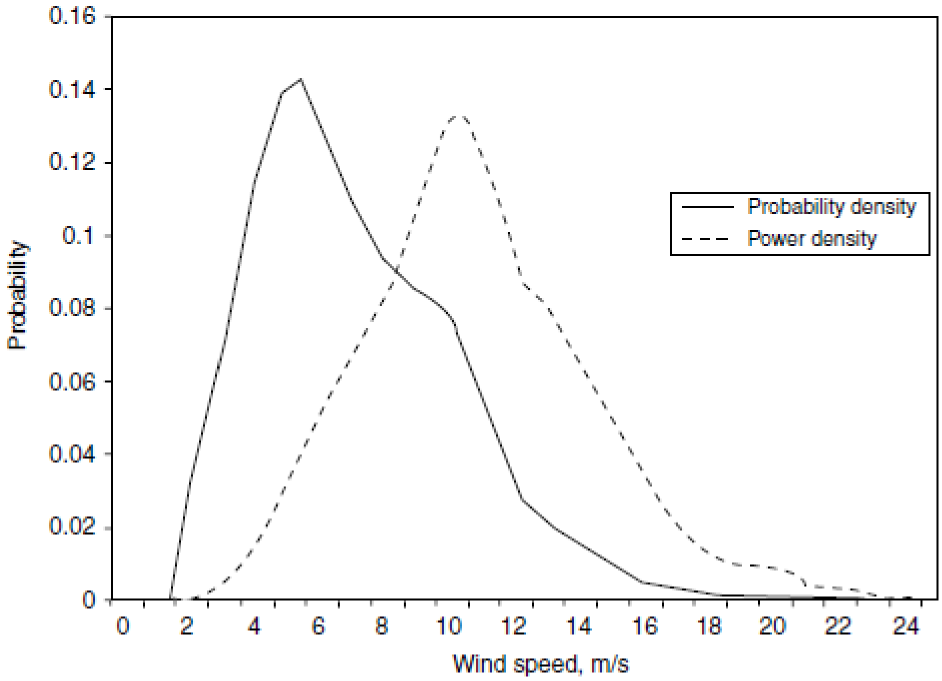


Fig. 6.14 An example of windspeed and windpower probability densities [23]

Generators and transmissions operate most efficiently at their design conditions, typically close to their maximum capacity. These efficiencies drop off quickly at conditions below design. Cost trade-off studies reveal that it is far more cost effective to limit the maximum power level to that achieved at, for instance, 13–14 m/s and to shut the turbine down completely at a cutout wind speed of, for example, 26 m/s, as illustrated in Fig.6.15, than to try to capture the maximum amount of power at the higher wind speeds. Under these conditions, the transmission and generator are operating near design conditions for a significant portion of the time, and the turbine can be built with far less material than would be required for a turbine that generates peak power at 25 m/s. The additional energy captured due to the increase in generator and transmission efficiencies at the lower wind speeds is usually many times greater than that lost due to limiting the peak power at the rather infrequent winds above 14 m/s (refer to the wind speed distribution in Fig. 6.14.

Nearly all modern large horizontal-axis turbines now use blade pitch control, where either the entire blade or a portion of it is rotated about the longitudinal axis to change the angle of attack and, therefore, the power output of the turbine, to limit peak power.

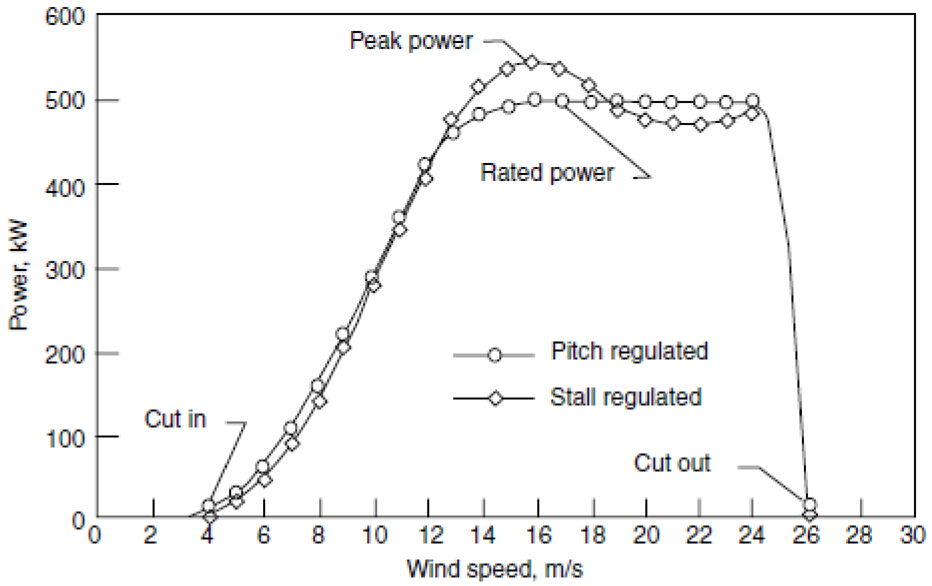


Fig. 6.15 Sample power curves for stall-regulated and pitch-regulated wind turbines.

The local pitch, θ, is a combination of the pitch angle, θ*p*, and the twist of the blade,β, as θ = θ*p* + β, where the pitch angle is the angle between the tip chord and the rotor plane and the twist is measured relative to the tip chord.

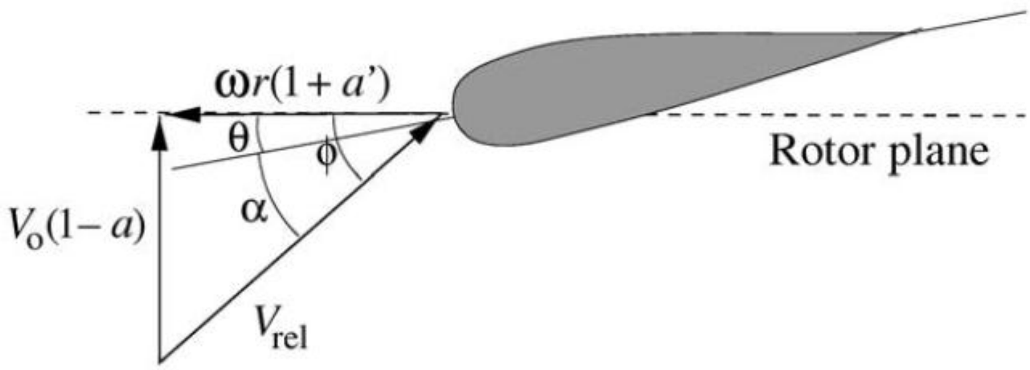


Fig. 6.16 Velocities at the rotor plane.

Some turbines are designed with fixed-pitch blades, and rely on airfoil stall at high winds to limit the maximum power output of the machine.

A stall regulated wind turbine is normally operated at an almost constant rotational speed and thus the angle of attack increases as the wind speed increases (Fig. 6.16). As the local angles of attack are increased, the blades stall, causing the lift coefficient to decrease and the drag coefficient to increase.

Example 6.3
Design the rotor for an aero generator to develop 100 W at a wind speed of 7 m/s. $C_P = 0.4$; $C_L = 0.8$; angle of attack = 4^0; number of blades = 3; rotational speed = 500 rpm. Radial induction factor, a=0.

Find:

a) Rotor diameter,

b) Local pitch angle at r/R = 0.2; r/R = 0.4; r/R = 0.6; r/R = 0.8; r/R = 1.0

6.5 Analysis of Wind Regimes

The earth receives around 1.7×10^{14} kW of power from the sun in the form of solar radiation. This radiation heats up the atmospheric air. The intensity of this heating will be more at the equator (0^o latitude) as the sun is directly overhead. Air around the poles gets less warm, as the angle at which the radiation reaches the surface is more acute. The density of air decreases with increase in temperature. Thus, lighter air from the equator rises up into the atmosphere to a certain altitude and then spreads around. This causes a pressure drop around this region, which attracts the cooler air from the poles to the equator. This movement of air causes the wind.

Thus, the wind is generated due to the pressure gradient resulting from the uneven heating of earth's surface by the sun. As the very driving force causing this movement is derived from the sun, wind energy is basically an indirect form of solar energy. One to two per cent of the total solar radiation reaching the earth's surface is converted to wind energy in this way.

The wind velocity is not the same everywhere, on the world. Changes in velocity and direction of wind near the surface, say up to 100 m above the ground, is more important as far as energy conversion is concerned. In this region, the wind pattern is further influenced by several local factors.

The wind power density is ***the available avarage wind power per m^2 of wind turbine area.***

The wind power density is measured from class 1(lowest) to class 7 (highest) and is specified at nominal 10 m and 50 m elevations (Table 6.1)

Table 6.1 Wind power density classes [15].

Wind Power Class	10 m (33 ft) Wind Power Density (W/m^2)	10 m (33 ft) Speed m/sec (mph)	50 m (164 ft) Wind Power Density (W/m^2)	50 m (164 ft) Speed m/sec (mph)
1	0	0	0	
2	100	4.4 (9.8)	200	5.6 (12.5)
3	150	5.1 (11.5)	300	6.4 (14.3)
4	200	5.6 (12.5)	400	7.0 (15.7)
5	250	6.0 (13.4)	500	7.5 (16.8)
6	300	6.4 (14.3)	600	8.0 (17.9)
7	400	7.0 (15.7)	800	8.8 (19.7)
	1000	9.4 (21.1)	2000	11.9 (26.6)

In Fig. 6.17, a wind power density distribution map is shown for Gönen, Turkey . The detailed calculations are available in [10].

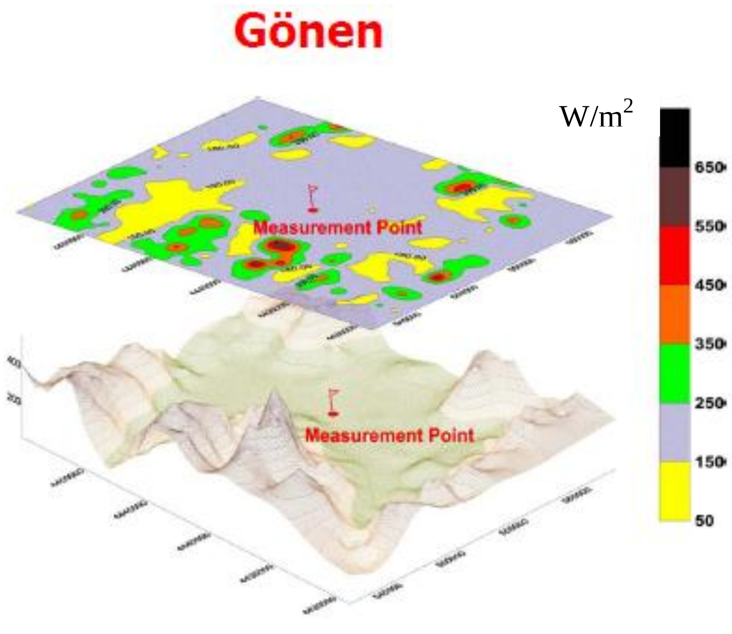


Fig. 6.17 Wind power density distribution for Gönen [10].

Statistics of the wind speed

The probability of occurrence of a given wind speed is expressed by the Weibull distribution,

$$h(v,k,c) = \frac{k}{c}(\frac{v}{c})^{k-1} \exp\left[-(\frac{v}{c})^k\right] \qquad (6.33)$$

Here, c is the scale parameter and k is the shape parameter.

The shape parameter controls the shape of the distribution. The larger the shape parameter ,the closer the distribution comes to Gaussian.

The scale parameter controls the value of the mode (the most probable speed). The larger the scale parameter, the higher the mode, and the lower the probability of the given speed less than the mode.

The shape parameter is dimensionless. The scale parameter is in the same dimensions with the speed. For wind analysis, the shape parameter value is usually 2 [15]. k = 2 usually provides an acceptable match for most of the cites (Fig. 6.18).

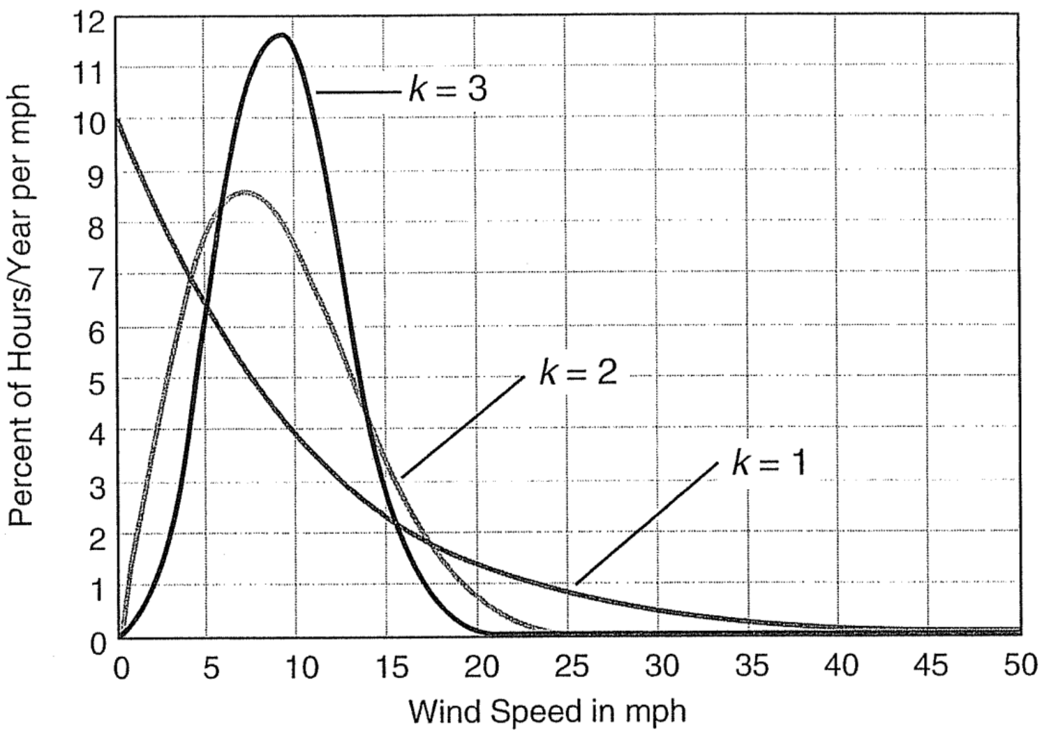


Fig. 6.18 Weibull distribution for c=10mph and varios k values.

The smaller the value of the scale parameters, the more hours at lower wind speeds. As the value of the c increases, the mode wind speed values increase, and the number of hours per year at wind sped higher than the mode increases (Fig. 6.19).

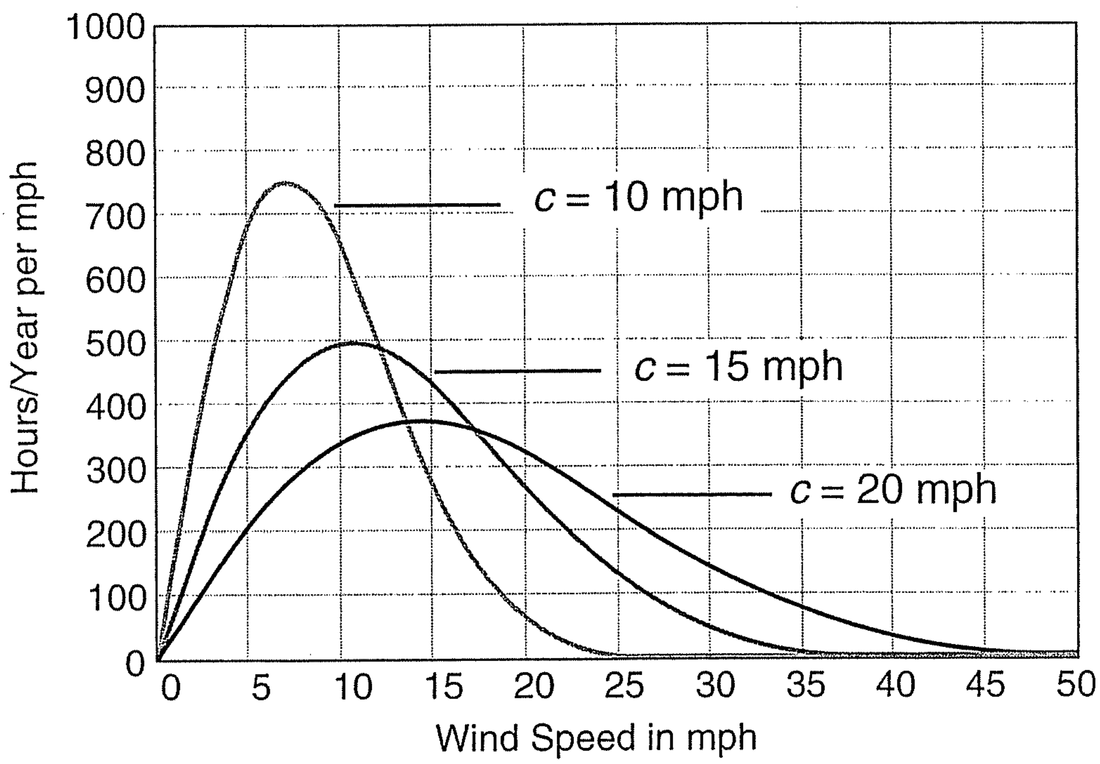


Fig. 6.19 Weibull distribution for k = 2 and varios c values.

The mode speed represents the most probable speed.

$$V_{mean} = \int_0^\infty h(v,k,c).v.dv \tag{6.34}$$

Since, the wind power is proportional to the cube of the wind speed, the average power density available for collection per unit of swept area is

$$Power_{available} = \int_0^\infty \frac{1}{2}.\rho.h(v,k,c).v^3.dv \tag{6.35}$$

Thus, the speed of interest for wind energy is the root-mean-cube-speed

$$V_{rmc} = \sqrt[3]{\int_0^\infty h(v,k,c).v^3.dv} \tag{6.36}$$

and the avarage annual power density becomes

$$Power_{available} = \frac{1}{2}\rho V_{rmc}^{3} \tag{6.37}$$

A reasonable power coefficient value for a modern, well designed turbine (See Fig. 6.10) is 0.5. The annual average extraction power density can be cast as

$$Power_{ext.} = \frac{1}{4}\rho V_{rmc}^{3} \tag{6.38}$$

The total energy that can be extracted per year for a given distribution is the integral of (6.38) for each velocity over all possible velocities.

Example 6. 7 [15]

Find V_{mode}, V_{mean}, V_{rmc}, the power density available distribution, and the power extracted per m^2 for a wind turbine at a site corresponding to a Weibull wind distribution with c = 15 m/sec and k = 1.5. The air density is 1.225 kg/m^3.

6.6 Operation of the Wind Turbines

Operation at the maximum cp would maximize the energy extracted from the wind but there are factors limiting this ideal case such as generator capacity. The maximum speed range will occur for only a few hours for a given speed distribution. Sizing a generator for an input corresponding to the maximum speed range would result in an oversize generator that would operate at maximum output only a few hours within a year. The tip-speed ratio would have to be maintained constant, in case of providing maximum cp. As the wind speed increased, the rotor rotation rate would have to increase to maintain a constant cp. However, the radial stresses are proportional to the rotational speed. Thus, operating at high speeds with constant tip-speed ratio would require a robust wind turbine.

The ultimate purpose of a wind turbine control strategy is to regulate the power output of the turbine a s function of wind speed and direction.

The major factors affecting the power produced by a Wind Energy Conversion System (WECS) are

(a) the strength of the wind spectra prevailing at the site and its availability to the turbine

(b) the aerodynamic efficiency of the rotor in converting the power available in the wind to mechanical shaft power and

(c) the efficiencies in manipulating, transmitting and transforming this power into the desired form.

Fig. 6. 20 shows the typical regimes of a turbine speed control.

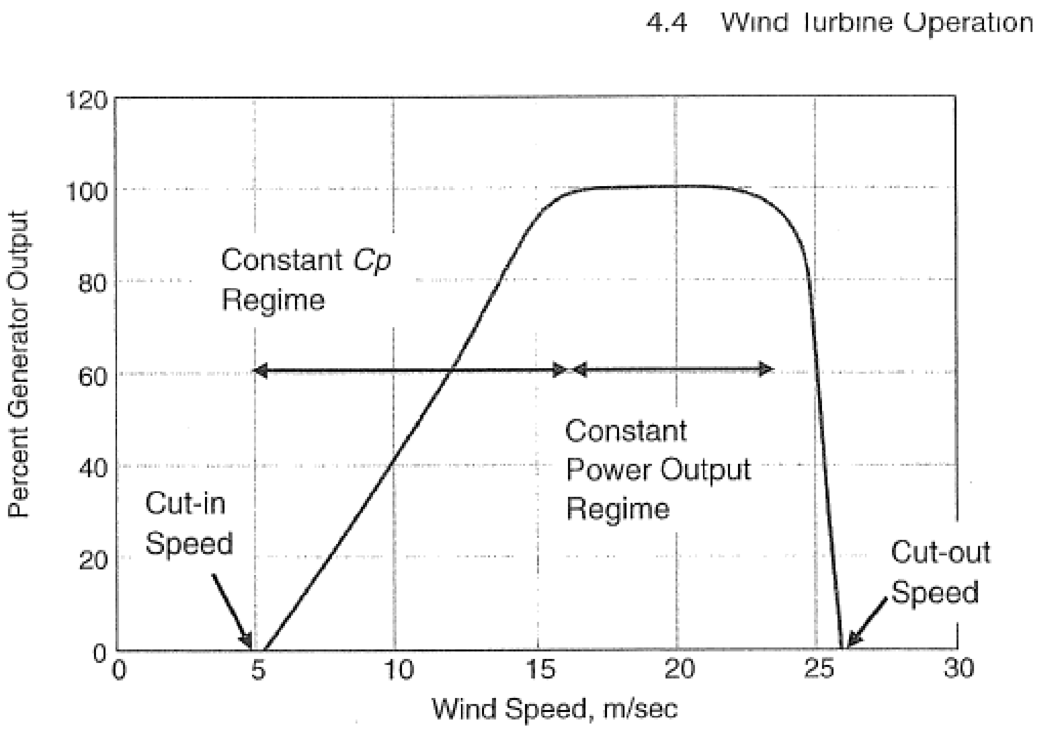


Fig. 6.20 Typical regimes of a turbine speed control.

Example 6.8 [15]

The system described in the previous example is specified to have cut-in speed of 5m/s, a cut-out speed of35 m/s, and a rated generator input of7.5 kW/m^2. The maximum power coefficient c_p is 0.5. Determine and plot the following for both the system with no controls and and the system controlled to meet the constraints: a) The power density of the system, b) the c_p versus wind speed required, c) the energy extraction, d) the total extracted by the system.

Capacity factor is one of the important indices for assessing the field performance of a wind turbine. It is the ratio of the energy actually produced by the system to the energy that could have been produced by it, if the machine would have operated at its rated power throughout the time period:

$$C_F = \frac{E_T}{P_{RATED} T} \tag{6.39}$$

The capacity factor for a reasonable efficient turbine at a potential site may range from 0.25 to 0.4.

A capacity factor 0.4 and higher means that system is very efficient.

6.7 Commercial Wind Energy Conversion Systems

Up to now a single wind turbine have been analyzed. On the other hand, wind turbine farms are becoming common. For wind turbines employed in arrays, the recommended space is 2-4 rotor diameters facing the prevailing wind and 8-12 diameters parallel to the wind. For more than a single row of wind turbines in an array , the turbine locations in the succeeding rows are staggered [15]. Fig. 6.21 shows a schematic of the recommended spacing of wind turbines on wind farms.

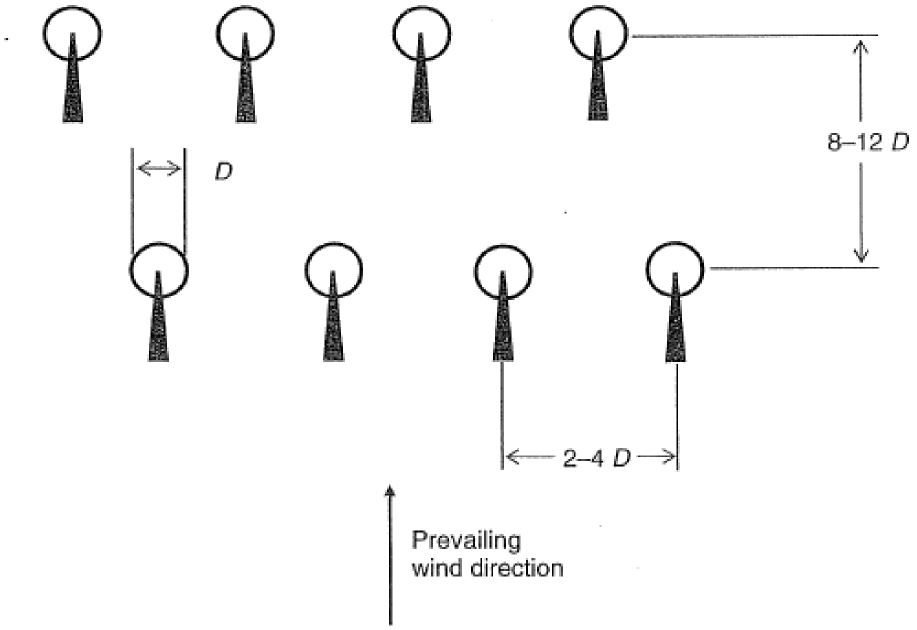


Fig. 6.21 Wind turbine arrangement for wind farms [15].

Three examples of commercial wind turbines used in these farms, or can be provided for single applications are given below.

GE 1.5 MW

GE Energy manufactures large wind turbines with nominal outputs of 1.5 MW, 2.5 MW, 3 MW and 3.6 MW. The technical information for the 1.5 MW family is given in Table 6.2. The power curve of the turbine is illustrated in Fig. 6.22.

Table 6.2 GE Power 1.5 MW specifications [15].

	1.5s	1.5se	1.5sl	1.5sle	1.5xle
Rated capacity (kW)	1500	1500	1500	1500	1500
Cut-in speed (m/sec)	4	4	3.5	3.5	3.5
Cut-out speed (m/sec)	25	25	20	25	20
Rated wind speed (m/sec)	13	13	14	14	12.5
Rotor diameter (m)	70.5	70.5	77	77	82.5
Swept area m^2	3904	3904	4657	4657	5346
Rotor speed (RPM)	12–22.2	12–22.2	11–20.4	11–20.4	10.1–18.7

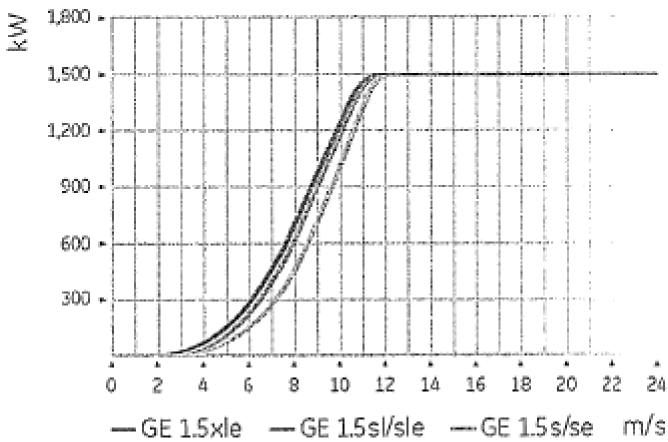


Fig. 6.22 Power vs wind speed for GE 1.5 MW.

<u>The Vestas V52 850 kW</u>

It is a popular wind turbine worldwide. The specifications is given in Table 6.3.

Table 6.3 The Vestas V52 850 kW specifications.

Rated capacity (kW)	850
Cut-in speed (m/sec)	4
Cut-out speed (m/sec)	25
Rated wind speed (m/sec)	16
Rotor diameter (m)	52
Swept area m^2	2124
Rotor speed (RPM)	14–31.4

The power curve for this turbine is illustrated in Fig. 6.23 with the sound levels.

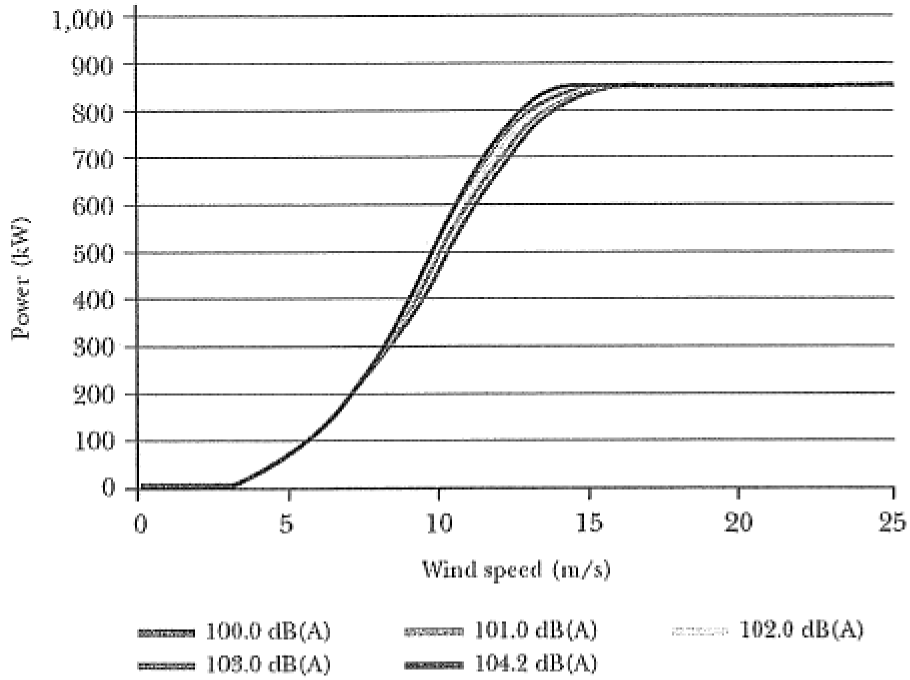


Fig. 6.23 The power vs wind speed for VestasV52 850 kW.

<u>Bergey 10 kW-Excel</u>

This is a small turbine for residential and small commercial needs. The specifications, and power curve for this turbine are given in Table 6.4 and Fig. 6.24, respectively.

Table 6.4 Specifications for Bergey 10 kW-Excel

Rated capacity (kW)	10
Cut-in speed (m/sec)	3.1
Cut-out speed (m/sec)	None (furled at 15.6 m/sec)
Rated wind speed (m/sec)	13.8
Rotor diameter (m)	6.7
Swept area m^2	35.3
Rotor speed (RPM)	14–31.4

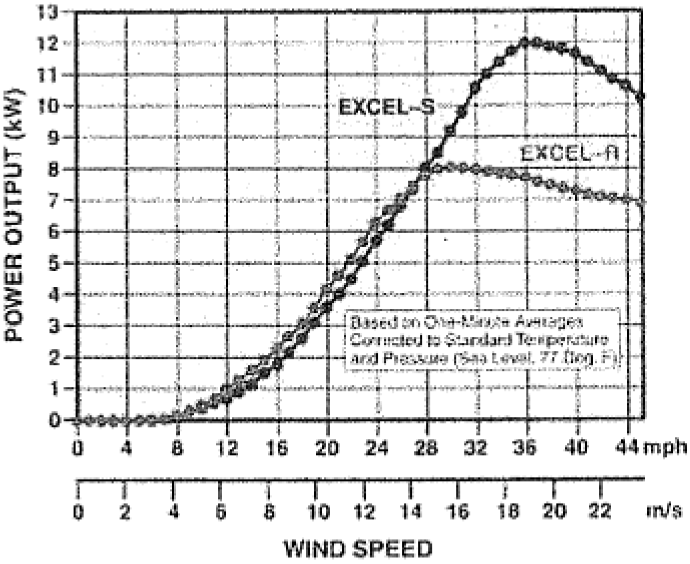


Fig. 6.24 Power curve for Bergey 10 kW Excel.

6.8 Situation of WECS in Turkey

The detailed information can be provided from eie.gov.tr. However, a short summary due to Feb. 2009 has been given in Table 6.7.

Table 6.5 Situation of WECS in Turkey due to Feb. 2009 [14]

Wind Projects in Türkiye					
Company	*Location*	*Comm. Date*	*Installed Cap. (MW)*	*Turbine manufacturer*	*Turbine capacity*
Alize A.Ş.	İzmir-Çeşme	1998	1.50	Enercon	3 X 500 kW
Güçbirliği A.Ş.	İzmir-Çeşme	1998	7.20	Vestas	12 X 600 kW
Bores A.Ş.	Çanakkale-Bozcaada	2000	10.20	Enercon	17 X 600 kW
Sunjüt A.Ş.	İstanbul-Hadımköy	2003	1.20	Enercon	2 X 600 kW
Yapısan A.Ş.	Balıkesir-Bandırma	I/2006	30.00	GE	20 X 1.500 kW
Ertürk A.Ş.	İstanbul-Silivri	II/2006	0.85	Vestas	1 X 850 kW
Mare A.Ş.	İzmir-Çeşme	I/2007	39.20	Enercon	49 X 800 kW
Deniz A.Ş.	Manisa-Akhisar	I/2007	10.80	Vestas	6 X 1.800 kW
Anemon A.Ş.	Çanakkale-İntepe	I/2007	30.40	Enercon	38 X 800 kW
Doğal A.Ş.	Çanakkale-Gelibolu	II/2007	14.90	Enercon	13 X 800 kW + 5 X 900 kW
Deniz A.Ş.	Hatay-Samandağ	I/2008	30.00	Vestas	15 X 2.000 kW
	Manisa-Sayalar	I/2008	30.60	Enercon	38 X 800 kW
İnnores A.Ş.	İzmir-Aliağa	I/2008	42.50	Nordex	17 X 2.500 kW
Lodos A.Ş.	İstanbul-Gaziosmanpaşa	I/2008	24.00	Enercon	12 X 2.000 kW
Ertürk A.Ş.	İstanbul-Çatalca	I/2008	60.00	Vestas	20 X 3.000

					kW
Baki A.Ş.	Balıkesir-Şamlı	II/2008	90.00	Vestas	38 X 3.000 kW
Dares A.Ş.	Muğla-Datça	II/2008	10.00	Enercon	27 X 800 kW + 8 X 900 kW
CAPACITY UNDER OPERATION			**433.35**		
Ayen A.Ş.	Aydın-Didim	I/2009	31.50	Suzlon	2.100 kW
Ezse Ltd. Şti.	Hatay-Samandağ	II/2009	35.10	Nordex	900 kW
Ezse Ltd. Şti.	Hatay-Samandağ	II/2009	22.50	Nordex	2.500 kW
Rotor A.Ş.	Osmaniye-Bahçe	II/2009	135.00	GE	54 X 2.500 kW
Mazı-3 Res Elk. Ür. A.Ş.	İzmir - Çeşme	II/2009	22.50	Nordex	9 X 2500 kW
Kores A.Ş.	İzmir-Çeşme	II/2009	15.00	Nordex	2.500 kW
Soma A.Ş.	Manisa-Soma	II/2009	140.80	Enercon	176 X 800 kW

İ *CAPACITY UNDER CONSTRUCTION*			**402.40**		
Alize A.Ş.	Balıkesir-Susurluk		19.00	Enercon	17 X 800 kW ve 6 X 900 kW
Borasco A.Ş.	Balıkesir-Bandırma		45.00	Vestas	15 X 3000 kW
Alize A.Ş.	Tekirdağ-Şarköy		28.80	Enercon	14 X 2000 kW ve 1 X 800 kW

Alize A.Ş.	Balıkesir-Havran		16.00	Enercon	8 X 2000 kW
Alize A.Ş.	Çanakkale-Ezine		20.80	Enercon	10 X 2000 kW ve 1 X 800 kW
Belen A.Ş.	Hatay-Belen		30.00	Vestas	10 X 3000 kW
Alize A.Ş.	Manisa-Kırkağaç		25.60	Enercon	32 X 800 kW
Boreas A.Ş.	Edirne-Enez		15.00	Nordex	6 X 2.500 kW
Doruk A.Ş.	İzmir-Aliağa		30.00	Enercon	15 X 2.000 kW
Yapısan İnş. Elk. San.Tic. A.Ş.	İzmir-Aliağa		90.00	Nordex	36 X 2500 kW
Doğal A.Ş.	İzmir-Aliağa		30.00	Enercon	15 X 2000 kW
Doğal A.Ş.	İzmir-Foça		30.00	Enercon	15 X 2000 kW
Poyraz A.Ş.	Balıkesir-Kepsut		54.90	Enercon	61 X 900 kW
Bilgin Elektrik Üretim A.Ş.	Manisa-Soma-Kırkağaç		90.00	Nordex	36 X 2500 kW
Bares Elektrik Üretim A.Ş.	Balıkesir-Kepsut		142.50	Nordex	57 X 2500 kW

PROJECTS WITH A TURBINE SUPPLY CONTRACT	**667.60**		
TOTAL	**1.503.35**	**MW**	

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