



# EEE 471 POWER SYSTEM ANALYSIS - I

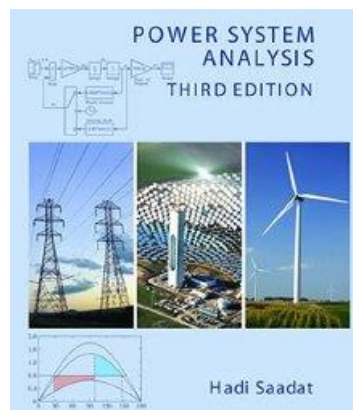
Assoc. Prof. Dr. A. Mete VURAL

E-mail: [mvural@gantep.edu.tr](mailto:mvural@gantep.edu.tr)

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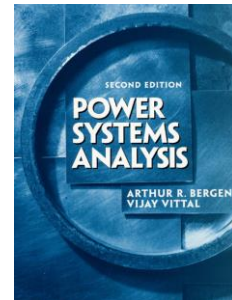
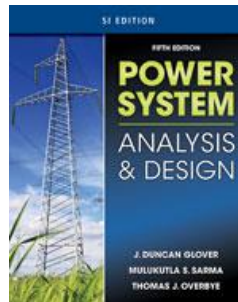
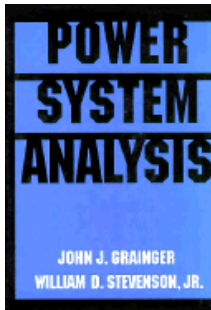
Course  
Book

1. Power System Analysis, Hadi Saadat, PSA  
Publishing, 2010, Third Edition, ISBN:  
0984543805.



2

Other sources	<ol style="list-style-type: none"> <li>1. Power System Analysis and Design, , J Duncan Glover, Mulukutla Sarma, Thomas Overbye, Cengage Learning, 5th Edition, 2011, ISBN: 1111425779.</li> <li>2. Arthur R. Bergen, Vijay Vittal, "Power System Analysis", Prentice-Hall, 2000, ISBN: 0136919901.</li> <li>3. Power System Analysis, John J. Grainger, William D. Stevenson JR, McGraw-Hill, 1994, ISBN: 0070612935.</li> </ol>
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## Course Objectives

- To introduce the sources for electric power generation
- To review power concept in single and three-phase systems
- To review per-unit (pu) calculations in single and three-phase systems
- To provide identifying basic power system components (Generator, transformer, transmission line, line compensation equipment)
- To provide identifying transmission lines and modeling them mathematically for steady-state operation
- To provide basic skills to mathematically analyze the steady-state operation of simple power systems
- To provide an understanding to the power flow analysis concept

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## Learning Outcomes

- Students will be able to identify and model major types of power system components, such as; transformers, synchronous generators, transmission lines, and loads in steady-state conditions.
- Students will be able to analyze basic power systems by calculating currents, real / reactive power flows and able to use basic methods for reactive power compensation.
- Students will be able to derive matrix models for a given power network.
- Students will be able to analyze simple power systems operating under steady-state conditions.
- Students will be able to solve power flow problem for a simple power network by applying Gauss-Seidel or Newton-Raphson methods.

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## EEE 471 Contents

**Chapter 1** – The Power System and Electric Power Generation

**Chapter 2** – Basic Principles (A review)

**Chapter 3** - Models for Power System Analysis

**Chapter 4** - Transmission Line Parameters

**Chapter 5** - Line Model and Performance

**Chapter 6** - Power Flow Analysis

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## Grading Policy

- Midterm-1 : **30%**
- Midterm-2 : **30%**
- Final : **40%**
- TOTAL : **100%**

- ✓ Exams are closed-book
- ✓ **Homework/Project/Quiz** can be assigned during the semester  
*(The performances of the students will be included into the grading policy)*
- ✓ Attendance is minimum 70% to class

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*Students who has registered to this course **MUST** follow the web page of Dr. A. Mete VURAL for all announcements and getting other course related materials.*

<http://eee.gantep.edu.tr/pages.php?url=akademik-personel-2>

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## Some Advices for You !



- Keep attendance as much as possible ! (70% or more)
- Take your own notes
- Practice is good. Do it as much as possible
- Do not try to summarize, try to learn the fundamental idea
- Solve examples, problems as many as possible
- Make your study plan by yourself
- Know yourself ! Study alone or within a group
- Do not postpone anything ! Do it as now as possible

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Do not hesitate to contact to me !

*via E-mail*

[mvural@gantep.edu.tr](mailto:mvural@gantep.edu.tr)

*or*

*Come to my office*

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## Greek alphabet letters used as symbols in electrical engineering

UPPER CASE



A α	alpha	N ν	nu
B β	beta	Ξ ξ	ksi
Γ γ	gamma	Ο ο	omicron
Δ δ	delta	Π π	pi
Ε ε	epsilon	Ρ ρ	rho
Ζ ζ	zeta	Σ σς	sigma
Η η	eta	Τ τ	tau
Θ θ	theta	Υ υ	upsilon
Ι ι	iota	Φ φ	phi
Κ κ	kappa	Χ χ	chi
Λ λ	lambda	Ψ ψ	psi
Μ μ	mu	Ω ω	omega

lower case



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## Voltage Levels according to ANSI

Standard nominal three-phase system voltages per **ANSI C84.1-1989** (*American National Standards Institute*)

Voltage Class	Three-wire	Four-wire
Low Voltage	240	208 Y/120
	480	240/120
	600	480 Y/277
Medium Voltage	2,400	
	4,160	4,160 Y/2400
	4,800	
	6,900	
		8,320 Y/4800
		12,000 Y/6,930
		12,470 Y/7,200
		13,200 Y/7,620
	13,800	13,800 Y/7,970
		20,780 Y/12,000
	22,860 Y/13,200	
	24,940 Y/14,400	
	34,500 Y/19,920	
	46,000	
	69,000	
High Voltage	115,000	
	138,000	
	161,000	
	230,000	
Extra-High Voltage	345,000	
	500,000	
	765,000	
Ultra-High Voltage	1,100,000	

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## Voltage Levels according to IEC

The International Electrotechnical Commission (**IEC**) has classified the voltages into the following levels (**IEC 60038**). This classification system is gaining fast acceptance:

**Low Voltage** - upto 1000V

**Medium Voltage** - 1000V to 35kV

**High Voltage** - 35kV to 230 kV

**Extra High Voltage** - above 230 kV

*P.S:* In some Turkish sources, **154 kV** is given instead of **230 kV**

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# Chapter 1: The Power System and Electric Power Generation

- Electric Energy is the most popular form of energy because it can be transferred to long distances at high efficiency with reasonable cost
- The first electric network was built by Thomas Edison in 1882 in New York City. It was a DC network
- With the invention of transformer by Stanley in 1885 and AC motor by Nikola Tesla in 1888, AC became advantageous over DC and AC was begun to be used for transmission and distribution of electrical power.



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## Conventional Sources of Energy for Electricity Production

- Water
- Fossil fuel
- Uranium



Atatürk Dam 2400 MW



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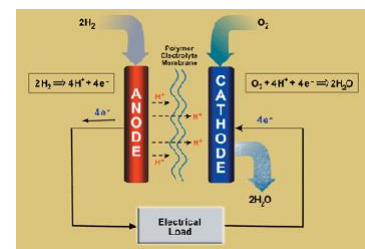
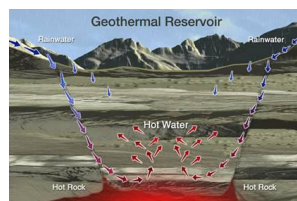
- Many sources of electrical energy pose **environmental concerns**.
- Renewable energy sources are **good** alternatives to conventional sources because,
- they are **clean** and **inexhaustible** to produce energy



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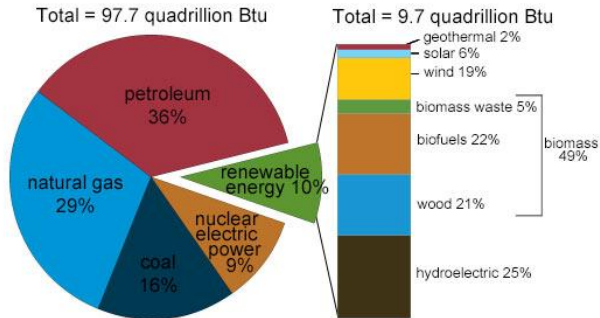
## Renewable Sources of Energy for Electricity Production

- Wind
- Solar
- Geothermal
- Fuel-cell



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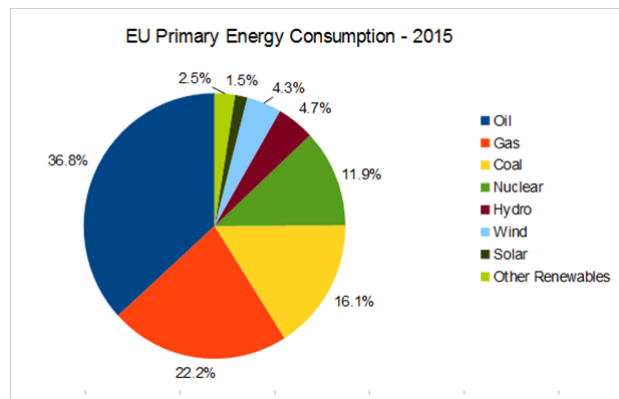
### U.S. energy consumption by energy source, 2015

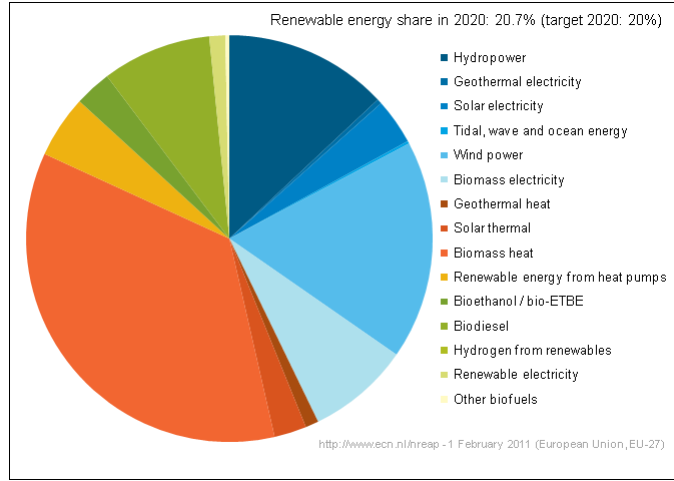


Note: Sum of components may not equal 100% because of independent rounding.  
 Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1 (April 2016), preliminary data



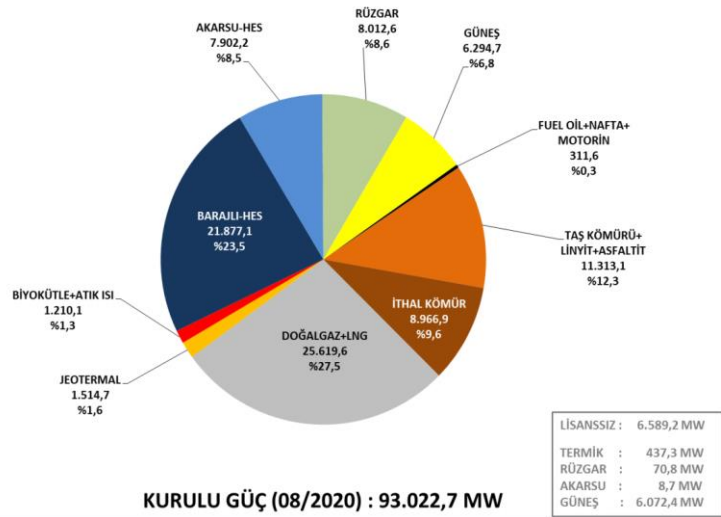
### EU Primary Energy Consumption - 2015





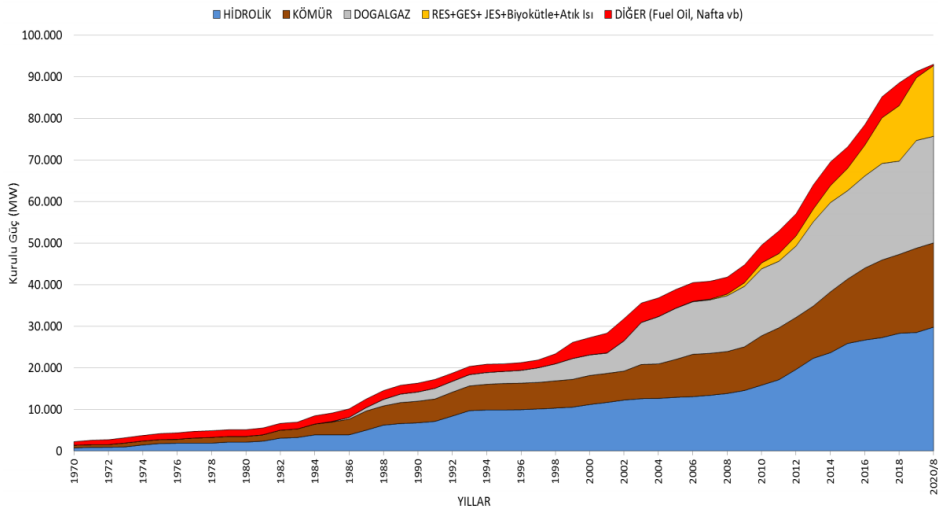
EU renewable energy share in 2020

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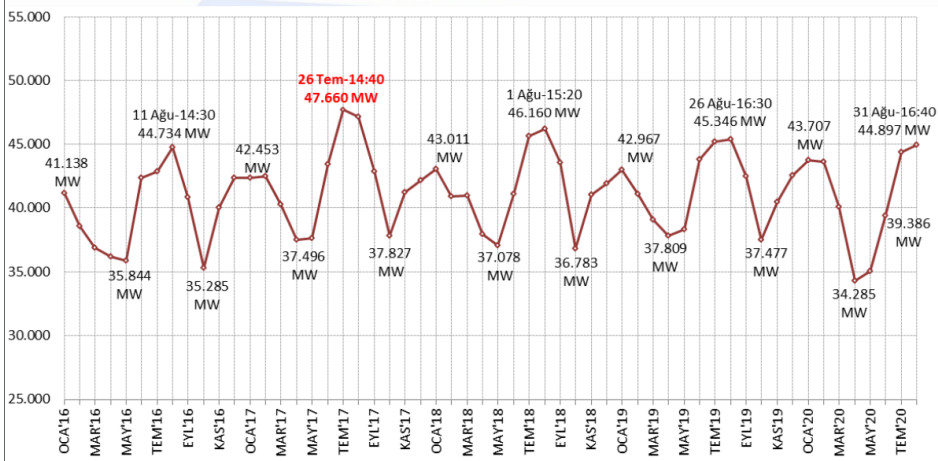
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## TÜRKİYE'DE ELEKTRİK ENERJİSİ KURULU GÜCÜNÜN KAYNAKLARA GÖRE DEĞİŞİMİ (1970-2020)



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## SİSTEM AYLIK MAKSİMUM ANİ PUANTI (MW)



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## Fossil Fuel Power Plants

- Most of the electrical power is generated by burning coal and producing steam, which is then used to drive a **synchronous generator** rotates at

either

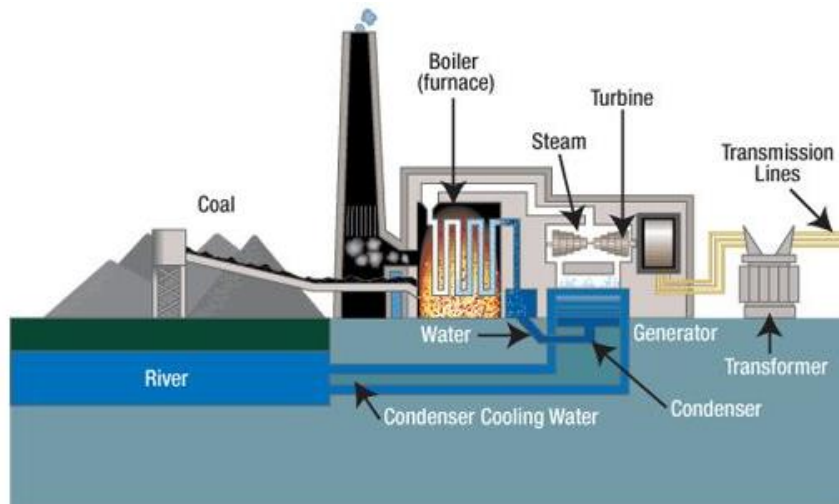
- 1800 rpm or 3600 rpm for 60 Hz operation,
- 1500 rpm or 3000 rpm for 50 Hz operation.



$$n = \frac{120 \cdot f}{p}$$

n: Generator shaft speed at rev/min or rpm  
f: electrical frequency (Hz)  
p: pole number of generator

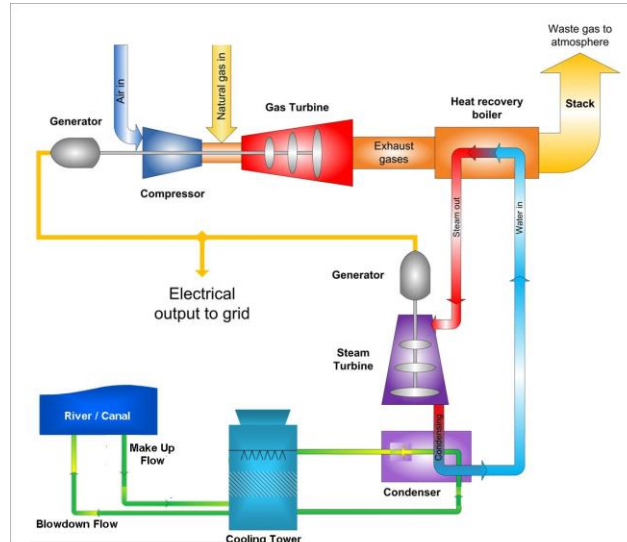
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Fossil Fuel Power Plant

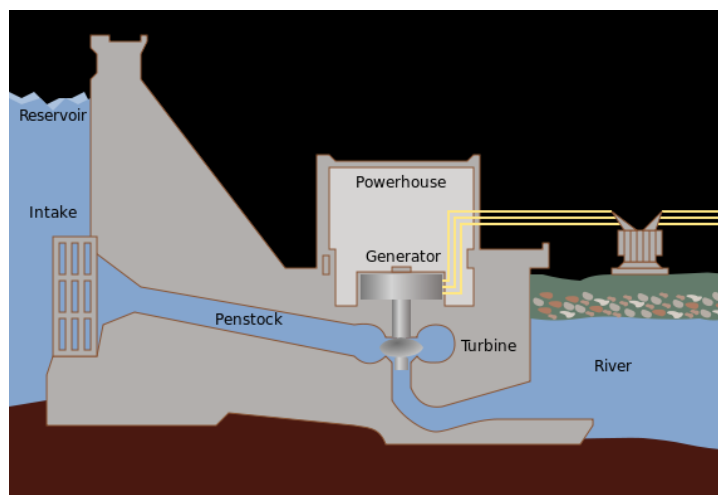
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## Gas Turbine Power Plants



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## Hydroelectric Power Plant



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# Hydroelectric Power Plant

## Power equations:

$$P_w = q \cdot \rho \cdot g \cdot h$$

$P_w$ : Hydro power (power obtained from water flow) (W)  
 $q$ : Flow rate of water ( $\text{m}^3/\text{s}$ )  
 $\rho$ : Water density  $\approx 1000 \text{ kg}/\text{m}^3$   
 $g$ : Acceleration of gravity =  $9.81 \text{ m}/\text{s}^2$   
 $h$ : Effective head of water (m)

$$P_o = P_w \cdot \eta$$

$P_o$ : Electrical power output of the hydropower plant (W)  
 $\eta$ : Overall efficiency of the hydropower plant

$$\eta = \eta_p \cdot \eta_t \cdot \eta_g$$

$\eta$ : Overall efficiency of the hydropower plant  
 $\eta_p$ : Penstock efficiency  
 $\eta_t$ : Turbine efficiency  
 $\eta_g$ : Generator efficiency

$$E = P_o \cdot t$$

$E$ : Electrical energy supplied by the hydropower plant for given time (Wh)  
 $t$ : Given time or duration (hour, h)

**Note:** If any of them is unclear, take it 1 or 100%

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**Example 1.1:** A large hydroelectric power plant has a head of **116 m** and an average flow of **3100  $\text{m}^3/\text{s}$** .

Assume the following efficiencies:

Penstock efficiency = **97 %**

Turbine efficiency = **77 %**

Generator efficiency = **95 %**

- Calculate the generated electrical power and annual electrical energy generation of this hydroelectric power plant.
- Assuming an average household consumes **11000 kWh** in one year (annual) (including transmission and distribution losses). How many homes are supplied by this hydropower plant in one year?

$$P_w = q \cdot \rho \cdot g \cdot h$$

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**Example 1.2:** A hydroelectric power plant has **eight** generators rated at **64 MW** each under a **20 m** head, and **two** generators rated at **42 MW** each under **15 m** head. Each turbine discharges water at a rate of **400 m<sup>3</sup>/s**. Determine the **overall efficiency** of the hydroelectric power plant.

$$P_w = q \cdot \rho \cdot g \cdot h$$

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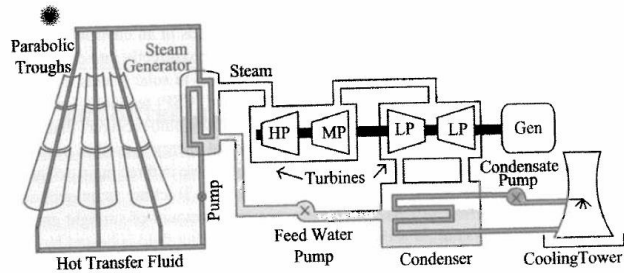
## Solar Polar

We can use the energy of sun that reaches to the world in **two** ways:

1. By photovoltaic systems (PV): They convert solar energy **directly** into electricity using **semiconductor** materials
2. By concentrating solar power systems: (CSP). They use **mirrors** to **reflect** and **concentrate** sunlight into receivers that **heat a fluid** to higher temperature. The resulting heat energy is used to power a **steam turbine** to drive a generator.

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## Parabolic Troughs (CSP)



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## Solar Power plant (CSP)



In California's Mojave Desert. Ivanpah, which began commercial operation in **2013**, is delivering power to PG&E and Southern California Edison. **The project is currently the largest solar thermal power plant in the world.** Ivanpah was constructed by Bechtel and is operated by NRG Energy, one of the project's equity investors.

Rated power = 377 MegaWatts (MW)

The complex will reduce carbon dioxide (CO<sub>2</sub>) emissions by more than **400,000 tons per year.**

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Another photo of Ivanpah Project

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## Some big PV power plants in the world



**Arnedo Solar Plant, Spain**

The plant produces an impressive **34 GWh every year**, which will power **12,000 households** and prevent **375,000 tonnes of CO<sub>2</sub>**. The facility sits on seventy hectares and houses **172,000 panels**. The project's budget was around **€180,000,000**. La Rioja, a Spanish region known for its wine, already covers 62% of its electricity with renewable sources.

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**Waldpolenz Solar Park, Germany**

Waldpolenz Solar Park, which is the **world's largest thin-film photovoltaic (PV) power system**, is built in on military air base to the east of Leipzig in Germany. The power plant is a **40-megawatt solar power system** using state-of-the-art thin film technology. 550,000 First Solar thin-film modules are used, which supplies **40,000 MWh of electricity per year**. The investment cost for the Waldpolenz solar park amounts to some **Euro 130 million**.

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**Moura photovoltaic power station, Portugal**

The Moura photovoltaic power station is located in the municipality of Moura, in Alentejo, Portugal, which is one of the sunniest regions in Europe and also one of the most economically depressed. Its construction involves two stages, with the first one being constructed in 13 months and completed in 2008, and the other will be completed by 2010, at a total cost of €250 million for the project.

The power station will have an **installed capacity of 46 MW**, counting a total of over **376,000 solar panels**. Almost 190,000 panels (32 MW) are fitted on fixed structures, 52,000 (10 MW) on single-axis trackers, which follow the sun across the sky, and a further 20 MW of power capacity will be added during phase two of the project. It will occupy an area of 320 acres (130 hectares), producing **88 GWh** of electrical energy per year.

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Renovialia developed this power station in Puertollano, Ciudad Real, housing an energy park with an installed capacity of **50 megawatts (MW)**. The power generated here is equivalent to the annual domestic consumption of electricity of about **39,000 households**. The energy produced here will replace a theoretical discharge of **84,000 tons of CO<sub>2</sub>/year** or, **2.1 million tons of CO<sub>2</sub>** over the 25 years during its production.



**Puertollano Photovoltaic Park, Spain**

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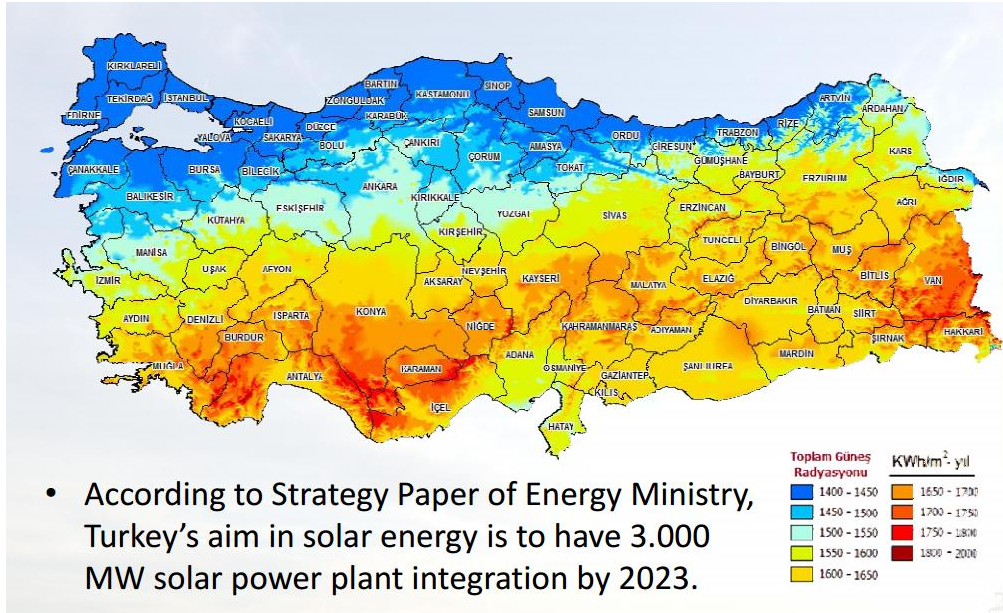


**Olmedilla Photovoltaic Park, Spain**

The Olmedilla Photovoltaic (PV) Park uses **162,000** flat solar photovoltaic panels to deliver **60 megawatts** of electricity on a sunny day. The entire plant was completed in 15 months at a cost of about **\$530 million** at current exchange rates. Olmedilla was built with conventional solar panels, which are made with silicon and tend to be heavy and expensive.

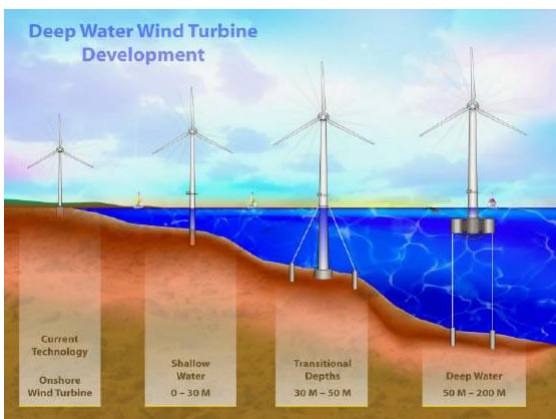
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## Solar Energy Potential of Turkey



## Wind Power Plants

- Wind turbines convert kinetic energy from the wind into mechanical energy which is then used to drive a generator that converts this energy into electricity.



## Some wind power plant examples



Osmaniye-Bahçe 135 MW wind power plant

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845 MW wind farm in the U.S.-Oregon

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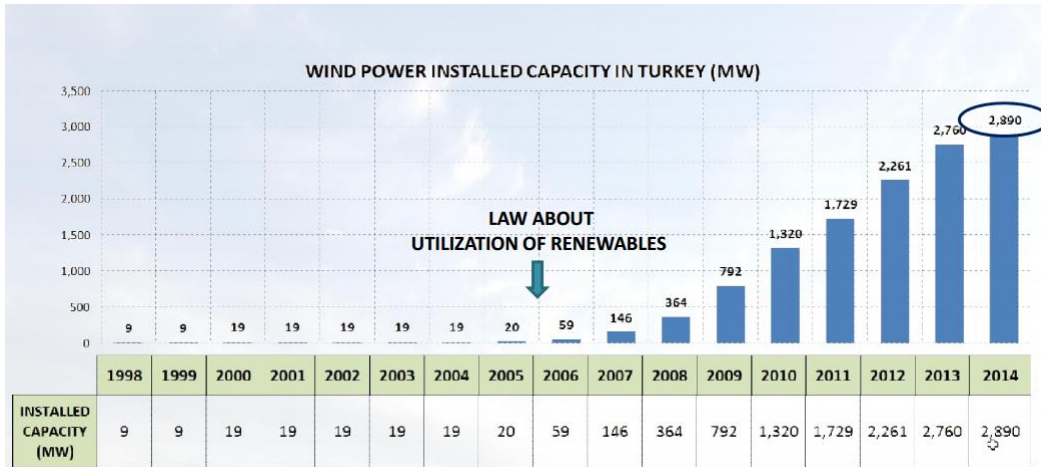
1020 MW wind power plant USA-California

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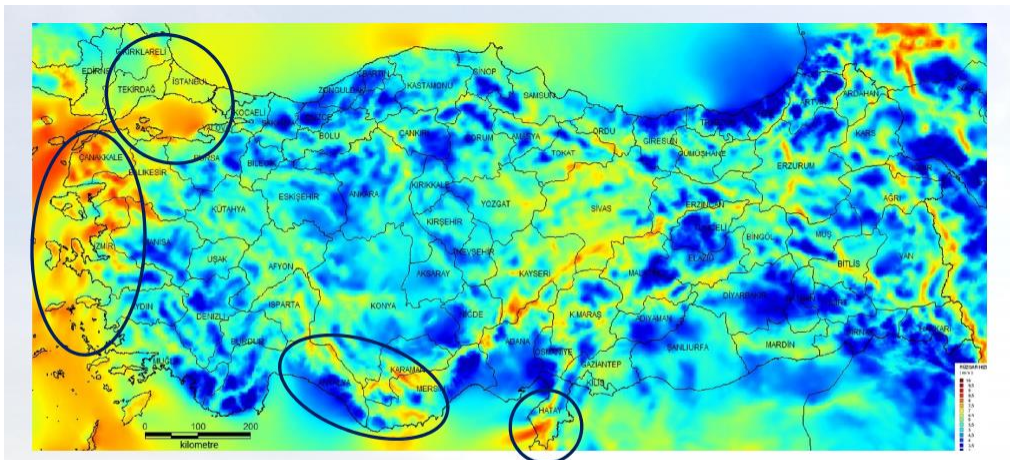
504 MW off-shore wind farm on sandbanks 23 kilometres (14 mi) off the coast of Suffolk in England at a cost between £650 million

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### Wind Energy Potential of Turkey

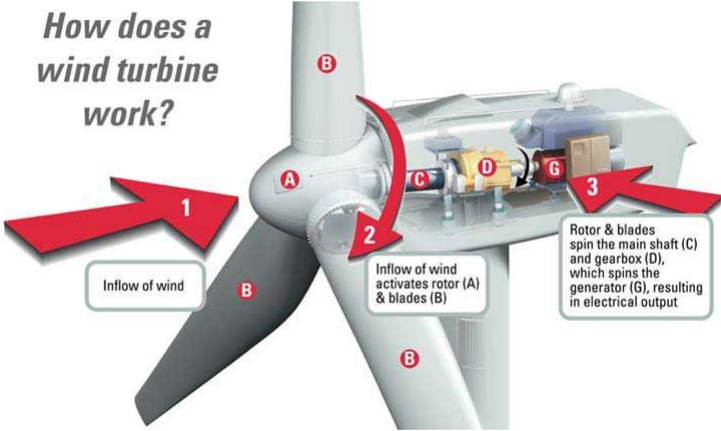


The techno-economic wind potential of Turkey is **48 GW**, according to General Directorate of Renewable Energy.

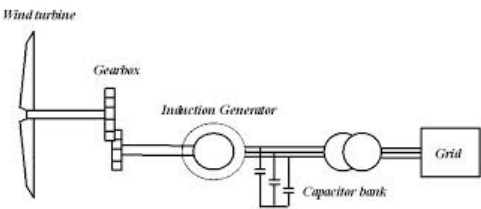
The locations with highest potential are in the Aegean, Marmara, and Eastern Mediterranean and Hatay.

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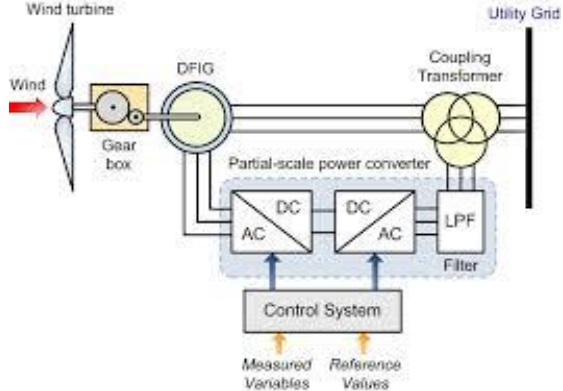
### How does a wind turbine work?



### Comparison of Fixed and Variable Speed Wind Turbines



Fixed-speed wind turbine



Variable-speed wind turbine

## Comparison of Fixed and Variable Speed Wind Turbines

### ➤ Fixed-speed Wind Turbine

- ✓ The generator is typically squirrel-cage induction generator
- ✓ There is gearbox to increase speed from 15-60 rpm to 900 rpm for 8-pole 60-Hz generator
- ✓ There is gearbox to increase speed from 15-60 rpm to 1800 rpm for 4-pole 60-Hz generator
- ✓ Reactive power by shunt capacitors is required to produce electrical power
- ✓ Grid-connected wind turbine should be rotated at fixed speed to produce fixed frequency electrical power
- ✓ Speed is very limited controlled by means of pitched blades and external resistances connected to the slip-ring

### ➤ Variable-speed Wind Turbine

- ✓ Mostly, doubly-fed induction generator is used
- ✓ Synchronous generator based systems are also available
- ✓ Power is captured in a wide range of wind speed with different voltages and frequencies
- ✓ Desired voltage/frequency can be obtained with power electronic based inverter/rectifier systems
- ✓ More expensive than fixed-speed wind turbine but more efficient and powerful

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## Net Output power of a Wind Turbine

$$P_o = (\eta_{gb} \cdot \eta_b \cdot \eta_g) \frac{\pi}{8} \cdot C_p \cdot \rho \cdot D^2 \cdot v^3$$

$P_o$ : Output electrical power of a wind turbine (W)

$\eta_{gb}$ : Gearbox efficiency

$\eta_b$ : Blade efficiency

$\eta_g$ : Generator efficiency

$C_p$ : Power coefficient (unitless)

$\rho$ : air density  $\approx 1.225 \text{ kg/m}^3$

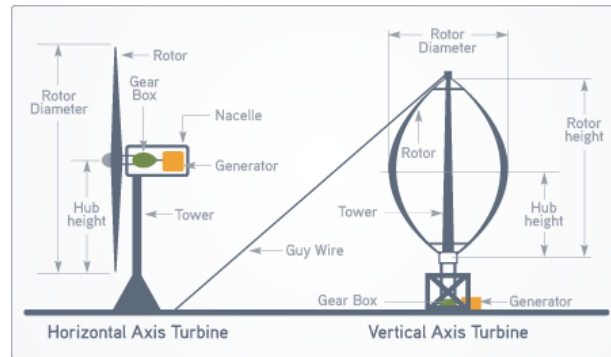
D: Rotor diameter (m)

v: wind speed (m/s)

**Note:** If there is no gearbox, take  $\eta_{gb}$  as 1 or 100%

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# Horizontal and Vertical Axis Wind Turbine



Source: <http://www.hillcountrywindpower.com/images/wind-basics-turbine.png>

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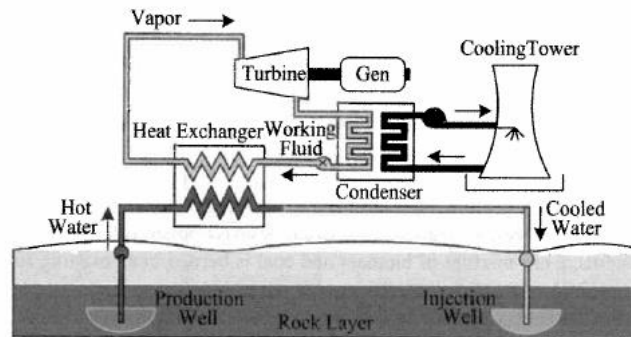
**Example 1.3:** A very large horizontal wind turbine is mounted with its hub at **135 m** and has a rotor diameter of **126 m**. The turbine operates in an area with an average wind speed of **12 m/s** at **135 m** altitude and air density of **1.18 kg/m<sup>3</sup>** at **70° F**. The turbine power coefficient is **0.46**. The generator is directly coupled to the turbine without a gearbox. Assume the following efficiencies: Turbine blade efficiency = **94.6%**, generator efficiency = **96%**. Determine the electrical power output and annual energy generation.

$$P_0 = (\eta_{gb} \cdot \eta_b \cdot \eta_g) \frac{\pi}{8} \cdot C_p \cdot \rho \cdot D^2 \cdot v^3$$

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## Geothermal Power

- Geothermal energy is derived from heat within the earth, usually in the form of underground steam or hot water.



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## Biomass Power Plants

- Biomass is renewable organic material which contains stored energy from the sun
- It may be **wood, plant, agricultural residues, animal wastes, and etc...**
- Biomass can also be converted into fuels like ethanol, biodiesel, methane.
- Combustion of biomass produces heat that can be used to generate electrical energy.

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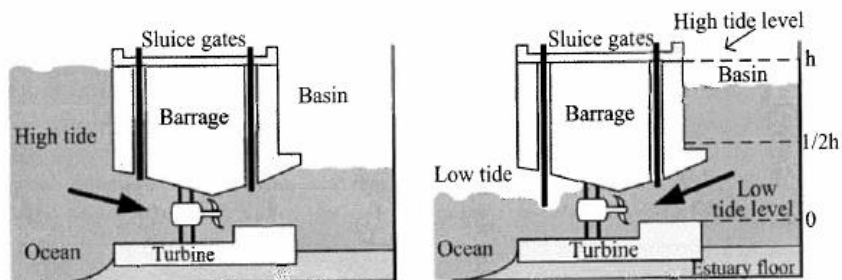
# Tidal Power Plants

There are **two** main categories:

- **Tidal energy systems**
- **Tidal wave systems**

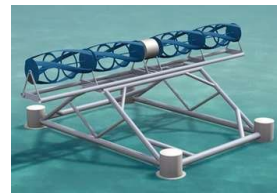
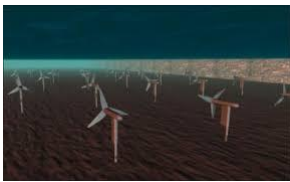
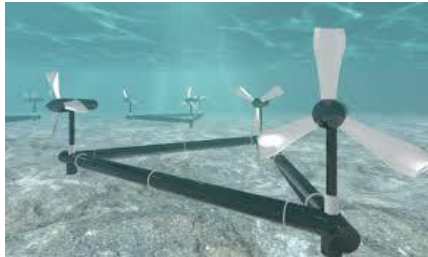
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**Tidal energy systems:** Power is generated by capturing the energy of tides caused by the gravitational pull of the moon and sun on the world's oceans.



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**Tidal wave systems:** They extract the kinetic energy of tidal motion in the horizontal direction similar to a wind turbine.



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## Output power of a Tidal Energy System

$$P_0 = (\eta_g \cdot \eta_t) \cdot C_p \frac{\rho \cdot g \cdot A \cdot h^2}{2T}$$

For systems designed to operate only in one-way tides

$P_0$ : Output electrical power of a tidal energy system (W)

$\eta_g$ : Generator efficiency

$\eta_t$ : Turbine efficiency

$C_p$ : Power coefficient (unit less)

$\rho$ : Seawater density ( $\text{kg/m}^3$ )

$g$ : Acceleration of gravity =  $9.81 \text{ m/s}^2$

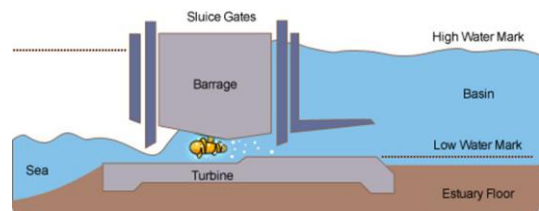
$A$ : Area of tidal basin ( $\text{m}^2$ )

$h$ : Range (m)

$T$ : Tidal period (s)

$$P_0 = (\eta_g \cdot \eta_t) \cdot C_p \frac{\rho \cdot g \cdot A \cdot h^2}{T}$$

For systems designed to operate both incoming and outgoing tides



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**Example 1.4:** A tidal barrage is constructed in an area where the average range between low tide and high tide level is **8.5 m** and the seawater density is **1025 kg/m<sup>3</sup>**. The area of the tidal basin is **22 km<sup>2</sup>** and the blade capacity factor is **33%**. The tidal period is about **12.5 hours**. Determine the average power output and annual energy production of the tidal plant by assuming turbine efficiency to be **90.5%** and the generator efficiency to be **94.4%**.

$$P_0 = (\eta_g \cdot \eta_t) C_p \frac{\rho \cdot g \cdot A \cdot h^2}{2 \cdot T}$$

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## Output power of a Tidal Wave System

$$P_0 = (\eta_{gb} \cdot \eta_b \cdot \eta_g) \frac{\pi}{8} \cdot C_p \cdot \rho \cdot D^2 \cdot v^3$$

$P_0$ : Output electrical power of a tidal wave system (W)

$\eta_{gb}$ : Gearbox efficiency

$\eta_b$ : Blade efficiency

$\eta_g$ : Generator efficiency

$C_p$ : Power coefficient (unit less) (0.3-0.59)

$\rho$ : Seawater density (kg/m<sup>3</sup>)

$D$ : Rotor diameter (m)

$v$ : Seawater flow speed (stream velocity) (m/s)



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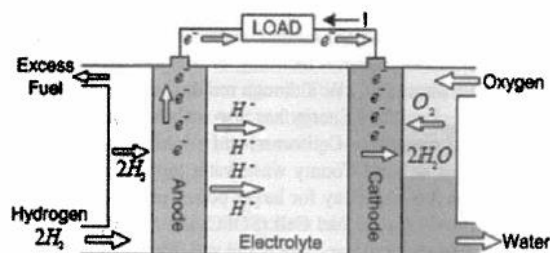
**Example 1.5:** A tidal stream turbine generator, consisting of a **twin rotor**, gearbox, and generator is designed. Rotors are located on either side of a single monopile and each has a rotor diameter of **16 m**. The seawater density is **1025 kg/m<sup>3</sup>**. Determine the unit power output when the tidal current is **2.78 m/s**. Assume gearbox efficiency to be **94%**, blade efficiency to be **92%**, generator efficiency to be **95%**, and a power coefficient of **33%**.

$$P_0 = (\eta_{gb} \cdot \eta_b \cdot \eta_g) \frac{\pi}{8} \cdot C_p \cdot \rho \cdot D^2 \cdot v^3$$

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## Fuel Cells

- A fuel cell is an electrochemical device that converts the chemical energy of a fuel directly into electrical energy.
- Like batterie fuel cell contains two electrodes, an anode and a cathode, seperated by an electrode that serves as an ion conductor.
- The fuel reactant typically hydrogen or carbon monoxide is supplied from an external source.



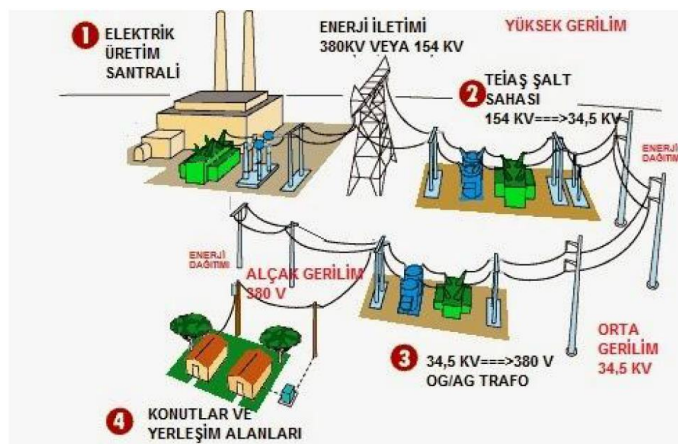
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# Modern Power System Components

- Generation
- Transmission and Subtransmission
- Distribution
- Loads

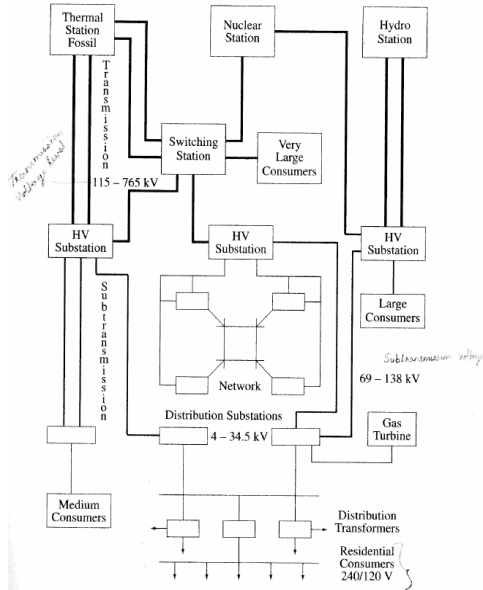
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## Simplified Turkish Power System Layout and Voltage Levels

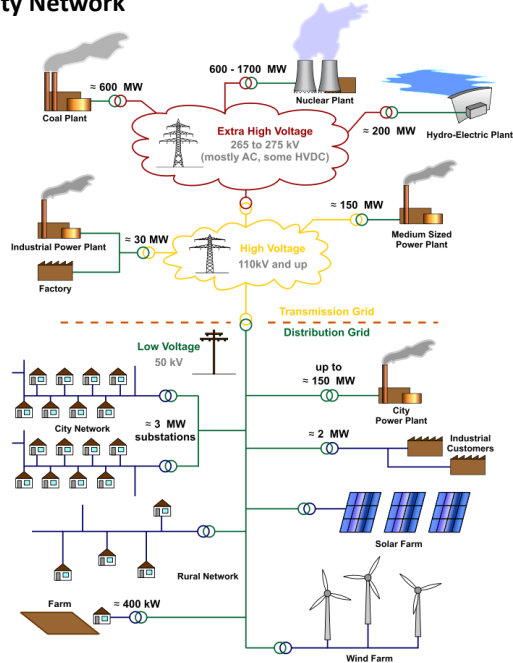


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### Simplified USA Power System Layout and Voltage Levels



### General Layout of EU Electricity Network



# TEİAŞ

- TÜRKİYE ELEKTRİK İLETİM ANONİM ŞİRKETİ
- TURKISH ELECTRICITY TRANSMISSION CORPORATION



- ✓ TEİAŞ is the the **sole owner** of Turkish Electricity Transmission System
- ✓ TEİAŞ is mainly responsible for
  - ✓ The operating & maintaining Turkish Electricity Transmission Network economically and reliably in compliance with international standards
  - ✓ The expansion of Turkish transmission network infrastructure
  - ✓ The construction of new transmission facilities
  - ✓ The monitoring real-time system reliability, purchasing and providing Ancillary Services Through "Ancillary Service Agreements"
  - ✓ Carrying out studies for the Interconnection Lines with neighboring countries

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## Turkish Electrical Power System



High resolution version can be downloaded from  
[http://www.emo.org.tr/ekler/821e4acae0886a8\\_ek.jpg?tipi=2&turu=X&sube=12](http://www.emo.org.tr/ekler/821e4acae0886a8_ek.jpg?tipi=2&turu=X&sube=12)

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➤ Turkey has a total of 53,725 km transmission line (2014)

- ✓ 380 kV : 17,747 km
- ✓ 154 kV : 35,384 km (*more common*)
- ✓ 220 kV : 85 km
- ✓ 66 kV : 509 km

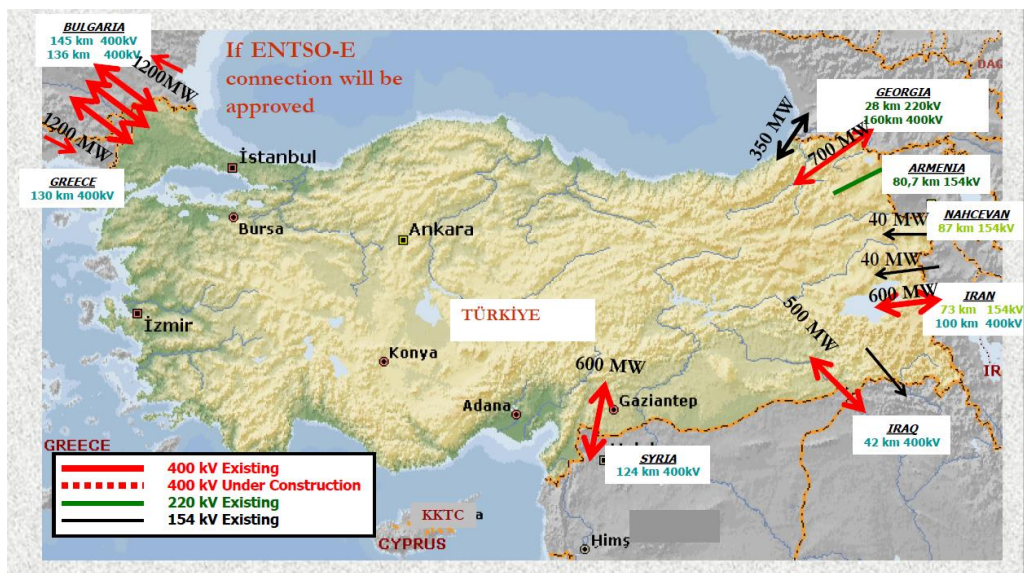


➤ Turkey has a total of 693 transformer substations (2014)

- ✓ 380 kV : 93
  - ✓ 220 kV : 1
  - ✓ 154 kV : 575
  - ✓ 66 kV : 14
- Total capacity: 127,705 MVA

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### Turkey Existing Interconnections (since 2015)



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➤ Why do we need high voltages to transmit electrical power ?

**Example 1.6:**

**Three-phase 200 kW** power is to be transmitted **10 km** away. Per-phase resistance of the transmission line is **0.2 Ω/km**. If the power factor is taken as **unity**, Calculate the real power loss of the transmission line for the following transmission voltages (line-to-line):

- 1 kV
- 5 kV
- 10 kV

**Solution:**

a) Line current for 1 kV transmission is  $I_{line} = 115 \text{ A}$

Real power loss =  $3 \times R \times I^2 = 3 \times (0.2 \times 10) \times (115^2) = 79350 \text{ W}$

b) Line current for 5 kV transmission is  $I_{line} = 23 \text{ A}$

Real power loss =  $3 \times R \times I^2 = 3 \times (0.2 \times 10) \times (23^2) = 3174 \text{ W}$

c) Line current for 10 kV transmission is  $I_{line} = 11 \text{ A}$

Real power loss =  $3 \times R \times I^2 = 3 \times (0.2 \times 10) \times (11^2) = 726 \text{ W}$

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Transmission voltage	Transmission line loss
1 kV	79350 W
5 kV	3174 W
10 kV	726 W

**Comments:**

- As transmission voltage **increases**, transmission line losses **reduce**
- However transmission voltage level can **not be so high** and should be **optimized** since
  - ✓ High cost of power transformers
  - ✓ High cost of insulation system
  - ✓ High cost of installation and maintenance
  - ✓ Higher towers

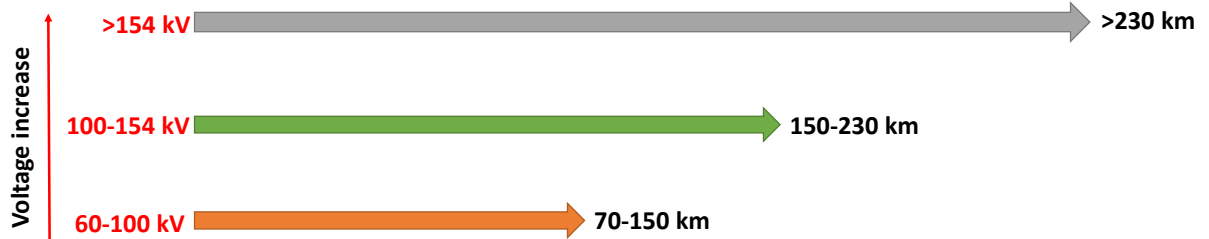


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➤ Transmission voltage levels according to distance

60 kV < *High Voltage* ≤ 154 kV

154 kV < *Very High Voltage*



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**Thank you**  
**End of Chapter 1**  
**Questions and Discussion ?**

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