ME 445 Solar Energy Engineering

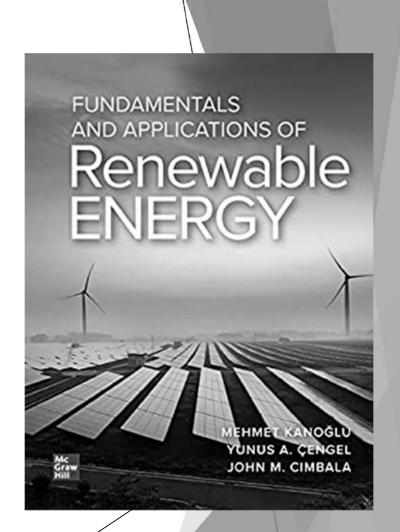
Prof. Dr. Adem ATMACA

Mechanical Engineering
Gaziantep University
2023-2024 Fall

1

The book

► Mehmet Kanoğlu, Yunus A. Çengel and John M. Cimbala



Grading

- ► Midterm Exam
- ▶ 30% Will be announced (Duration 60 min.).

- ► Final Exam
- ▶ 70% Will be announced (Duration 60 min.).

CONTENT

- ► Energy and Environment
- ► CO2 levels
- ► Energy and CO2
- ▶ Global warming
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- ▶ World Energy consumption
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- ▶ Development & Welfare = Energy
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- Solar power tower plant
- Solar pond
- Photovoltaic cell
- Passive solar applications
- Trombe Wall
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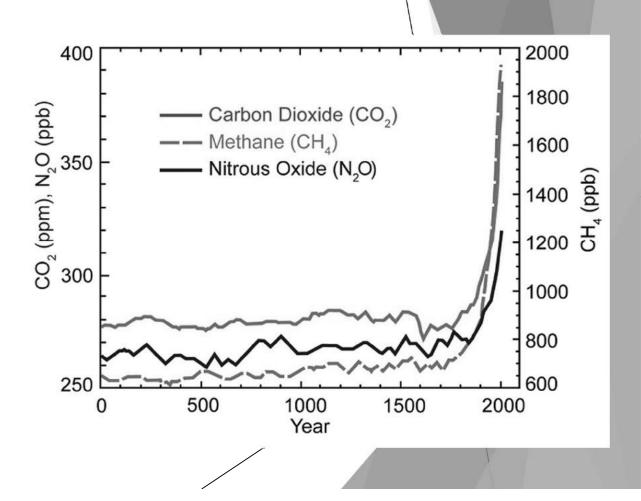
Energy and Environment

► Population growth and development of nations are pushing up global power demand, and so CO2 levels in the atmosphere.

 80% of world power generation is based on fossil fuels.

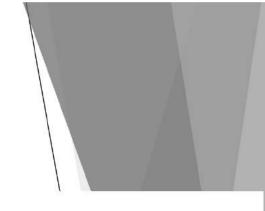


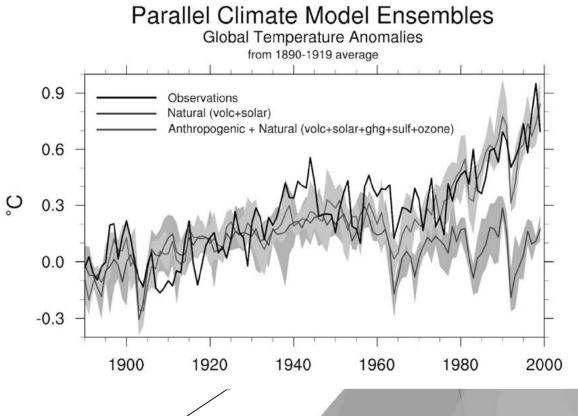
▶ Since the Industrial Revolution started in the mid-19th century, human activities have contributed significantly to climate change by adding more carbon dioxide and other heat-trapping gases to the atmosphere.



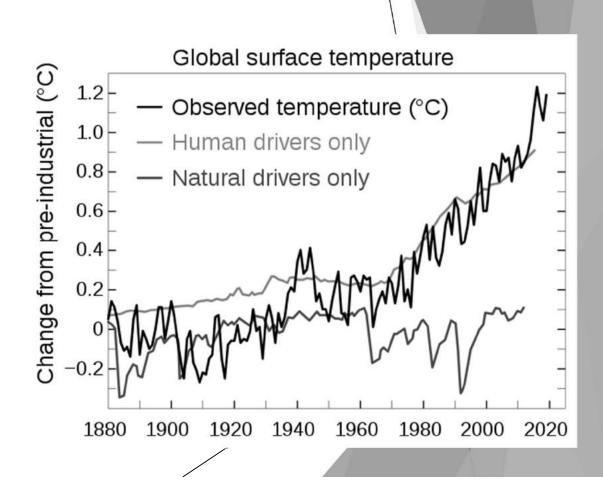


- ► Anthropogenic:
- Environmental pollution and pollutants <u>ORIGINATING IN</u> <u>HUMAN ACTIVITY</u>
- ► The red line!

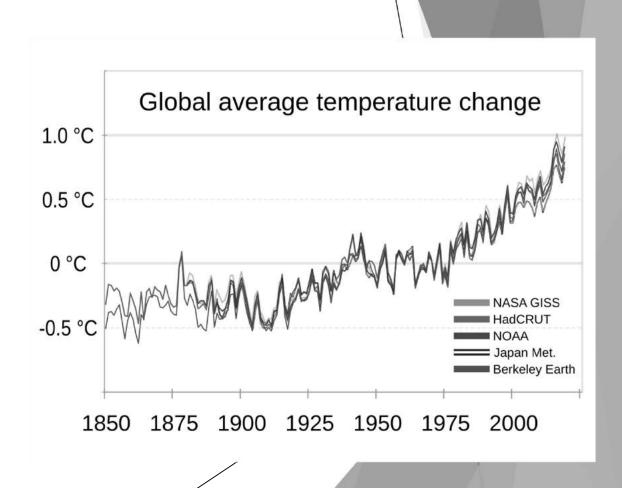


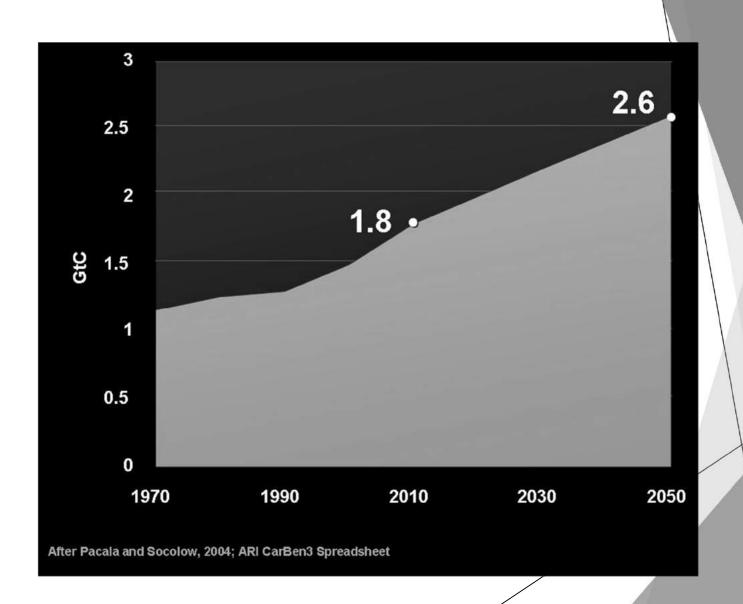


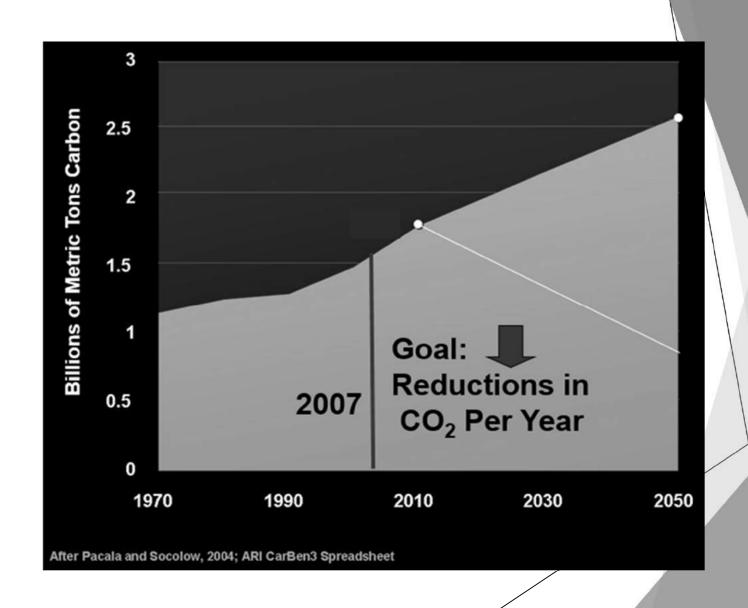
► The results of a new study released by EPA in 2020.

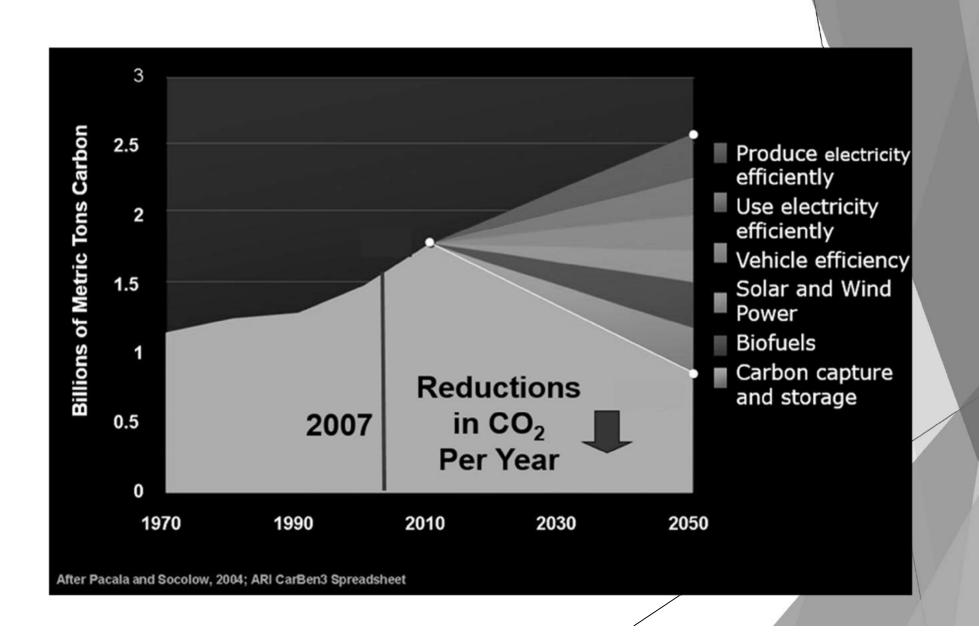


► The difference in results about the Global average temperature change.

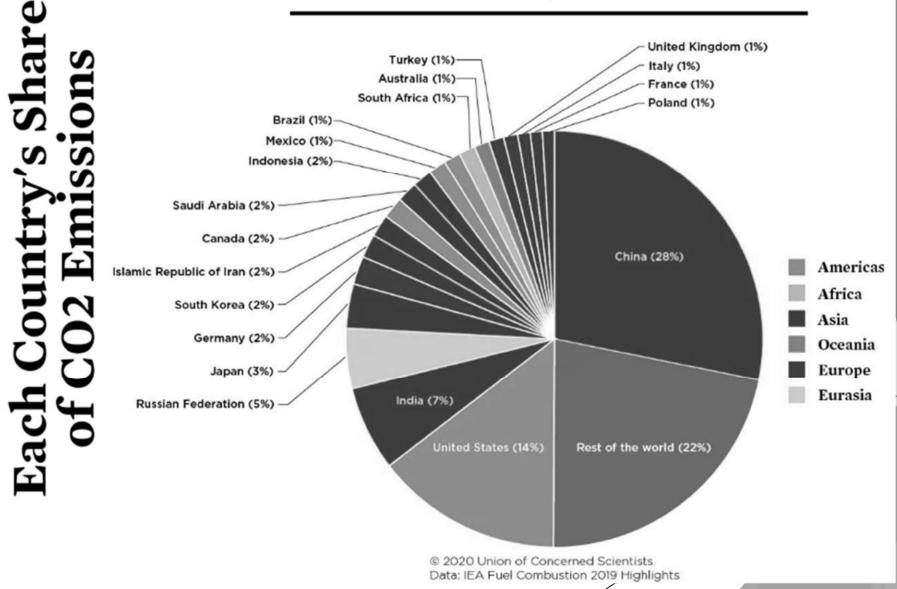


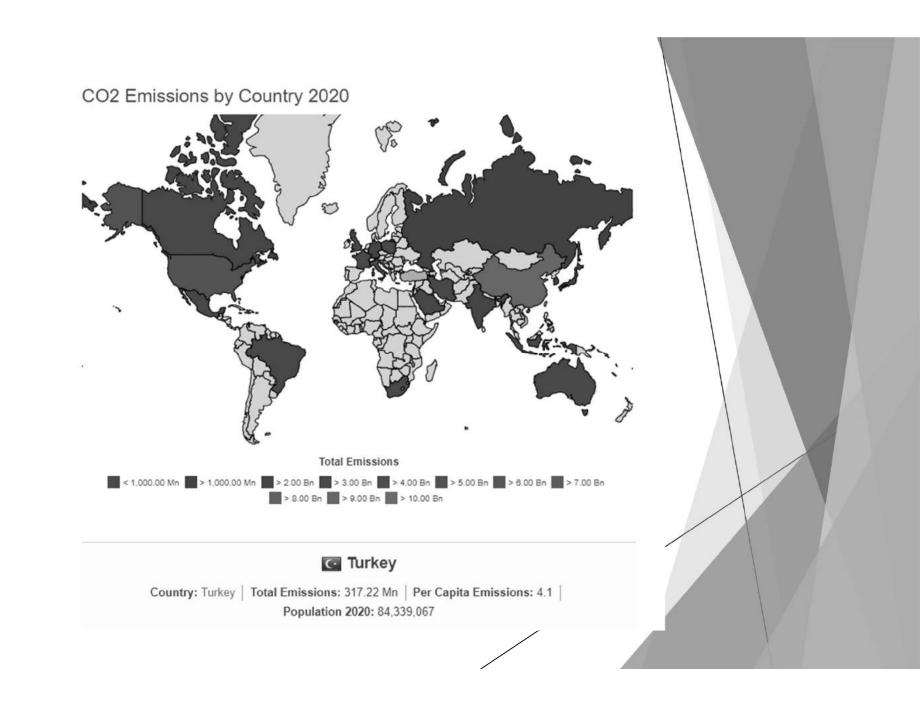






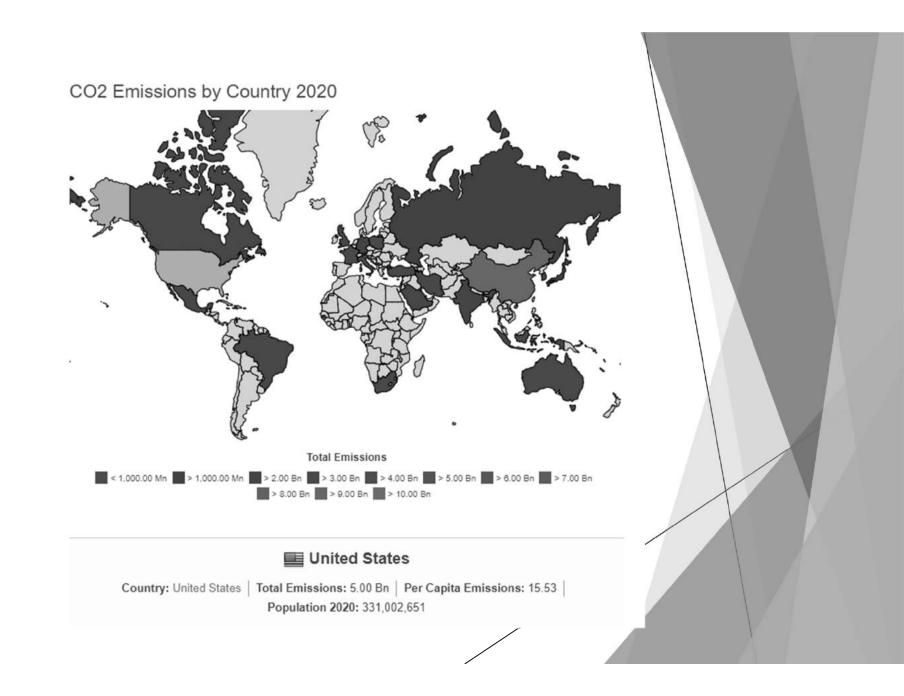














Energy and CO2

▶ With rapid industrialisation, increased population, urbanisation density and significant change in lifestyle, the burning of coal, oil and natural gas has emitted approximately 500 billion tons of carbon dioxide, around half of which remains in the atmosphere.

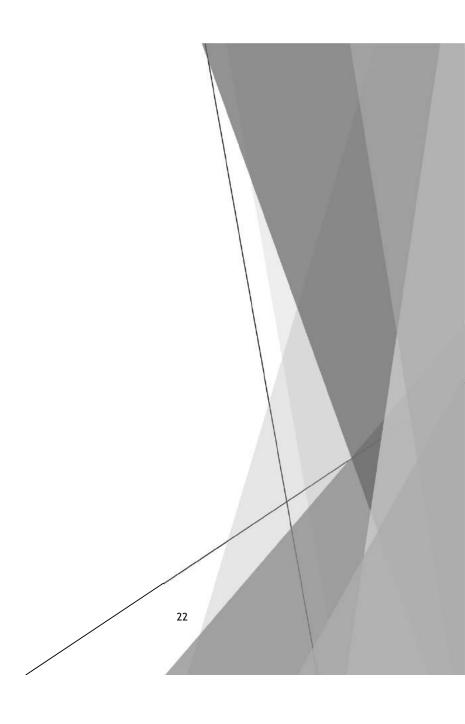


- ▶ Rising CO2 levels!
 - ►Global Warming!

► And...!?

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►END OF COURSE





Change Will Continue Through This Century and Beyond



Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases emitted globally, and how sensitive the Earth's climate is to those emissions.

Temperatures Will Continue to Rise



Because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, uniform or smooth across the country or over time.

Frost-free Season (and Growing Season) will Lengthen



The length of the frost-free season (and the corresponding growing season) has been increasing nationally since the 1980s, with the largest increases occurring in the western United States, affecting ecosystems and agriculture. Across the United States, the growing season is projected to continue to lengthen.

Changes in Precipitation Patterns



Average U.S. precipitation has increased since 1900, but some areas have had increases greater than the national average, and some areas have had decreases. More winter and spring precipitation is projected for the northern United States, and less for the Southwest, over this century.

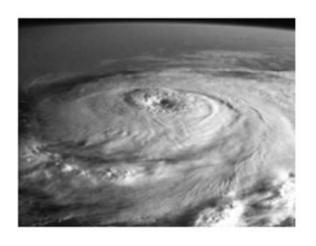
More Droughts and Heat Waves



Droughts in the Southwest and heat waves (periods of abnormally hot weather lasting days to weeks) everywhere are projected to become more intense, and cold waves less intense everywhere.

Summer temperatures are projected to continue rising, and a reduction of soil moisture, which exacerbates heat waves, is projected for much of the western and central U.S. in summer. By the end of this century, what have been once-in-20-year extreme heat days (one-day events) are projected to occur every two or three years over most of the nation.

Hurricanes Will Become Stronger and More Intense



The intensity, frequency and duration of North Atlantic hurricanes, as well as the frequency of the strongest (Category 4 and 5) hurricanes, have all increased since the early 1980s. The relative contributions of human and natural causes to these increases are still uncertain. Hurricane-associated storm intensity and rainfall rates are projected to increase as the climate continues to warm.

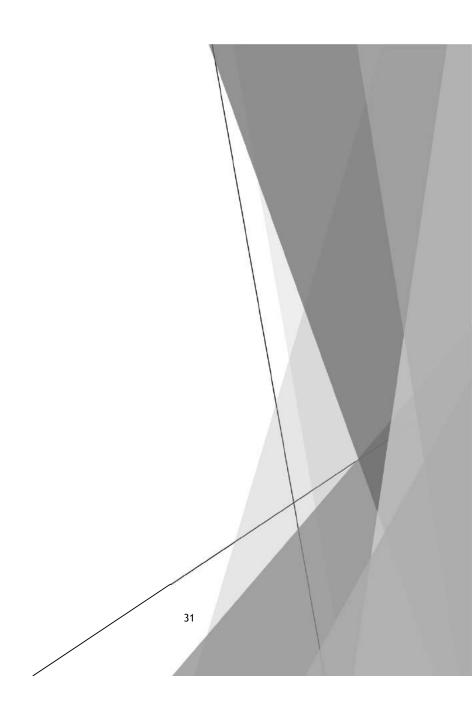
Sea Level Will Rise 2 m by 2100



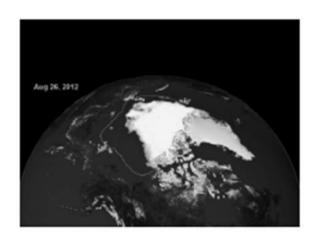
Global sea level has risen by about 8 inches since reliable record keeping began in 1880. It is projected to rise another 1 to 8 feet by 2100. This is the result of added water from melting land ice and the expansion of seawater as it warms.

In the next several decades, storm surges and high tides could combine with sea level rise and land subsidence to further increase flooding in many regions. Sea level rise will continue past 2100 because the oceans take a very long time to respond to warmer conditions at the Earth's surface. Ocean waters will therefore continue to warm and sea level will continue to rise for many centuries at rates equal to or higher than those of the current century.

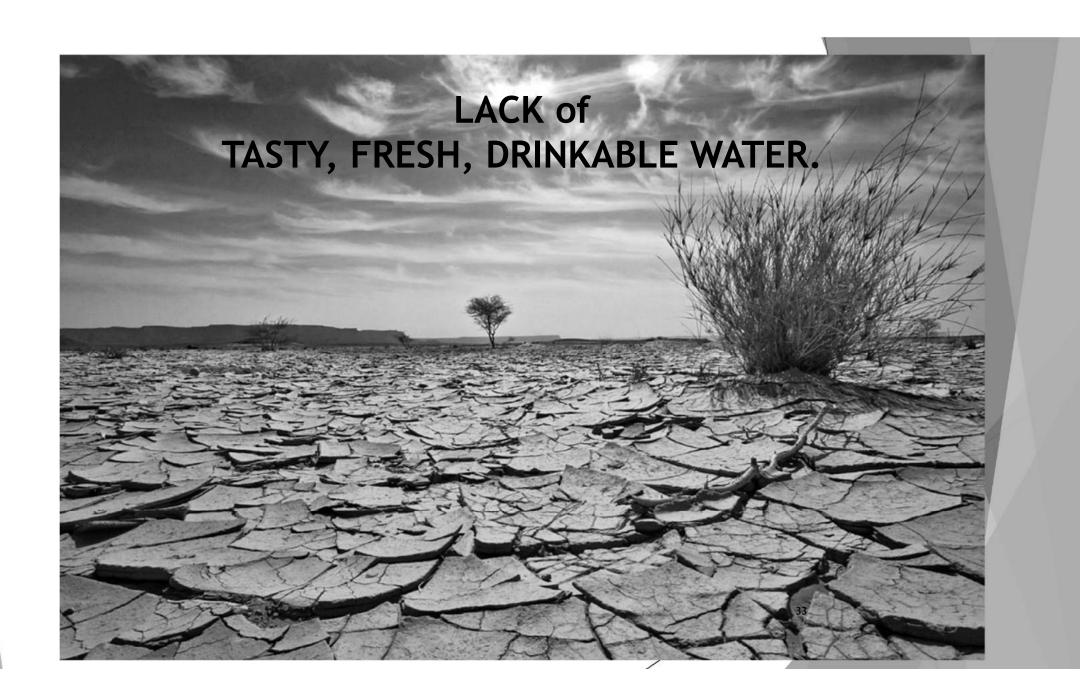
Finally!!!



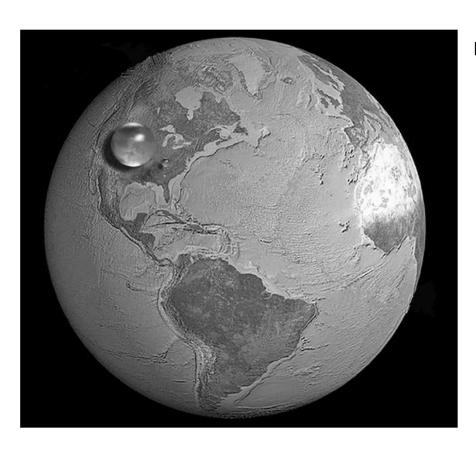
Arctic Likely to Become Ice-Free



The Arctic Ocean is expected to become essentially ice free in summer before mid-century.



Water Facts Worldwide Water Supply



While nearly 71 percent of the world is covered by water, only 2.5 percent of it is fresh. The rest is saline and ocean-based. Even then, just 1 percent of our freshwater is easily accessible.

Water Facts Worldwide Water Supply

- ▶ Water covers about 71% of the earth's surface.
- ▶ 326 million cubic miles of water on the planet
- ▶ 97% of the earth's water is found in the oceans (too salty for drinking, growing crops, and most industrial uses except cooling).
- ▶ 320 million cubic miles of water in the oceans
- ▶ 3% of the earth's water is fresh.

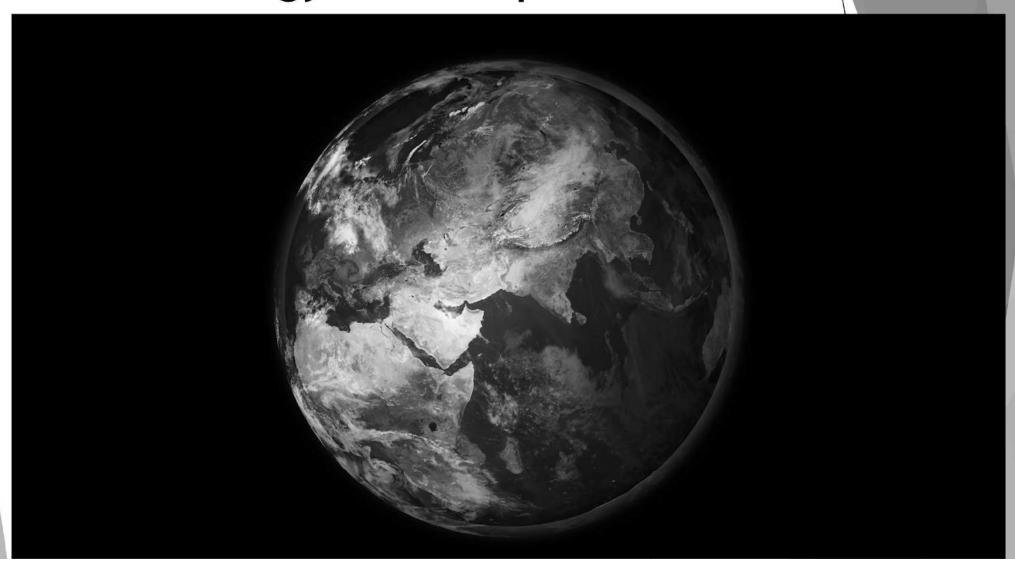
Water Facts Worldwide Water Supply

- ▶ 2.5% of the earth's fresh water is unavailable: locked up in glaciers, polar ice caps, atmosphere, and soil; highly polluted; or lies too far under the earth's surface to be extracted at an affordable cost.
- ▶ 0.5% of the earth's water is available fresh water.

Share of total Water

Oceans	97.2%
Ice Caps/Glaciers	2.0%
Groundwater*	0.62%
Freshwater Lakes	0.009%
Inland seas/salt lakes	0.008%
Atmosphere	0.001%
Rivers	0.0001%
TOTAL	99.8381%

World energy consumption



Energy Agenda in the World

- ► The world is going through a period when the balances in the economy and energy sector are changing and extremely dynamic.
- ▶ Developments in the Middle East, where there are low-cost and large oil resources, bring global energy security to the top of the international agenda.
- ▶ On the other hand, energy demand and environmental relations remain important, and energy efficiency and environmental impact constitute the main agenda even for countries with the richest resources.

Development & Welfare = Energy

- ► Energy, which is of primary importance in ensuring the development, welfare and development of countries, has become one of the most strategic tools in the international system.
- ► Energy policies address issues such as the safe access of energy resources to international markets in the short term, supply and pricing, and development plans and policies in the long term.

Foreign policy = Energy

- ► Having energy resources, being able to produce energy and keeping the transportation ways to bring the energy to the market under control are among the subjects that the states focus on in foreign policy making today.
- ► Energy security will continue to be one of the main issues that shape the foreign policies of the states in the coming period, both nationally and globally.

The Energy Agenda in Turkey

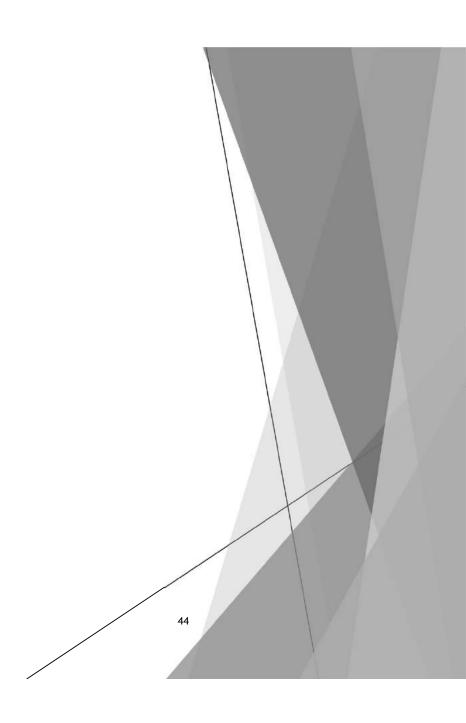
- ► Turkey's economy contracted at a time when the economies of many countries due to the global financial crisis, after the slowdown in 2008 and has provided significant contraction in 2009, growth recovered. The energy sector plays a vital role in ensuring this economic growth.
- ► The fact that our primary energy supply grew by an average of 4.2% per year between 2003 and 2016 shows that the economy has grown with energy consumption.

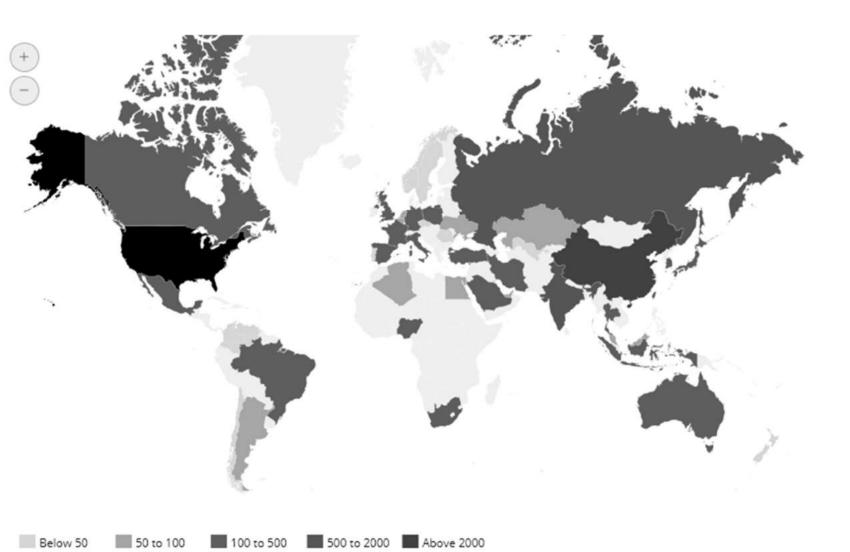
Current situation in Turkey

- ► The installed Energy generation capacity of the country has to meet Turkey's growing electricity needs in electricity generation.
- ▶ There has been a significant increase over the last 30 years.
- ► The installed power, which was below 10,000 MW in the mid-1980s, reached the level of 90,000 MW by the end of 2019.

Energy conversion

- ▶ ktoe: Tonne of oil equivalent
- ▶ 1 ktoe = 11.63 MWh



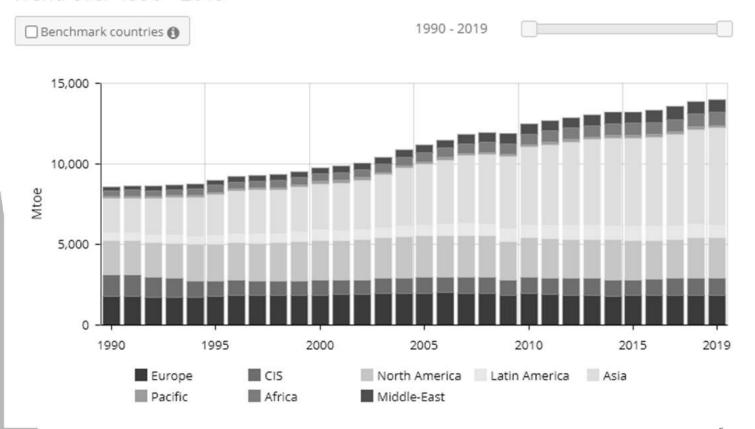


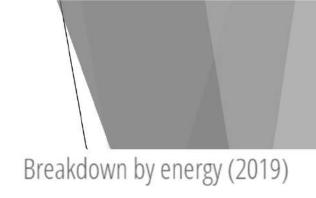
Below 50

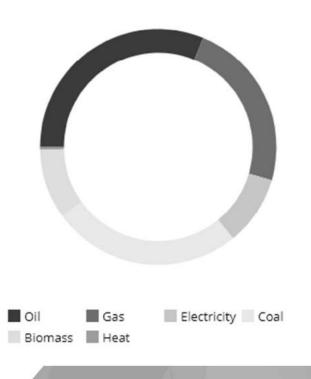
Unit: Mtoe	Highest ▼	
China	3,284	
United States	2,213	
India	913	
Russia	779	
Japan	421	
South Korea	298	
Germany	296	
Canada	295	
Brazil	288	
Indonesia	269	
Iran	258	
France	241	

Energy consumption in the World

Trend over 1990 - 2019



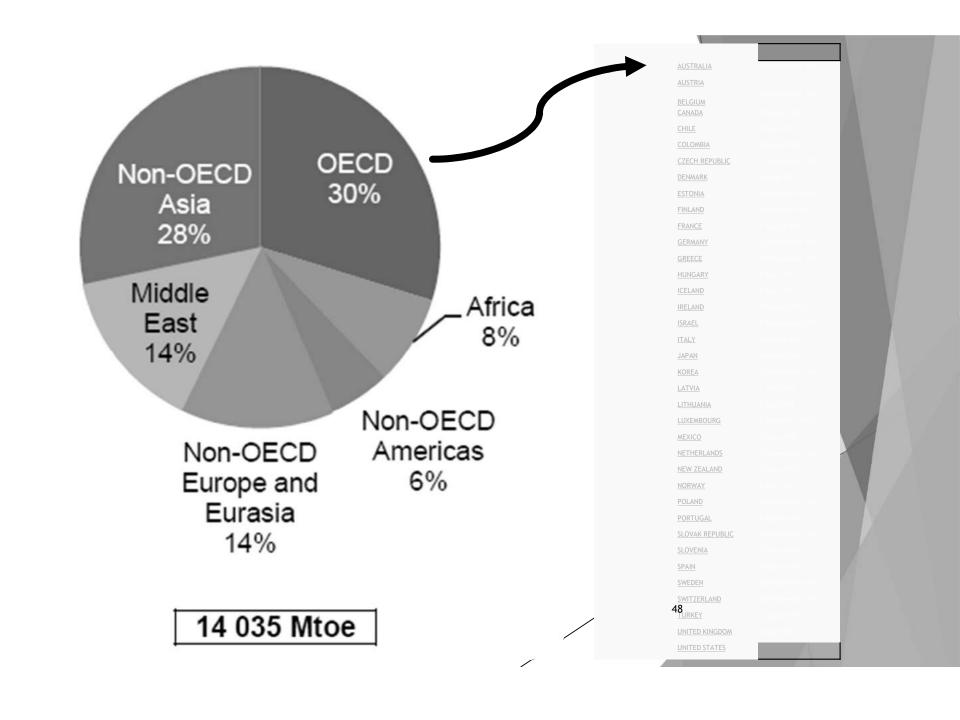




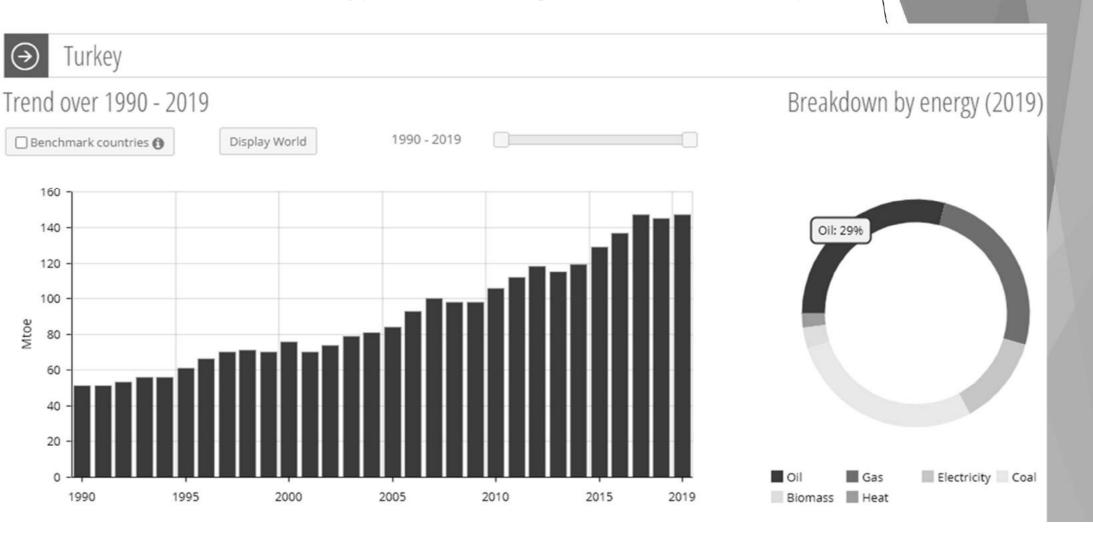
Energy consumption in the World



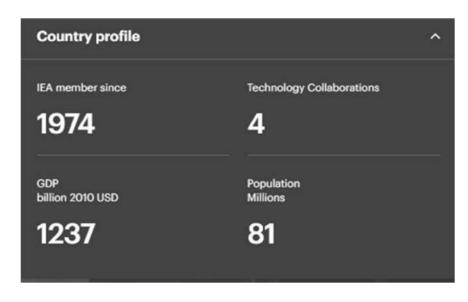
- ► GDP: Gross domestic product. 80,000 billion USD.
- ▶ Per capita is around 10,000 USD.



110 Mtoe energy consumption in Turkey

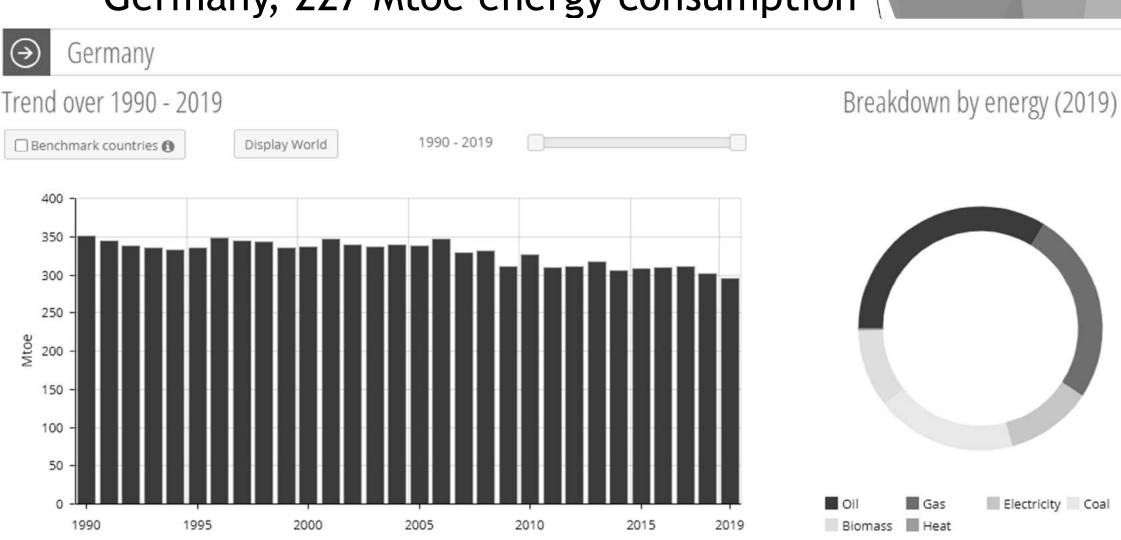


Energy consumption in Turkey

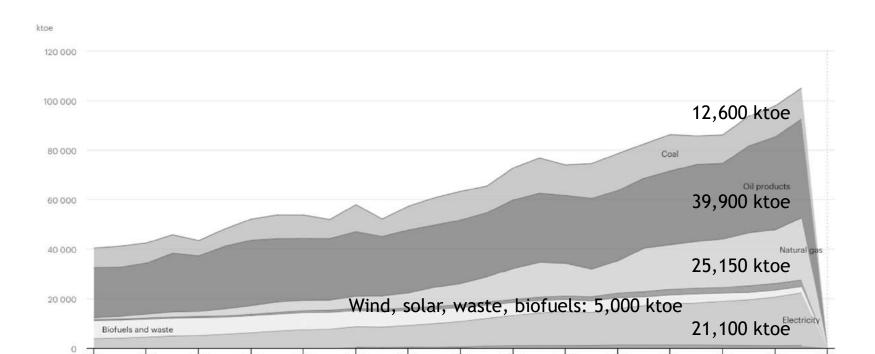


- ► GDP Per capita is around 15,000 U\$D.
- ► Turkey consumes around 110 Mtoe of energy

Germany, 227 Mtoe energy consumption



Total final consumption (TFC) by source, Turkey 1990-2018

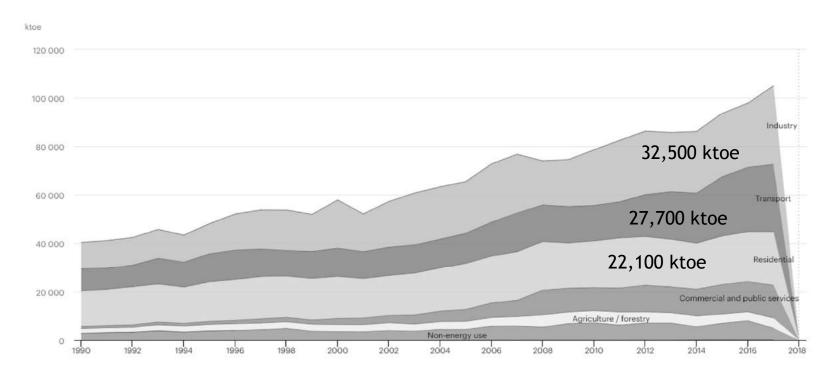


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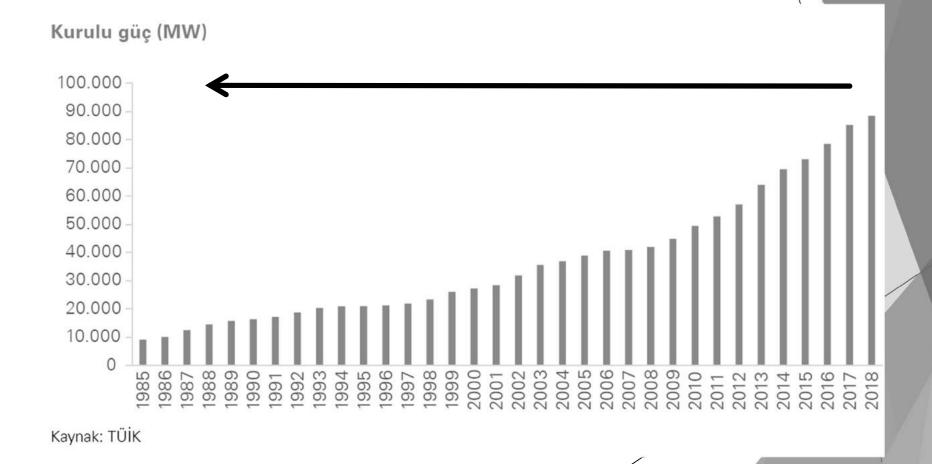
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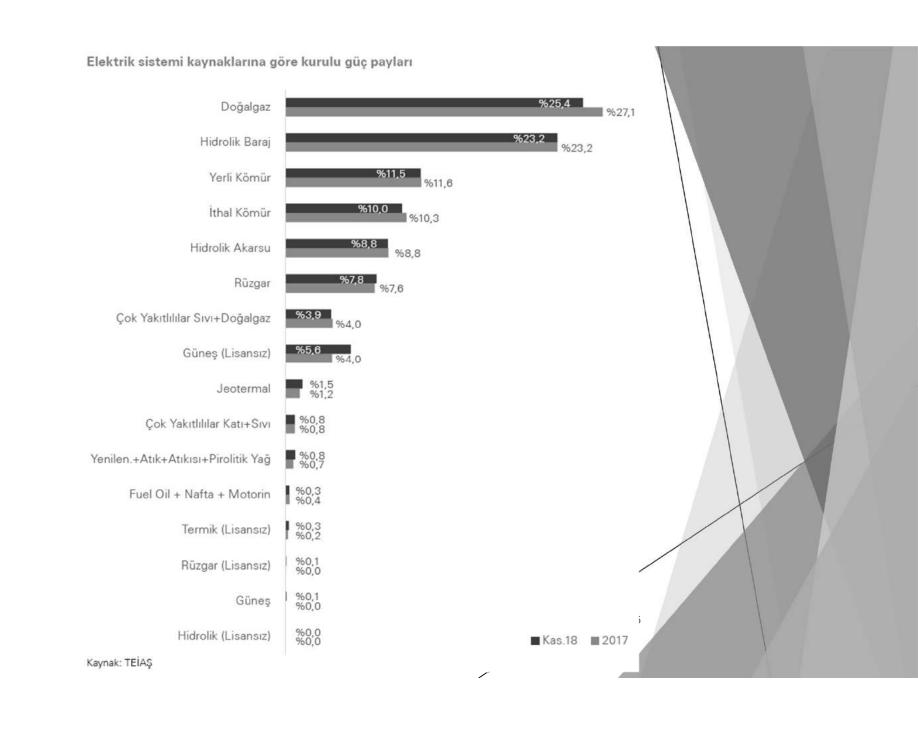
Total final consumption (TFC) by sector, Turkey 1990-2018



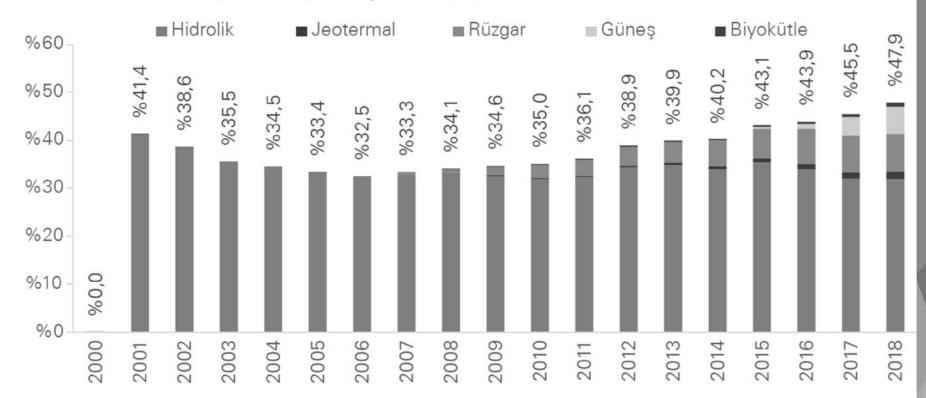


Electrical Energy in Turkey



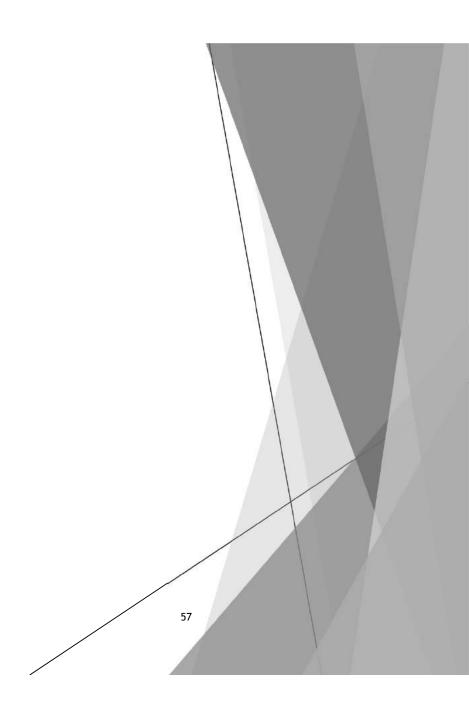


Yenilenebilir kurulu gücün toplam içindeki payı



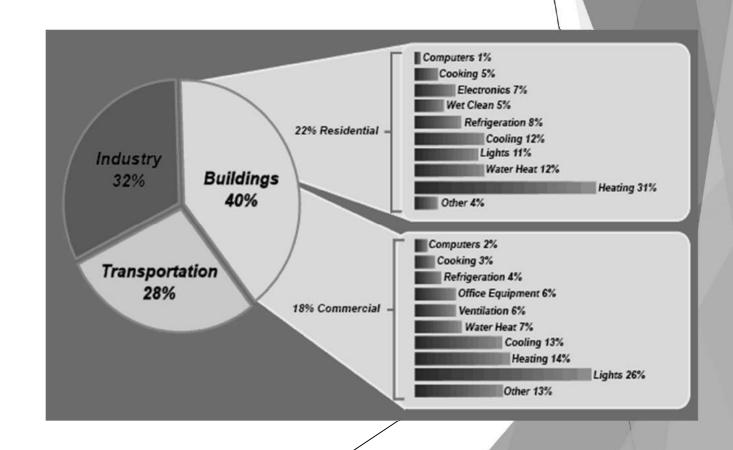
Kaynak: TEİAŞ

► END OF THE COURSE



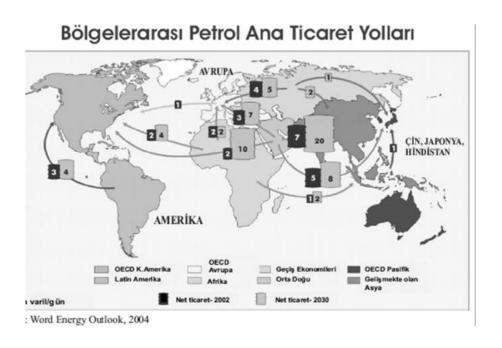
Main sectors in energy consumption

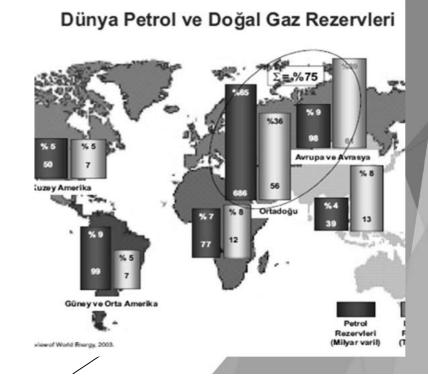
- World energy consumption is divided into three major economic sectors:
- 1) Buildings
- 2) Transportation
- 3) Industrial



Energy Transmission Lines Around the World

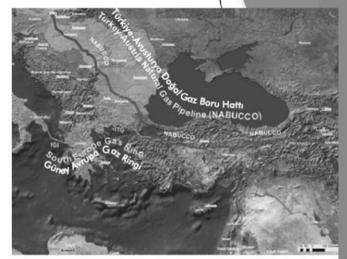
▶ According to the routes of interregional oil and natural gas trade, oil trade is expected to double by 2030, while interregional gas trade is expected to increase three times.

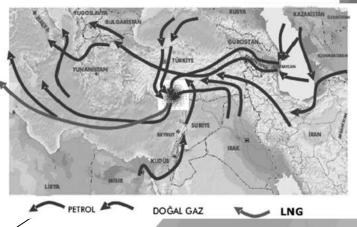




Crossroads Turkey

- ► Turkey, providing income to meet the needs of both existing international pipelines as well as increase the strategic importance of energy resources by means of the transfer.
- ► Turkey, the Central Asian pipeline project will be implemented by international Caspian and rich natural gas and oil reserves in the Middle East region will be one of Europe's most important energy bridge that leads to the main consumption centers.





Energy and Wars

- ► The energy crisis and energy wars are two concepts that have been drawn and talked about since the 20th century. Increasing population rate and a more comfortable desire to lead to energy crises, while energy wars emerge as a more political issue.
- ▶ In the time that has been going on since the birth of colonialism, a power war has been experienced in the sharing of lands with rich energy resources.
- ► "A drop of oil is more valuable than a drop of blood." Winston CHURCHILL



Energy and Wars

- ► States and terrorist groups, called superpower, follow an energy-oriented strategy.
- ► Therefore, when we look at the main causes of international political crises and conflicts, it is seen that there is an important factor called:

► ENERGY!



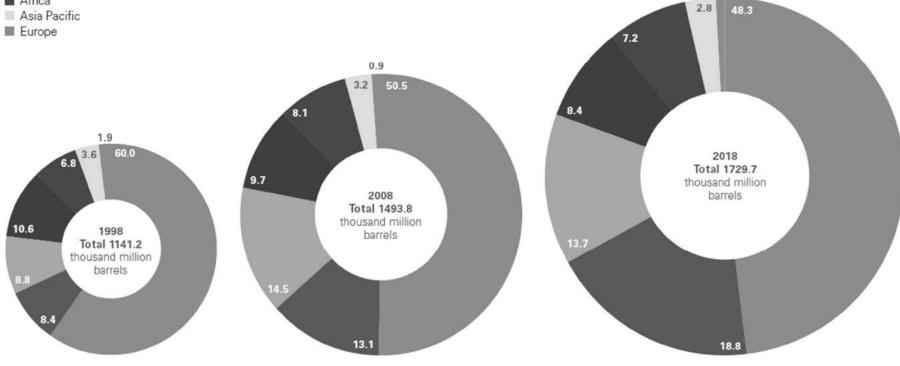
Proven Oil Reserves

BÖLGE	Miktar (Milyar varil)	Dünya Toplamındaki payı (%)
Orta Doğu	804	47,3%
Güney ve Orta Amerika	329	19,4%
Kuzey Amerika	238	14,0%
Avrupa ve Avrasya	155	9,1%
Afrika	129	7,6%
Asya Pasifik	43	2,5%
Dünya Toplamı	1.698	100%

Distribution of proved reserves in 1998, 2008 and 2018

Percentage

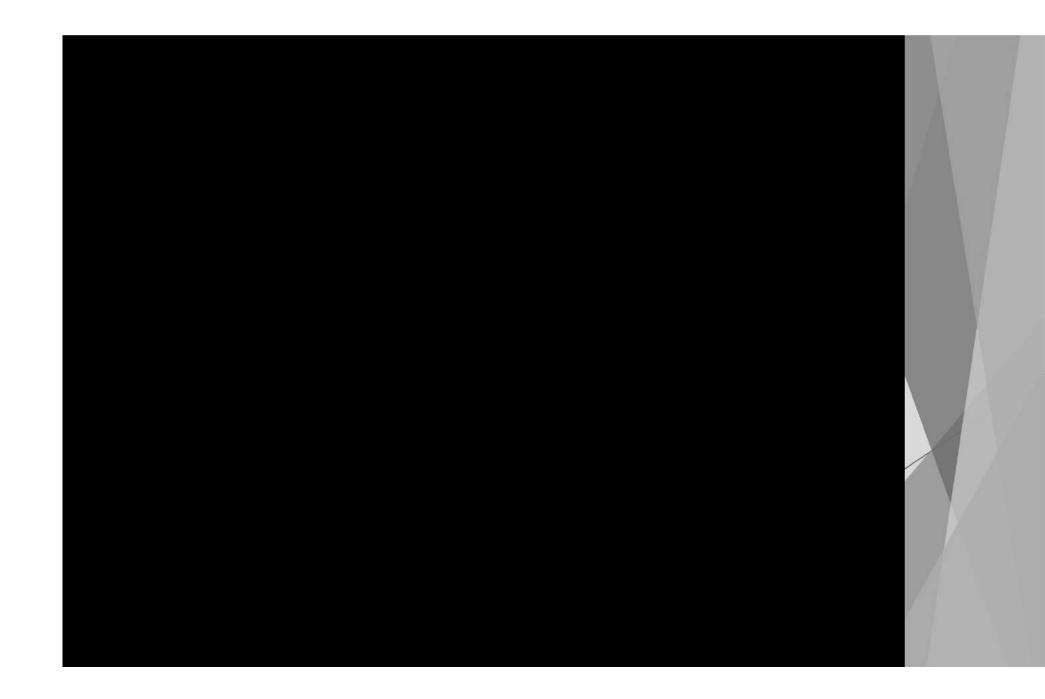
- Middle East
- S. & Cent. America
- North America
- CIS
- Africa
- Asia Pacific



8.0



►We need more energy



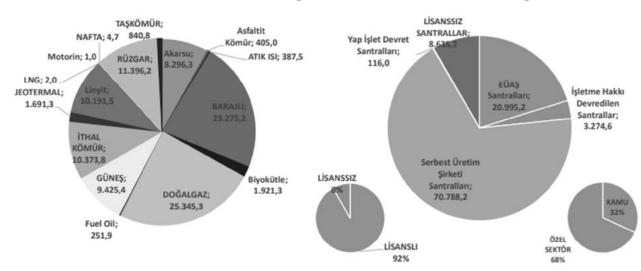




YÜK TEVZİ DAİRESİ BAŞKANLIĞI - KURULU GÜÇ RAPORU-ARALIK 2022

BİRİNCİL KAYNAKLARA GÖRE SANTRAL ADETLERİ VE KURULU GÜÇ SANTRAL ADEDI KURULU GÜÇ (MW) **BIRINCIL KAYNAK** Akarsu 610 8.296,3 Asfaltit Kömür 1 405,0 ATIK ISI 94 387,5 BARAJLI 141 23.275,2 Biyokütle 384 1.921,3 DOĞALGAZ 345 25.345,3 Fuel Oil 9 251,9 GÜNES 9.353 9.425,4 **İTHAL KÖMÜR** 16 10.373,8 **JEOTERMAL** 63 1.691,3 46 Linyit 10.191,5 LNG 2,0 Motorin 1 1,0 NAFTA 4.7 RÜZGAR 358 11.396.2 TASKÖMÜR 840.8 4 **TOPLAM** 11.427 103.809.3

KAYNAKLARA ve KURULUŞLARA GÖRE KURULU GÜÇ

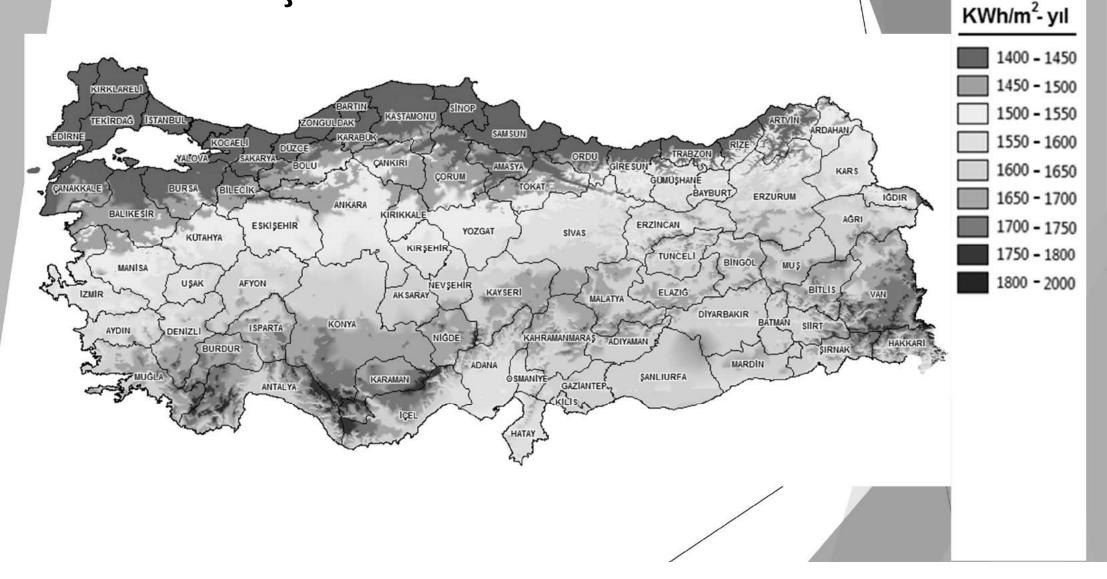


BİRİNCİL KAYNAKLARA VE KURUL		A VE KURULUŞLARA G	RA GÖRE KURULU GÜÇ (MW)			
IRINCIL KAYNAK	EÜAŞ Santralları	İşletme Hakkı Devredilen Santrallar	Serbest Üretim Şirketi Santralları	Yap İşlet Devret Santralları	LİSANSSIZ SANTRALLAR	TOPLAM
Akarsu	56,3	671,7	7.535,9	16,0	16,4	8.296,3
Asfaltit Kömür	0,0	0,0	405,0	0,0	0,0	405,0
ATIK ISI	0,0	0,0	164,9	0,0	222,5	387,5
BARAJLI	13.761,6	974,5	8.439,1	100,0	0,0	23.275,2
Biyokütle	0,0	0,0	1.831,4	0,0	89,9	1.921,3
DOĞALGAZ	4.734,9	258,4	20.083,9	0,0	268,2	25.345,3
Fuel Oil	0,0	0,0	251,9	0,0	0,0	251,9
GÜNEŞ	0,0	0,0	1.468,8	0,0	7.956,6	9.425,4
THAL KÖMÜR	0,0	0,0	10.373,8	0,0	0,0	10.373,8
JEOTERMAL	0,0	15,0	1.676,3	0,0	0,0	1.691,3
Linyit	2.424,0	1.355,0	6.412,5	0,0	0,0	10.191,5
LNG	0,0	0,0	2,0	0,0	0,0	2,0
Motorin	1,0	0,0	0,0	0,0	0,0	1,0
NAFTA	0,0	0,0	4,7	0,0	0,0	4,7
RÜZGAR	17,4	0,0	11.297,2	0,0	81,6	11.396,2
TAŞKÖMÜR	0,0	0,0	840,8	0,0	0,0	840,8
TOPLAM	20.995,2	3.274,6	70.788.2	116,0	8.635,2	103.809,3

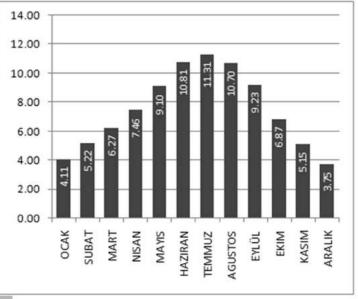
GÜNEŞ ENERJİSİ POTANSİYEL ATLASI

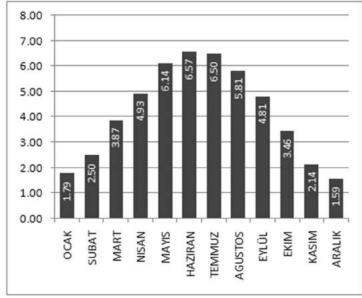
Toplam Güneş

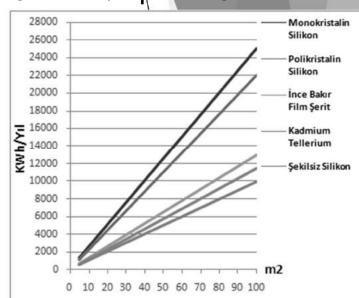
Radyasyonu

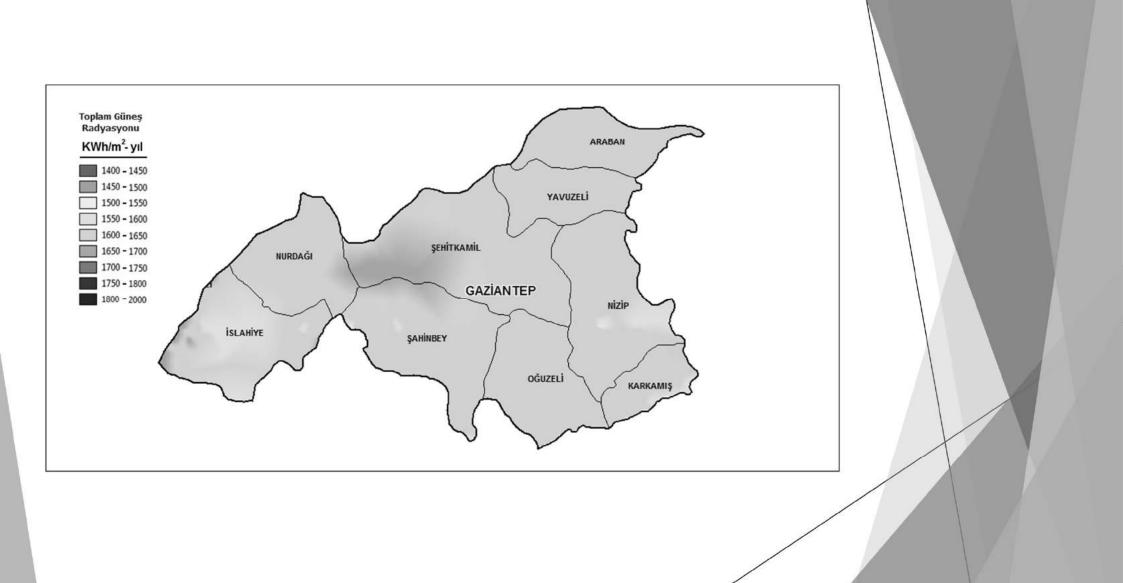


TÜRKİYE Güneşlenme Süreleri (Saat) TÜRKİYE Global Radyasyon Değerler**î**TÜRKİYE PV Tipi-Alan-Üretilebilecek E

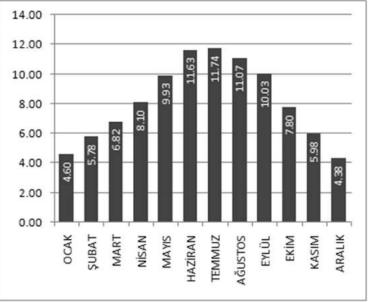




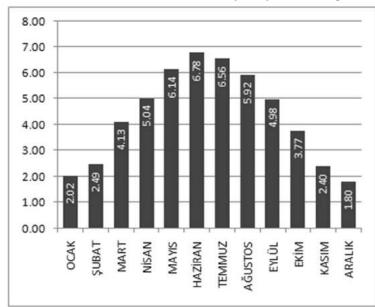




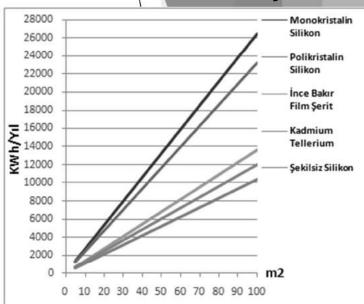
GAZİANTEP Güneşlenme Süreleri

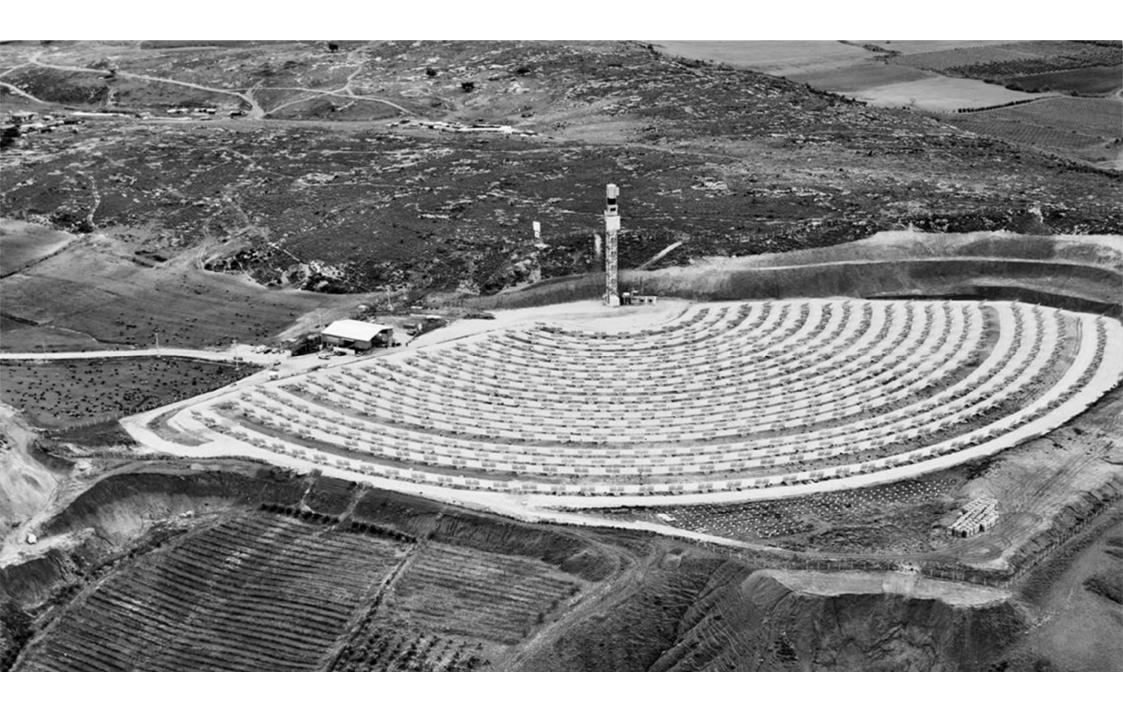


GAZİANTEP Global Radyasyon Değerleri

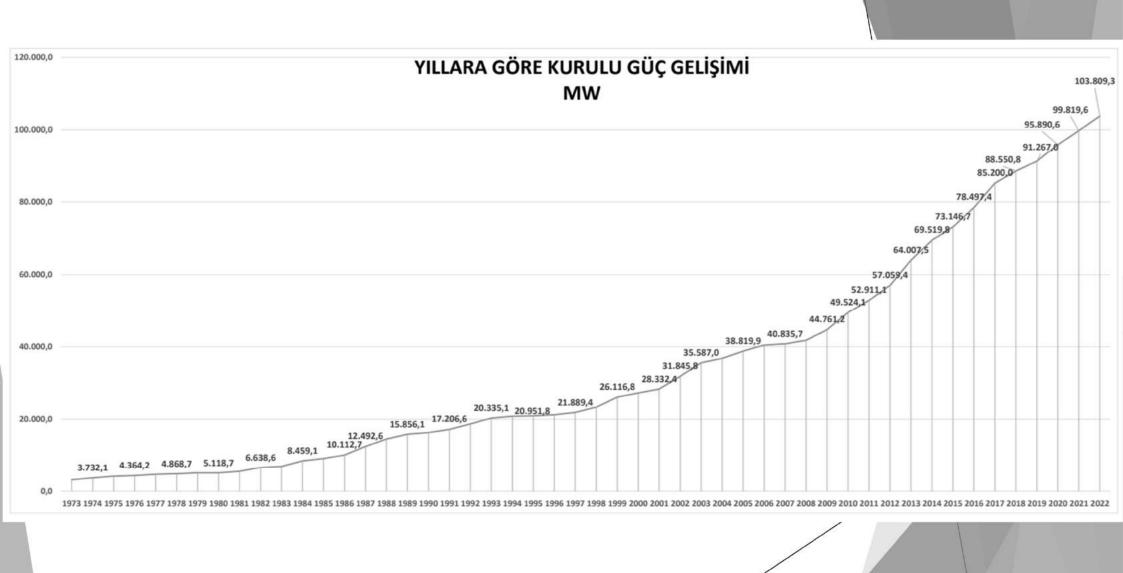


GAZİANTEP PV Tipi-Alan-Üretilebilecek Enerji



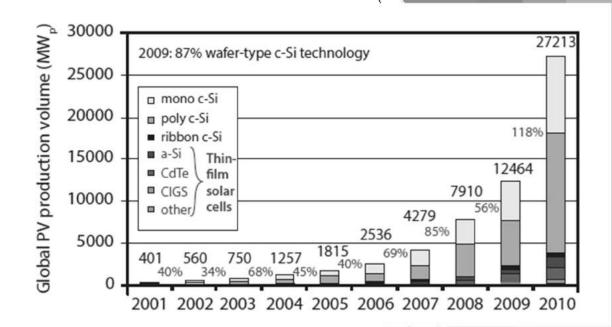




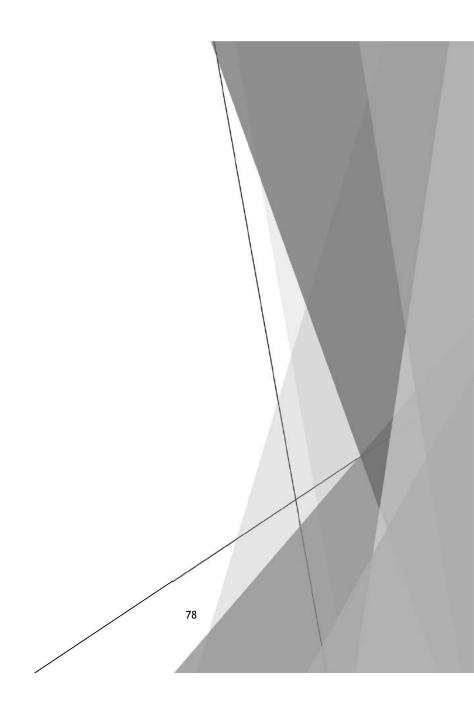


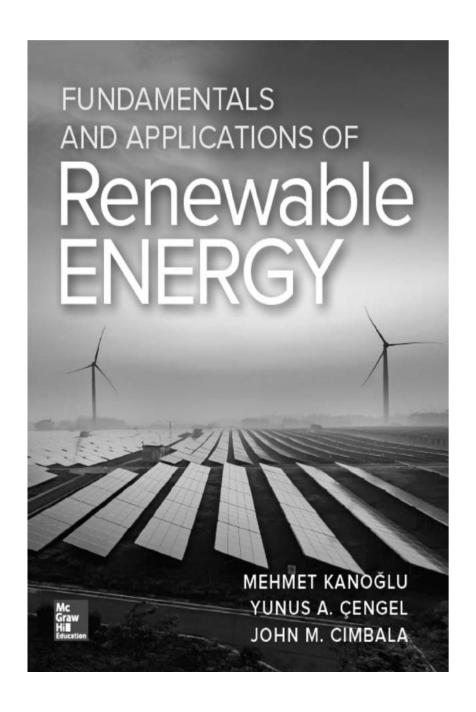
Status and prospects of PV technology

► The global production of PV modules in recent years is shown. The vertical axis represents the annual production expressed in the total produced power capacity in MWp.



► END OF THE COURSE





Chapter 3 FUNDAMENTALS OF SOLAR ENERGY

Fundamentals and Applications of

Renewable Energy

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McGraw-Hill, 2020



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3-1 INTRODUCTION

Solar radiation (solar energy) (solar heat): The electromagnetic energy emitted by the sun.

Tremendous amounts of energy are created within the sun and only a fraction of this energy reaches earth.

This keeps earth at a temperature suitable for life.

Amount of solar energy: The amount of solar energy reaching earth's surface can easily meet entire energy needs of the world.

However, this is not practical due to low concentration of solar energy and its relatively high cost.

Solar vs. other renewables: Other renewable energies such as geothermal, wind, hydro, and biomass appear to be less costly than direct solar energy but their potentials with the current technologies are also much less than direct solar energy.

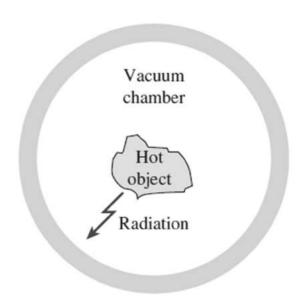
Solar energy reaches earth by radiation.

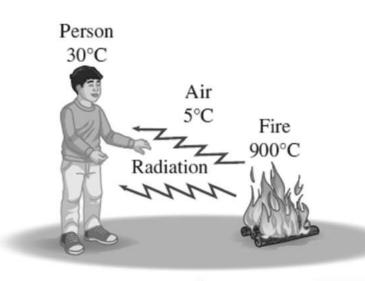
3-2 RADIATION FUNDAMENTALS

The hot object in vacuum chamber will eventually cool down and reach thermal equilibrium with its surroundings by a heat transfer mechanism: radiation.

How does radiation differ from conduction and convection: It does not require the presence of a material medium to take place.

Radiation transfer occurs in solids as well as liquids and gases.





Accelerated charges or changing electric currents give rise to electric and magnetic fields. These rapidly moving fields are called electromagnetic waves or electromagnetic radiation, and they represent the energy emitted by matter as a result of the changes in the electronic configurations of the atoms or molecules.

Electromagnetic waves transport energy and they are characterized by their frequency v or wavelength λ .

$$\lambda = \frac{c}{v}$$
 $c = c_0 / n$
 c , the speed of propagation of a wave in that medium
 $c_0 = 2.9979 \times 10^8$ m/s, the *speed of light* in a vacuum
 n , the *index of refraction* of that medium
 $n = 1$ for air and most gases, $n = 1.5$ for glass, and $n = 1.33$ for

It has proven useful to view electromagnetic radiation as the propagation of a collection of discrete packets of energy called photons or quanta. In this view, each photon of frequency n is considered to have an energy of

$$e = hv = \frac{hc}{\lambda}$$
 The energy of a photon is inversely proportional to its wavelength.

$$h = 6.626069 \times 10^{-34}$$
 J·s is Planck's constant

water

Thermal radiation: The type of electromagnetic radiation that is pertinent to heat transfer is the thermal radiation.

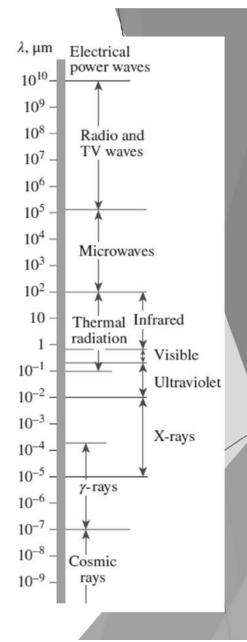
It is emitted as a result of energy transitions of molecules, atoms, and electrons of a substance.

Effect of temperature on thermal radiation:

Temperature is a measure of the strength of these activities at the microscopic level, and the rate of thermal radiation emission increases with increasing temperature.

Thermal radiation is continuously emitted by all matter whose temperature is above absolute zero.

Figure 3-1 The electromagnetic wave spectrum.



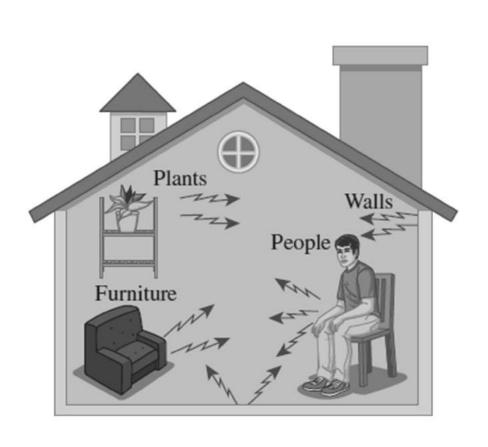


Figure 3-2
Everything around us constantly emits thermal radiation.

Light: It is simply the *visible* portion of the electromagnetic spectrum that lies between 0.40 and 0.76 μ m.

Light source: A body that emits some radiation in the visible range.

Our primary light source: Sun

Solar radiation: The electromagnetic radiation emitted by the sun is known as solar radiation, and nearly all of it falls into the wavelength band 0.3-3 μm .

Almost *half* of solar radiation is light (i.e., it falls into the visible range), with the remaining being ultraviolet and infrared.

TABLE 3-1 The Wavelength Ranges of Different Colors

Color	Wavelength Band (µm)
Violet	0.40-0.44
Blue	0.44-0.49
Green	0.49 - 0.54
Yellow	0.54-0.60
Orange	0.60-0.67
Red	0.63-0.76

Infrared radiation: The radiation emitted by bodies at room temperature falls into the infrared region of the spectrum, which extends from 0.76 to 100 μ m.

Ultraviolet radiation: The ultraviolet radiation includes the low-wavelength end of the thermal radiation spectrum and lies between the wavelengths 0.01 and 0.40 μ m.

Ultraviolet rays are to be avoided since they can kill microorganisms and cause serious damage to humans and other living beings.

About 12 percent of solar radiation is in the ultraviolet range.

The ozone (O₃) layer in the atmosphere acts as a protective blanket and absorbs most of this ultraviolet radiation.

Blackbody Radiation

Different bodies may emit different amounts of radiation per unit surface area.

Blackbody: It emits the *maximum* amount of radiation by a surface at a given temperature.

It is an *idealized body* to serve as a standard against which the radiative properties of real surfaces may be compared.

A blackbody is a perfect emitter and absorber of radiation.

A blackbody absorbs *all* incident radiation, regardless of wavelength and direction.

Blackbody emissive power: The radiation energy emitted by a blackbody

$$E_b(T) = \sigma T^4$$

$$\sigma = 5.670 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$$

Stefan-Boltzmann law

Stefan-Boltzmann constant 87

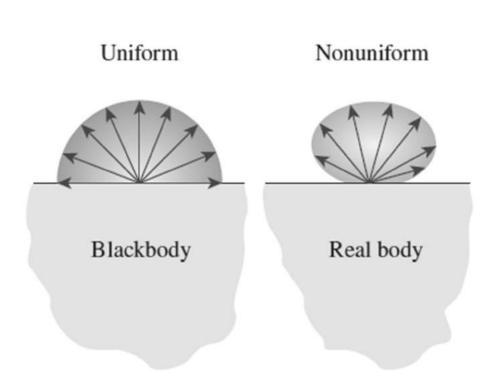


Figure 3-3
A blackbody is said to be a diffuse emitter since it emits radiation energy uniformly in all directions.

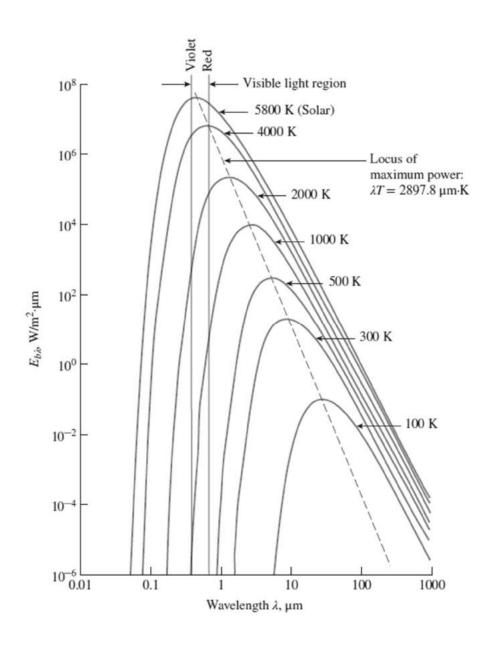
Spectral blackbody emissive power: The amount of radiation energy emitted by a blackbody at a thermodynamic temperature T per unit time, per unit surface area, and per unit wavelength about the wavelength λ .

$$E_{b\lambda}(\lambda,T) = \frac{C_1}{\lambda^5 [\exp(C_2/\lambda T) - 1]} \qquad (W/m^2 \cdot \mu m) \quad \begin{array}{l} \text{Planck's} \\ \text{law} \end{array}$$

$$C_1 = 2\pi h c_0^2 = 3.74177 \times 10^8 \text{ W} \cdot \mu\text{m}^4/\text{m}^2$$

$$C_2 = hc_0/k = 1.43878 \times 10^4 \ \mu \text{m} \cdot \text{K}$$

 $k = 1.38065 \times 10^{-23} \text{ J/K}$ Boltzmann's constant



The wavelength at which the peak occurs for a specified temperature is given by Wien's displacement law

$$(\lambda T)_{\text{max power}} = 2897.8 \,\mu\text{m} \cdot \text{K}$$

Figure 3-4

The variation of the blackbody emissive power with wavelength for several temperatures.

Observations from the figure

Effect of wavelength: The emitted radiation is a continuous function of wavelength. At any specified temperature, it *increases* with wavelength, reaches a peak, and then decreases with increasing wavelength.

Effect of temperature: At any wavelength, the amount of emitted radiation *increases* with increasing temperature.

As temperature increases, the curves shift to the left to the shorter wavelength region. Consequently, a larger fraction of the radiation is emitted at *shorter wavelengths* at higher temperatures.

Solar radiation: The radiation emitted by the *sun*, which is considered to be a blackbody at 5780 K, reaches its peak in the visible region of the spectrum. Therefore, the sun is in tune with our eyes.

Infrared radiation: On the other hand, surfaces at T < 800 K emit almost entirely in the infrared region and thus are not visible to the eye unless they reflect light coming from other sources.

$$E_b(T) = \int_0^\infty E_{b\lambda}(\lambda, T) d\lambda = \sigma T^4 \qquad (W/m^2)$$

(W/m²) Total blackbody emissive power

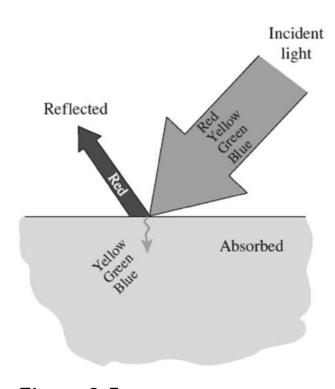


Figure 3-5
A surface that reflects red while absorbing the remaining parts of the incident light appears red to the eye.

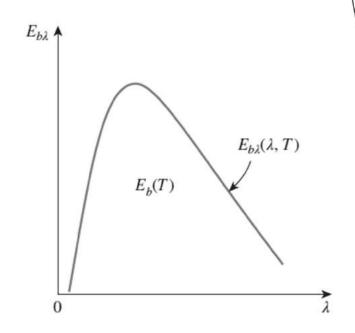


Figure 3-6 On an $E_{b\lambda}$ – λ chart, the area under a curve for a given temperature represents the total radiation energy emitted by a blackbody at that temperature.

3-3 RADIATIVE PROPERTIES

Most materials encountered in practice, such as metals, wood, and bricks, are *opaque* to thermal radiation, and radiation is considered to be a *surface phenomenon* for such materials.

Radiation through *semitransparent* materials such as glass and water cannot be considered to be a surface phenomenon since the entire volume of the material interacts with radiation.

A blackbody can serve as a convenient *reference* in describing the emission and absorption characteristics of real surfaces.

Emissivity

Emissivity: The ratio of the radiation emitted by the surface at a given temperature to the radiation emitted by a blackbody at the same temperature.

$$0 \le \varepsilon \le 1$$

Emissivity of blackbody: Emissivity is a measure of how closely a surface approximates a blackbody ($\varepsilon = 1$).

Metals generally have low emissivities, as low as 0.02 for polished surfaces, and nonmetals such as ceramics and organic materials have high ones.

Effect of temperature: The emissivity of metals increases with temperature.

Effect of oxidation: Oxidation causes significant increases in the emissivity of metals.

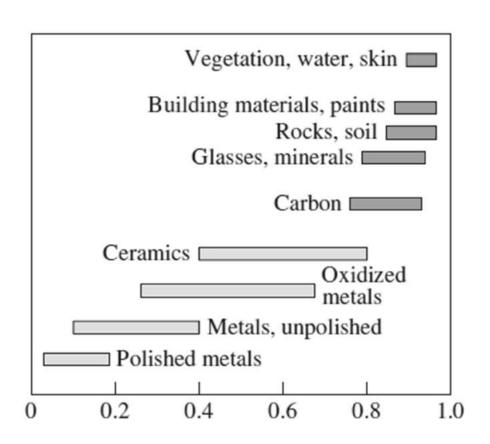


Figure 3-7
Typical ranges of emissivity for various materials.

Absorptivity, Reflectivity, and Transmissivity

Absorptivity:

$$\alpha = \frac{G_{\text{abs}}}{G}$$
 $0 < \alpha < 1$

Reflectivity:

$$\alpha = \frac{G_{\text{abs}}}{G} \qquad 0 < \alpha < 1$$

$$\rho = \frac{G_{\text{ref}}}{G} \qquad 0 < \rho < 1$$

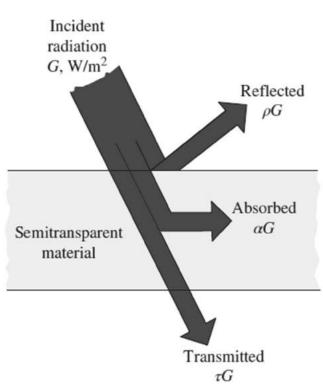
$$\tau = \frac{G_{\text{tr}}}{G} \qquad 0 < \tau < 1$$

Transmissivity:

$$\tau = \frac{G_{\rm tr}}{G} \qquad 0 < \tau < 1$$

Irradiation, G:

Radiation flux incident on a surface.



$$G_{\text{abs}} + G_{\text{ref}} + G_{\text{tr}} = G$$

$$\alpha + \rho + \tau = 1$$

$$\alpha + \rho = 1$$
 for opaque surfaces

Figure 3-8

The absorption, reflection, and transmission of incident radiation by a semitransparent material.

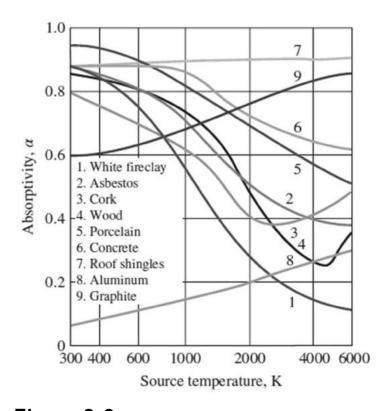


Figure 3-9
Variation of absorptivity with the temperature of the source of irradiation for various common materials at room temperature.

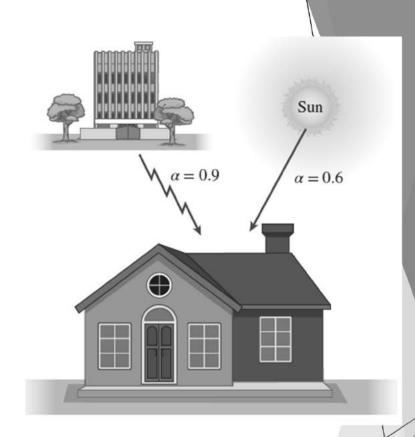


Figure 3-10
The absorptivity of a material may be quite different for radiation originating from sources at different temperatures.

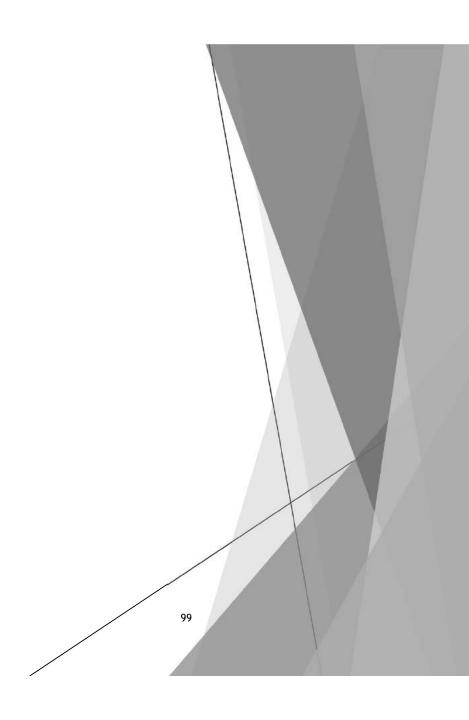
97

$$\varepsilon(T) = \alpha(T)$$
 Kirchhoff's law

The emissivity of a surface at temperature *T* is equal to its absorptivity for radiation coming from a blackbody at the same temperature.

This relation is derived under the condition that the surface temperature is equal to the temperature of the source of irradiation, and the reader is cautioned against using it when considerable difference (more than a few hundred degrees) exists between the surface temperature and the temperature of the source of irradiation.

► END OF THE COURSE



The Greenhouse Effect

Glass has a transparent window in the wavelength range 0.3 μ m < λ < 3 μ m in which over 90% of solar radiation is emitted.

The entire radiation emitted by surfaces at room temperature falls in the infrared region ($\lambda > 3 \mu m$).

Glass allows the solar radiation to enter but does not allow the infrared radiation from the interior surfaces to escape. This causes a rise in the interior temperature as a result of the energy buildup in the car.

This heating effect, which is due to the nongray characteristic of glass (or clear plastics), is known as the greenhouse effect.

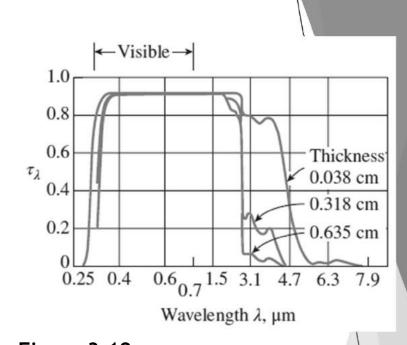


Figure 3-12
The spectral transmissivity of lowiron glass at room temperature for
different thicknesses.

100

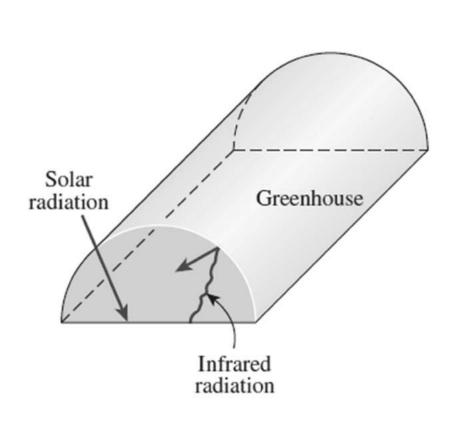


Figure 3-13
A greenhouse traps energy by allowing solar radiation to come in but not allowing IR radiation to go out.

3-4 SOLAR RADIATION

Atmospheric radiation: The radiation energy emitted or reflected by the constituents of the atmosphere.

Fusion: The energy of the sun is due to the continuous *fusion* reaction during which two hydrogen atoms fuse to form one atom of helium.

The sun is essentially a *nuclear reactor*, with temperatures as high as 40,000,000 K in its core region.

The temperature drops to about 5800 K in the outer region of the sun, called the convective zone, as a result of the dissipation of this energy by radiation.

Total solar irradiance G_s : The solar energy reaching the earth's atmosphere.

Solar constant: The total solar irradiance. It represents the rate at which solar energy is incident on a surface normal to the sun's rays at the outer edge of the atmosphere when the earth is at its mean distance from the sun. $G_s = 1373 \text{ W/m}^2$

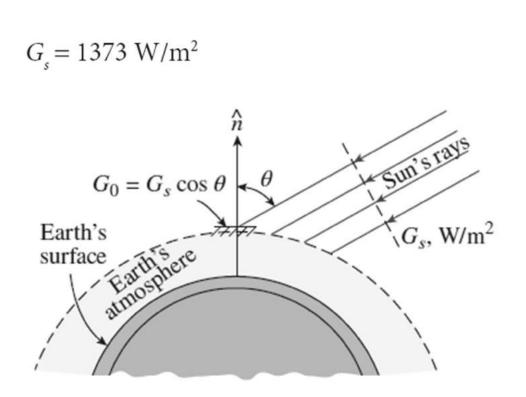


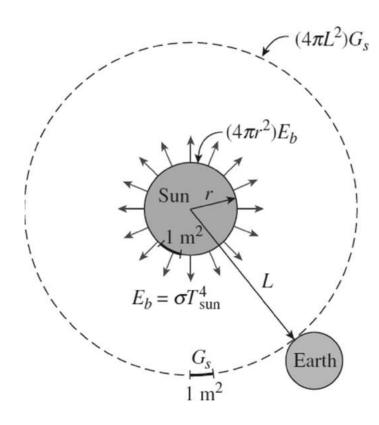
Figure 3-14
Solar radiation reaching the earth's atmosphere and the total solar irradiance.

The value of the total solar irradiance can be used to estimate the effective surface temperature of the sun from this equation:

$$(4\pi L^2)G_s = (4\pi r^2)\sigma T_{\rm sun}^4$$

L the mean distance between the sun's center and the earth

r the radius of the sun

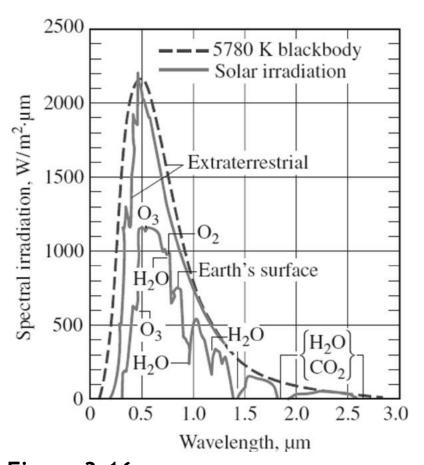


The effective surface temperature of the sun is T_{sun} = 5780 K.

The sun can be treated as a blackbody at a temperature of 5780 K.

Figure 3-15

The total solar energy passing through concentric spheres remains constant, but the energy falling per unit area decreases with increasing radius.



The spectral distribution of solar radiation on the ground plotted in Fig. 3-16 shows that the solar radiation undergoes considerable attenuation as it passes through the atmosphere as a result of absorption and scattering.

As a result, the solar energy reaching the earth's surface is weakened considerably, to about 950 W/m² on a clear day and much less on cloudy or smoggy days.

Figure 3-16
Spectral distribution of solar radiation just outside the atmosphere, at the surface of the earth on a typical day, and comparison with blackbody radiation at 5780 K.

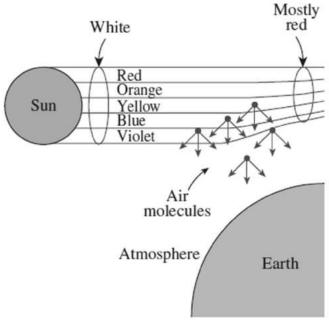


Figure 3-17

Air molecules scatter blue light much more than they do red light. At sunset, light travels through a thicker layer of atmosphere, which removes much of the blue from the natural light, allowing the red to dominate. Another mechanism that attenuates solar radiation as it passes through the atmosphere is scattering or reflection by air molecules and the many other kinds of particles such as dust, smog, and water droplets suspended in the atmosphere.

The solar energy incident on a surface on earth is considered to consist of *direct* and *diffuse* parts.

Direct solar radiation G_D : The part of solar radiation that reaches the earth's surface without being scattered or absorbed by the atmosphere.

Diffuse solar radiation G_d : The scattered radiation is assumed to reach the earth's surface uniformly from all directions.

The *total* solar energy incident on the unit area of a *horizontal surface* on the ground is

$$G_{\text{solar}} = G_D \cos\theta + G_d$$

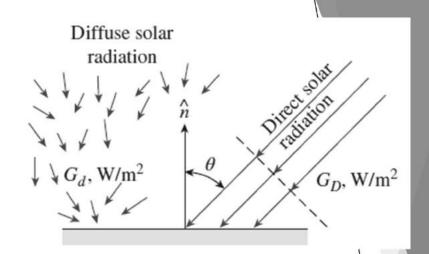


Figure 3-18
The direct and diffuse radiation incident on a horizontal surface on earth's surface.

It is found convenient in radiation calculations to treat the atmosphere as a blackbody at some lower fictitious temperature that emits an equivalent amount of radiation energy. This fictitious temperature is called the effective sky temperature $T_{\rm sky}$. The radiation emission from the atmosphere to the earth's surface is

$$G_{\rm sky} = \sigma T_{\rm sky}^4$$
 (W/m²)

The value of $T_{\rm sky}$ depends on the atmospheric conditions. It ranges from about 230 K for cold, clear-sky conditions to about 285 K for warm, cloudy-sky conditions.

$$E_{\text{sky,absorbed}} = \alpha G_{\text{sky}} = \alpha \sigma T_{\text{sky}}^4 = \varepsilon \sigma T_{\text{sky}}^4$$
 (W/m²)

Net rate of radiation heat transfer to a surface exposed to solar and atmospheric radiation

$$\dot{q}_{
m net,rad} = E_{
m solar,absorbed} + E_{
m sky,absorbed} - E_{
m emitted}$$

$$= \alpha_s G_{
m solar} + \varepsilon \sigma T_{
m sky}^4 - \varepsilon \sigma T_s^4$$

$$= \alpha_s G_{
m solar} + \varepsilon \sigma (T_{
m sky}^4 - T_s^4)$$

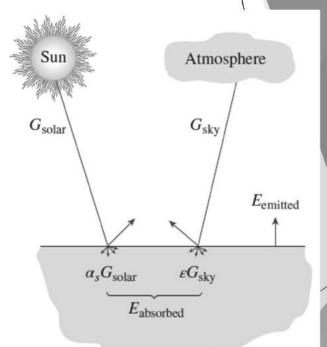


Figure 3-19
Radiation interactions of a surface exposed to solar and atmospheric radiation.

The absorption and emission of radiation by the *elementary* gases such as H_2 , O_2 , and N_2 at moderate temperatures are negligible, and a medium filled with these gases can be treated as a *vacuum* in radiation analysis.

The absorption and emission of gases with *larger molecules* such as H_2O and CO_2 , however, can be *significant* and may need to be considered when considerable amounts of such gases are present in a medium.

For example, a 1-m-thick layer of water vapor at 1 atm pressure and 100°C emits more than 50 percent of the energy that a blackbody would emit at the same temperature.

The radiation properties of surfaces are quite different for the incident and emitted radiation.

The surfaces are assumed to have two sets of properties:

- one for solar radiation
- another for infrared radiation at room temperature.

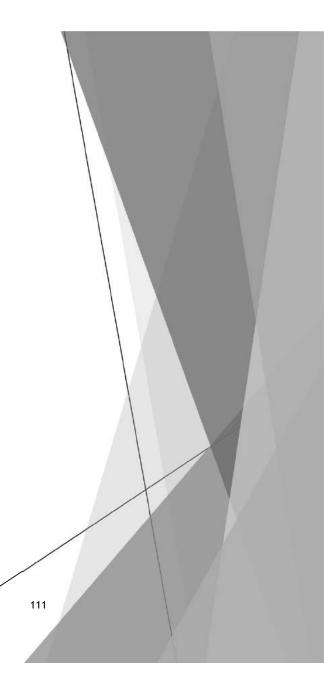
Surfaces that are intended to collect solar energy, such as the absorber surfaces of solar collectors, are desired to have high solar absorptivity but low emissivity values to maximize the absorption of solar radiation and to minimize the emission of radiation.

TABLE 3-2 Comparison of the Solar Absorptivity α_s of Some Surfaces with Their Emissivity ε at Room Temperature

Surface	$\alpha_{_{s}}$	ε
Aluminum		
Polished	0.09	0.03
Anodized	0.14	0.84
Foil	0.15	0.05
Copper		
Polished	0.18	0.03
Tarnished	0.65	0.75
Stainless steel		
Polished	0.37	0.60
Dull	0.50	0.21
Plated metals		
Black nickel oxide	0.92	0.08
Black chrome	0.87	0.09
Concrete	0.60	0.88
White marble	0.46	0.95
Red brick	0.63	0.93
Asphalt	0.90	0.90
Black paint	0.97	0.97
White paint	0.14	0.93
Snow	0.28	0.97
Human skin (Caucasian)	0.62	0.97

TABLE 3-3 Solar Radiative Properties of Materials

Description/Composition	Solar Absorptivity, α	Emissivity, ε , at 300 K	Ratio, α/ε	Solar Transmissivity, 1
	rassiparity, w	at 500 IC	wyc	mansims.
Aluminum	0.00	0.02	2.0	
Polished Anodized	0.09	0.03	3.0 0.17	
Quartz-overcoated	0.14	0.37	0.17	
Foil	0.15	0.05	3.0	
Brick, red (Purdue)	0.63	0.93	0.68	
Concrete	0.60	0.88	0.68	
Galvanized sheet metal				
Clean, new	0.65	0.13	5.0	
Oxidized, weathered	0.80	0.28	2.9	
Glass, 3.2-mm thickness				
Float or tempered				0.79
Low iron oxide type				0.88
Marble, slightly off-white (nonreflective)	0.40	0.88	0.45	
Metal, plated				
Black sulfide	0.92	0.10	9.2	
Black cobalt oxide	0.93	0.30	3.1	
Black nickel oxide Black chrome	0.92	0.08	11	
	0.87	0.09	9.7	0.07
Mylar, 0.13-mm thickness				0.87
Paints Black (Parsons)	0.98	0.98	1.0	
White, acrylic	0.98	0.98	0.29	
White, zinc oxide	0.16	0.93	0.17	
Paper, white	0.27	0.83	0.32	
Plexiglas, 3.2-mm thickness	0.27	0.00	0.02	0.90
Porcelain tiles, white (reflective glazed surface)	0.26	0.85	0.30	0.50
	0.20	0.83	0.30	
Roofing tiles, bright red Dry surface	0.65	0.85	0.76	
Wet surface	0.88	0.91	0.76	
Sand, dry	0.00	0.71	0.70	
Off-white	0.52	0.82	0.63	
Dull red	0.73	0.86	0.82	
Snow				
Fine particles, fresh	0.13	0.82	0.16	
Ice granules	0.33	0.89	0.37	
Steel				
Mirror-finish	0.41	0.05	8.2	
Heavily rusted	0.89	0.92	0.96	
Stone (light pink)	0.65	0.87	0.74	
Tedlar, 0.10-mm thickness	and the second		36.67.38.3	0.92
Teflon, 0.13-mm thickness				0.92
	0.50	0.00	0.66	0.72
Wood	0.59	0.90	0.66	



3-5 SOLAR DATA

The amount of solar radiation incident on a surface depends on

- orientation of the surface
- the latitude
- elevation of the location
- humidity of air
- clearness of the sky
- the time of the day

Table 3-4: It gives hourly solar radiation incident on various surfaces at 40° latitude. Data is also available at other latitudes.

Table 3-5: Average daily solar radiation values on a horizontal surface in the United States are given for selected cities in Table 3-5.

Extensive solar data at various latitudes and locations are available in literature.

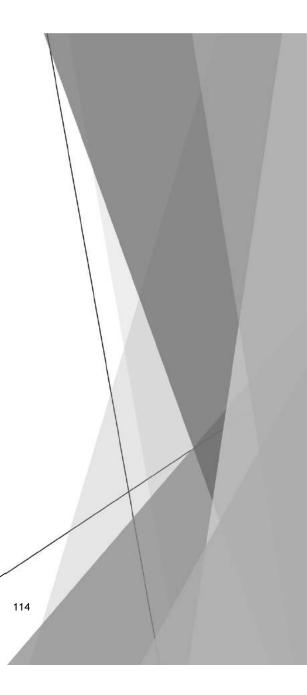
There are also calculation methods of solar radiation input to various surfaces on earth.

TABLE 3-4 Hourly Variation of Solar Radiation Incident on Various Surfaces and the Daily Totals throughout the Year at 40° Latitude (ASHRAE, 1993)

						5	Solar R	adiation	n Inciden	t on th	e Surfa	ce,* W	/m²					
									Solar	Time								_
Date	Direction of Surface	5	6	7	8	9	10	11	12 noon	13	14	15	16	17	18	19	Daily Total	
Jan.	N	0	0	0	20	43	66	68	71	68	66	43	20	0	0	0	446	
	NE	0	0	0	63	47	66	68	71	68	59	43	20	0	0	0	489	
	E	0	0	0	402	557	448	222	76	68	59	43	20	0	0	0	1863	
	SE	0	0	0	483	811	875	803	647	428	185	48	20	0	0	0	4266	
	S	0	0	0	271	579	771	884	922	884	771	579	271	0	0	0	5897	
	SW	0	0	0	20	48	185	428	647	803	875	811	483	0	0	0	4266	
	W	0	0	0	20	43	59	68	76	222	448	557	402	0	0	0	1863	
	NW Hariaantal	0	0	0	20 51	43 198	59	68	71 482	68 448	66 348	47	63 51	0	0	0	489	
	Horizontal Direct	0	0	0	446	753	348 865	448 912	926	912	865	198 753	446	0	0	0	2568	
34.00m			10/10	-														
Apr.	N	0	41	57	79	97	110	120	122	120	110	97	79	57	41	0	1117	
	NE	0	262	508	462	291	134	123	122	120	110	97	77	52	17	0	2347	
	E SE	0	321 189	728	810	732	552 699	293 582	131	120	110	97	77 77	52 52	17	0	4006	
	S	0	189	518 59	682 149	736 333	437	528	392 559	187 528	116 437	97 333	149	59	17 18	0	4323 3536	
	sw	0	17	52	77	97	116	187	392	582	699	736	682	518	189	0	4323	
	W	0	17	52	77	97	110	120	392	293	552	732	810	728	321	0	4006	
	NW	0	17	52	77	97	110	120	122	123	134	291	462	508	262	0	2347	
	Horizontal	0	39	222	447	640	786	880	911	880	786	640	447	222	39	0	6938	
	Direct	0	282	651	794	864	901	919	925	919	901	864	794	651	282	0	_	
July	N	3	133	109	103	117	126	134	138	134	126	117	103	109	133	3	1621	
	NE	8	454	590	540	383	203	144	138	134	126	114	95	71	39	0	3068	
	E	7	498	739	782	701	531	294	149	134	126	114	95	71	39	0	4313	
	SE	2	248	460	580	617	576	460	291	155	131	114	95	71	39	0	3849	
	S	0	39	76	108	190	292	369	395	369	292	190	108	76	39	0	2552	
	SW	0	39	71	95	114	131	155	291	460	576	617	580	460	248	2	3849	
	W	0	39	71	95	114	126	134	149	294	531	701	782	739	498	7	4313	
	NW	0	39	71	95	114	126	134	138	144	203	383	540	590	454	8	3068	
	Horizontal	1	115	320	528	702	838	922	949	922	838	702	528	320	115	1	3902	
51,770	Direct	7	434	656	762	818	850	866	871	866	850	818	762	656	434	7	_	
Oct.	N	0	0	7	40	62	77	87	90	87	77	62	40	7	0	0	453	
	NE	0	0	74	178	84	80	87	90	87	87	62	40	7	0	0	869	200
	E	0	0	163	626	652	505	256	97	87	87	62	40	7	0	0	2578	/
	SE	0	0	152	680	853	864	770	599	364	137	66	40	.7	0	0	4543	
	S SW	0	0	44	321	547	711	813	847	813	711	547 853	321	152	0	0	5731	
	W	0	0	7	40	66 62	137 87	364 87	599 97	770 256	864 505	652	680 626	152 163	0	0	4543 2578	13
	NW	0	0	7	40	62	87	87	90	87	80	84	178	74	0	0	869	
	Horizontal	0	0	14	156	351	509	608	640	608	509	351	156	14	0	0	3917	
	Direct	0	0	152	643	811	884	917	927	917	884	811	643	152	0	0	3317	- 1

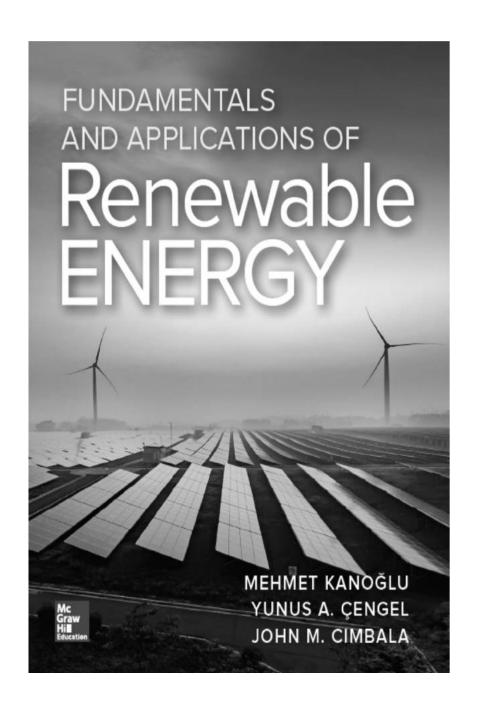
TABLE 3-5 Average Daily Solar Radiation on a Horizontal Surface in Selected Cities in the United States, in MJ/m²-day (NREL, 2018)

State and Location	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Averag
Alabama, Birmingham	9.20	11.92	13.67	19.65	21.58	22.37	21.24	20.21	17.15	14.42	10.22	8.40	16.01
Alaska, Anchorage	1.02	3.41	8.18	13.06	15.90	17.72	16.69	12.72	8.06	3.97	1.48	0.56	8.63
Arizona, Tucson	12.38	15.90	20.21	25.44	28.39	29.30	25.44	24.08	21.58	17.94	13.63	11.24	20.44
Arkansas, Little Rock	9.09	11.81	15.56	19.19	21.80	23.51	23.17	21.35	17.26	14.08	9.77	8.06	16.24
California, San Francisco	7.72	10.68	15.22	20.44	24.08	25.78	26.46	23.39	19.31	13.97	8.97	7.04	16.92
Colorado, Boulder	7.84	10.45	15.64	17.94	17.94	20.47	20.28	17.12	16.07	12.09	8.66	7.10	14.31
Connecticut, Hartford	6.70	9.65	13.17	16.69	19.53	21.24	21.12	18.51	14.76	10.68	6.59	5.45	13.74
Delaware, Wilmington	7.27	10.22	13.97	17.60	20.33	22.49	21.80	19.65	15.79	11.81	7.84	6.25	14.65
Florida, Miami	12.72	15.22	18.51	21.58	21.46	20.10	21.10	20.10	17.60	15.67	13.17	11.81	17.38
Georgia, Atlanta	9.31	12.26	16.13	20.33	22.37	23.17	22.15	20.56	17.49	14.54	10.56	8.52	16.43
Hawaii, Honolulu	14.08	16.92	19.42	21.24	22.83	23.51	23.74	23.28	21.35	18.06	14.88	13.40	19.42
Idaho, Boise	5.79	8.97	13.63	18.97	23.51	26.01	27.37	23.62	18.40	12.26	6.70	5.11	15.90
Illinios, Chicago	6.47	9.31	12.49	16.47	20.44	22.60	22.03	19.31	15.10	10.79	6.47	5.22	13.85
Indiana, Indianapolis	7.04	9.99	13.17	17.49	21.24	23.28	22.60	20.33	16.35	11.92	7.38	5.79	14.76
Iowa, Waterloo	6.81	9.77	13.06	16.92	20.56	22.83	22.60	19.76	15.33	10.90	6.70	5.45	14.20
Kansas, Dodge City	9.65	12.83	16.69	21.01	23.28	25.78	25.67	22.60	18.40	14.42	10.11	8.40	17.49
Kentucky, Lousville	7.27	10.22	13.63	17.83	20.90	22.71	22.03	20.10	16.35	12.38	7.95	6.25	14.76
Lousiana, New Orleans	9.77	12.83	16.01	19.87	21.80	22.03	20.67	19.65	17.60	15.56	11.24	9.31	16.35
Maine, Portland	6.70	9.99	13.78	16.92	19.99	21.92	21.69	19.31	15.22	10.56	6.47	5.45	13.97
Maryland, Baltimore	7.38	10.33	13.97	17.60	20.21	22.15	21.69	19.19	15.79	11.92	8.06	6.36	14.54
Massachusetts, Boston	6.70	9.65	13.40	16.92	20.21	22.03	21.80	19.31	15.33	10.79	6.81	5.45	14.08
Michigan, Detroit	5.91	8.86	12.38	16.47	20.33	22.37	21.92	18.97	14.76	10.11	6.13	4.66	13.63
Minnesota, Minneapolis	6.36	9.77	13.51	16.92	20.56	22.49	22.83	19.42	14.65	9.99	6.13	4.88	13.97
Mississippi, Jackson	9.43	12.38	16.13	19.87	22.15	23.05	22.15	19.08	14.54	10.11	6.25	5.11	13.74
Missouri, Kansas City	7.95	10.68	14.08	18.28	21.24	23.28	23.62	20.78	16.58	12.72	8.40	6.70	15.44
Montana, Lewistown	5.22	8.40	12.72	17.15	20.33	23.05	24.53	20.78	15.10	10.22	5.91	4.32	13.97
Nebraska, Lincoln	7.33	10.10	13.65	16.22	19.26	21.21	22.15	18.87	15.44	11.54	7.76	6.20	14.16
Nevada. Las Vegas	10.79	14.42	19.42	24.87	28.16	30.09	28.28	25.89	22.15	17.03	12.15	9.88	20.33
New Mexico, Albuquerque	11.47	14.99	19.31	24.53	27.60	29.07	27.03	24.76	21.12	17.03	12.49	10.33	19.99
New York, New York City	6.93	9.88	13.85	17.72	20.44	22.03	21.69	19.42	15.56	11.47	7.27	5.79	14.31
North Carolina, Charlotte	8.97	11.81	15.67	19.76	21.58	22.60	21.92	19.99	16.92	13.97	9.99	8.06	16.01
Ohio, Cleveland	5.79	8.63	12.04	16.58	20.10	22.15	21.92	18.97	14.76	10.22	6.02	4.66	13.51
Oklahoma, Oklahoma City	9.88	11.25	16.47	20.33	22.26	24.42	24.98	22.49	18.17	14.54	10.45	8.74	17.15
Oregon, Portland	4.20	6.70	10.68	15.10	18.97	21.24	22.60	19.53	14.88	9.20	4.88	3.52	12.61
Pennsylvania, Pittsburgh	6.25	8.97	12.61	16.47	19.65	21.80	21.35	18.85	15.10	10.90	6.59	5.00	13.63
South Carolina, Charleston	9.77	12.72	16.81	21.12	22.37	22.37	21.92	19.65	16.92	14.54	11.02	9.09	16.58
Tennessee, Memphis	8.86	11.58	15.22	19.42	22.03	23.85	23.39	21.46	17.38	14.20	9.65	7.84	16.24
Texas, Houston	9.54	12.26	15.22	18.06	20.21	21.69	21.35	20.21	17.49	15.10	11.02	8.97	15.90
Utah, Salt Lake City	6.93	10.45	14.76	19.42	23.39	26.46	26.35	23.39	18.85	13.29	8.06	6.02	16.47
Virginia, Norfolk	8.06	10.90	14.65	18.51	20.78	22.15	21.12	19.42	16.13	12.49	9.09	7.27	15.10
Washington, Seattle	3.52	5.91	10.11	14.65	19.08	20.78	21.80	18.51	13.51	7.95	4.20	2.84	11.92
West Virginia, Charleston	7.04	9.65	13.40	17.15	20.21	21.69	20.90	18.97	15.56	11.81	7.72	6.02	14.20
Wisconsin, Green Bay	6.25	9.31	13.17	16.81	20.56	22.49	22.03	18.85	14.20	9.65	5.79	4.88	13.74
Wyoming, Rock Springs	7.61	10.90	15.30	19.42	23.17	26.01	25.78	22.94	18.62	13,40	8,40	6.70	16.58



► END OF THE COURSE

►THE MIDTERM (Good Luck!)



Chapter 4 SOLAR ENERGY APPLICATIONS

Fundamentals and Applications of

Renewable Energy

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McGraw-Hill, 2020



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4-1 INTRODUCTION

Advantages of solar: Solar energy is free and nonpolluting.

Disadvantages of solar: The rate of solar radiation on a unit surface is quite low and solar collectors with large surface areas must be installed.

This is costly and requires a lot of space.

It is available in reasonable quantities only in certain locations of the world and certain seasons of the year and times of the day.

Heating of buildings is not needed in summer when solar energy is readily available.

Can we use solar for cooling? Solar heat can be used for cooling applications by absorption cooling systems but they are complex devices involving high initial cost.

Can solar energy be stored? Storage of solar energy for nighttime use is an option to tackle noncontinuous feature of solar energy but this adds to system cost.

Solar vision: We should try to get the best out of solar energy by utilizing the most current technologies and continue to work on improving the solar systems and making them more costeffective.

Potential of solar: Solar energy has the most potential among all energy sources and there is no limit to how much of it can be utilized for our energy needs.

Cost: The cost of solar systems has been steadily decreasing.

Methods of converting solar energy into other useful forms of energy:

Heliochemical process: Basically photosynthesis process, and it is responsible for the production of fossil fuel and biomass.

Heliothermal process: Solar energy is collected and converted to thermal energy or heat.

Flat-plate collectors, concentrating collectors, and heliostats are common devices that collect solar radiation for conversion to useful heat.

Solar collectors are used for space and water heating and space cooling.

Heliostats are mirrors that reflect solar radiation into a single receiver. The resulting high temperature thermal energy is converted to electricity by a heat engine.

Helioelectrical process: The production of electricity by photovoltaic or solar cells.

Difference between heliostat and solar cell: Solar energy is converted to electricity directly in solar cells while it is first converted to thermal energy in heliostats.

Flat-plate collector: The single most common application of solar energy . It is used to meet hot water needs of residential and commercial buildings.

This method of obtaining hot water is cost-effective.

Solar photovoltaic cells: They are becoming more common despite their high cost. Solar cells are already cost-effective for off-grid electricity applications.

Heliostat: Solar thermal power plants utilizing heliostats require large investments with large areas and there have been only few such installations worldwide.

Solar engineering processes can be divided into two main categories :

Active solar applications: They involve some mechanical/electrical operation and device such as a pump in the system, and they include almost all solar collector, solar cell, and heliostat applications.

Active solar applications: Any application that aims to utilize solar energy by passive design of a system.

The architectural design of a house to collect most of solar energy in winter to reduce heating cost can be achieved by correct orientation of buildings, selection of correct wall materials with proper wall surface properties.

The selection of correct windows with proper glazing can help

- maximize solar heat gain in winter
- minimize solar heat gain in summer

Trombe wall: The use of trombe wall on south walls can maximize the dissipation of solar heat into the house even after daytime hours.

Capturing solar energy and producing useful energy from it requires some special devices.

Hot water: Most solar collectors in operation today are used to produce hot water.

This hot water is used in residential and commercial buildings for kitchen use, bathroom use, shower, etc.

Process heating: Another use of solar hot water is process heating in industrial facilities.

Space heating: Solar collectors can also be used for space heating in winter.

Most solar heat is available in summer when space heating is not needed.

Most solar collectors are used to produce hot water, and they are very common in southern Europe and Asia.

4-2 FLAT-PLATE SOLAR COLLECTOR



Figure 4-1
Solar water collectors on the roof of residential buildings

A thermosyphon solar water heater system: It operates on a natural circulation.

An active, closed loop solar water heater: It uses a pump for the circulation of water containing antifreeze fluid.

The use of antifreeze fluid ensures that there is no freezing during subfreezing ambient temperatures.

Water containing antifreeze is heated in the collector and gives up its heat to water in a heat exchanger.

The resulting hot water is used in the residence.

This system may be equipped with an electric resistance heater to provide hot water when solar energy is not available.

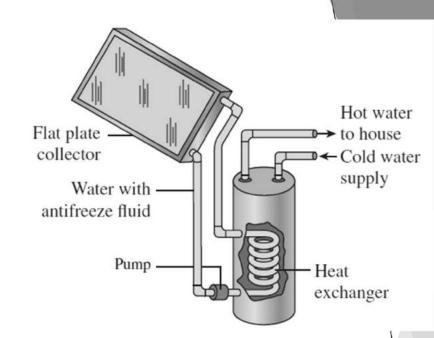


Figure 4-2
An active, closed loop solar water heater.

A flat-plate collector consists of

- glazing
- absorber plate
- flow tubes
- insulation
- glazing frame
- box enclosure

Absorber plate: absorbs solar energy transmitted through the glazing, which is a type of glass.

Flow tubes: are attached to the absorber plate and water is heated as it flows in the tubes by absorbing heat from the absorber plate.

Sides and back are insulated to minimize heat losses.

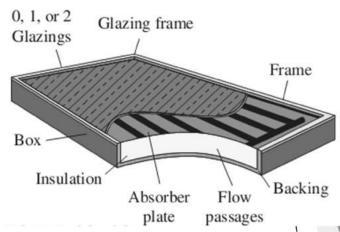


Figure 4-3
The cutaway view of a flat-plate solar collector.

Rate of solar heat absorbed by the absorber plate

$$\dot{Q}_{\rm abs} = \tau \alpha AG$$

- au the transmissivity of the glazing
- α the absorptivity of the absorber plate
- A the area of the collector surface, in m²
- **G** the solar insolation or irradiation (solar radiation incident per unit surface area), in W/m²

$$\dot{Q}_{\mathrm{abs}} = au \alpha AG$$
 The rate of solar heat absorbed by the absorber plate

$$\dot{Q}_{\rm loss} = \mathit{UA}(T_c - T_a)$$
 Heat loss from the collector by convection to the surrounding air and by radiation to the surrounding surfaces and sky

$$\dot{Q}_{\mathrm{useful}} = \dot{Q}_{\mathrm{abs}} - \dot{Q}_{\mathrm{loss}}$$
 The useful has transferred to water is the difference by $= A [\tau \alpha G - U(T_c - T_a)]$ the heat absolute and the heat

The useful heat transferred to the difference between the heat absorbed and the heat lost

If the mass flow rate of $Q_{\text{useful}} = \dot{m}c_p(T_{w,\text{out}} - T_{w,\text{in}})$ water flowing through the collector is known

U heat loss coefficient, W/m².°C.

c_n specific heat of water, J/kg.°C.

T_c average collector temperature, °C

 T_a air temperature, °¢

 $T_{w,in}$, $T_{w,out}$ inlet and outlet water temperatures, °C

The efficiency of a solar collector is the ratio of the useful heat delivered to water to the radiation incident on the

Collector efficiency as a function of average temperature of the collector

$$\eta_c = \frac{\dot{Q}_{\rm useful}}{\dot{Q}_{\rm incident}} = \frac{\tau \alpha AG - \mathit{UA}(T_c - T_a)}{AG} = \tau \alpha - \mathit{U}\frac{T_c - T_a}{G}$$

If the collector efficiency is plotted against the term $(T_c - T_a)/G$, we obtain a straight line. The slope of this line is equal to -U.

An unglazed collector allows more solar radiation input to the collector due to higher $\tau\alpha$ values but also involves higher heat transfer coefficients.

Even though the $\tau\alpha$ values go down slightly from no glazing to single and double glazing cases, the U value decreases much more significantly.

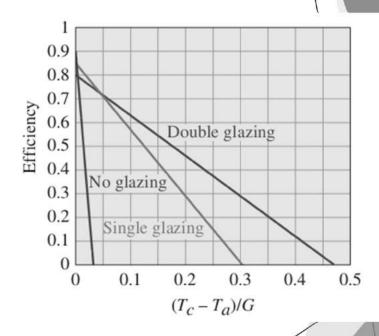


Figure 4-4
Collector efficiency for three different collectors.

TABLE 4-1 Typical Flat-Plate Solar Collector Properties (Mitchell, 1983)

-		U,	U,
	au lpha	$W/m^2^{\circ}C$	$Btu/h \cdot ft^2 \cdot {}^{\circ}F$
No glazing	0.90	28	5
Single glazing	0.85	2.8	0.5
Double glazing	0.80	1.7	0.3

When water temperature at the collector inlet is available, the collector efficiency may be defined as a function of the water inlet temperature

$$\eta_c = F_R \tau \alpha - F_R U \frac{T_{w,\text{in}} - T_a}{G}$$

where F_R is the *collector heat removal factor*. Details in the calculation of F_R can be found in Goswami et al. (2000), and Duffie and Beckman (2006). This relation is known as *Hottel-Whillier-Bliss equation*. This equation is also in a linear function format if the collector efficiency is plotted against the term $(T_c - T_a)/G$. Such a plot is given in Example 4-1. The slope of the resulting straight line is $-F_RU$. The maximum efficiency is obtained when the temperature difference and thus the term $F_RU(T_{w,\text{in}} - T_a)/G$ is zero. The maximum efficiency in this case is equal to intercept in the figure, and is equal to $F_R\tau\alpha$.

The solar collector is normally fixed in position. As the angle of solar incident radiation changes throughout the day, the product $\tau\alpha$ also changes.

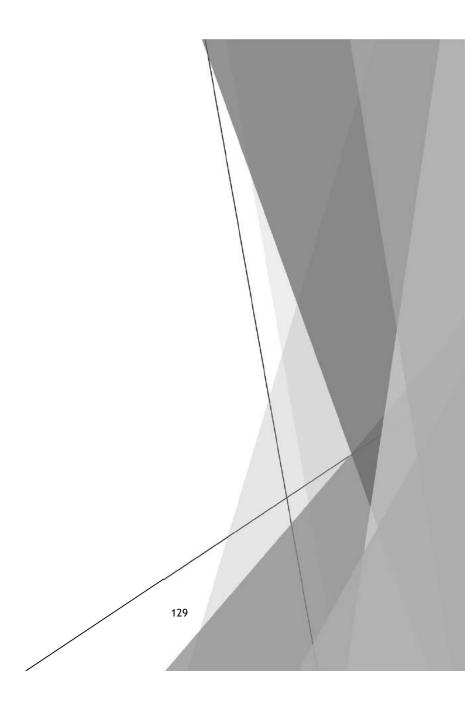
This change can be accounted for by including an incident angle modifier $\mathbf{K}_{\tau\alpha}$

$$\eta_c = F_R K_{\tau \alpha} \tau \alpha - F_R U \frac{T_{w, \text{in}} - T_a}{G}$$

The value of $K_{\tau\alpha}$ is a function of the incident angle.

The standard collector test data are normally based on a value of 1 for $K_{\tau\alpha}$.

► END OF THE COURSE



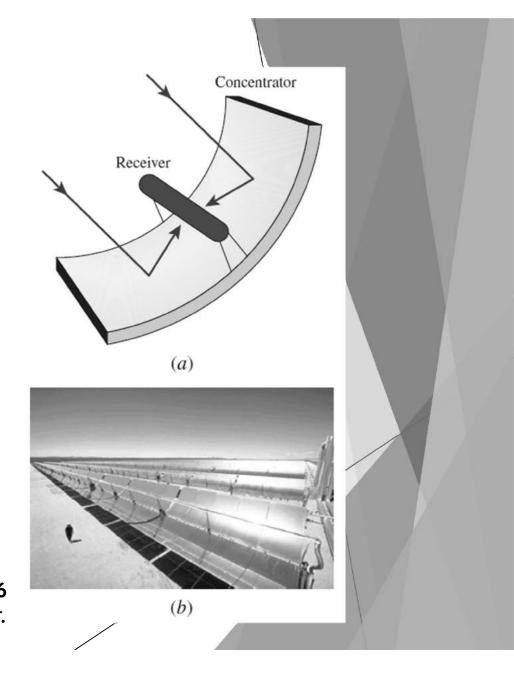
4-3 CONCENTRATING SOLAR COLLECTOR

For higher temperatures: Hot fluid (water, steam, air, or another fluid) at much higher temperatures can be produced using concentrating collectors by concentrating solar radiation on a smaller area.

Parabolic trough collector: The most common type of concentrating solar collector.

Concentration factor: In a concentrating collector, solar radiation is incident on the collector surface, called aperture area A_a and this radiation reflected or redirected into a smaller receiver area A_r . The concentration factor CR is greater than one.

$$CR = \frac{A_a}{A_r}$$
 Figure 4-6
Parabolic trough collector.



The effectiveness of the aperture-to-receiver process is functions of orientation of surfaces and their radiative properties such as absorptivity and reflectivity. This effectiveness is expressed by an **optical efficiency** term η_{ar} .

$$\dot{Q}_r = \eta_{ar} A_a G$$
 Net rate of solar radiation supplied to the receiver

$$\dot{Q}_{\rm loss} = UA_r(T_c - T_a)$$
 The rate of heat loss from the collector

$$\dot{Q}_{\text{useful}} = \dot{Q}_r - \dot{Q}_{\text{loss}} = \eta_{ar} A_a G - U A_r (T_c - T_a)$$
 The useful heat transferred to the fluid

to the fluid

$$\eta_c = \frac{\dot{Q}_{\text{useful}}}{\dot{Q}_{\text{incident}}} = \frac{\eta_{ar} A_a G - U A_r (T_c - T_a)}{A_a G}$$
Collector efficiency: The ratio of the useful heat delivered to

$$= \eta_{ar} - \frac{UA_r(T_c - T_a)}{A_a G} = \eta_{ar} - \frac{U(T_c - T_a)}{CR \times G}$$
 incident on the collector

of the useful heat delivered to the fluid to the radiation

 η_{ar} optical efficiency A_a aperture area, m²

 A_r receiver area, m² **G** incident radiation, W/m²

U heat loss coefficient, W/m^{2,o}C. T_c average collector temperature, °C

 T_a air temperature, °C **CR** (= A_a/A_r) concentration factor If the collector efficiency is plotted against the term $(T_c - T_a)/(CR \times G)$, we obtain a straight line. The slope of this line is equal to -U.

Temperatures in the receiver of a concentrating collector can reach 400°C.

The heated fluid is usually water and it can be used for space and process heating and cooling or to drive a steam turbine for electricity production.

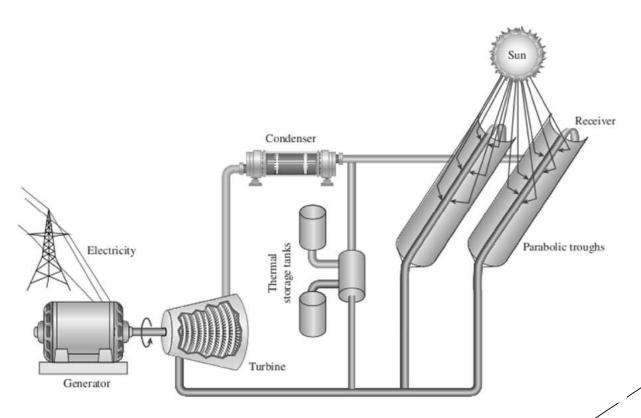


Figure 4-7 A solar concentrator power plant using parabolic trough collectors.

Linear concentrating solar power (CSP) collectors: used to capture and reflect solar radiation onto a linear receiver tube. The fluid contained in the tube is heated.

Operation: A common application is generating steam in the receiver tubes, and running this steam through a turbine to generate electricity. Water coming out of condenser is heated, boiled, and superheated by absorbing solar heat, and it is routed to turbine.

Some existing parabolic trough systems produce 80 MW of electricity.

Storage of solar: If the parabolic trough collectors are oversized, excess heat can be stored and this heat can be used during nighttime or cloudy days to produce electricity.

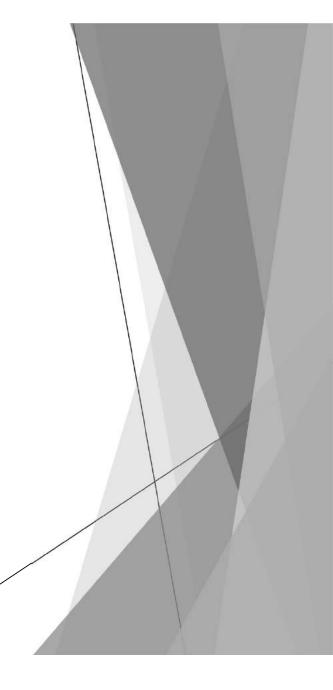
Integrating solar with conventional power plant: These solar plants can be integrated with conventional power plants utilizing natural gas or coal. The system may be designed such that electricity is supplied by solar as much as possible and conventional system is used as backup when solar heat is not available.

The efficiency of a solar system used to produce electricity may be defined as the power produced divided by the total solar irradiation.

$$\eta_{\rm th,solar} = \frac{\dot{W}_{\rm out}}{\dot{Q}_{\rm incident}} = \frac{\dot{W}_{\rm out}}{A_c G} \quad \begin{array}{l} {\rm Efficiency\ of\ solar} \\ {\rm power\ plant} \end{array}$$

 A_c the collector surface area receiving solar irradiation

G solar irradiation



4-4 SOLAR-POWER-TOWER PLANT

Heliostat: A solar-power-tower plant uses a large array of mirrors called heliostats that track the sun and reflects solar radiation into a receiver mounted on top of a tower.

Operation: Water is heated, boiled, and superheated by absorbing heat from the receiver system. The resulting steam is directed to a turbine to produce power. A generator is connected to turbine to convert turbine shaft power into electricity.

Energy storage in Solar 1 project: There is an *oil-sand storage unit* that can help supply electricity for 3 to 4 hours after sunset.

Cost of Solar 1 project: The total cost of Solar 1 plant was \$14,000/kW, which is 5 to 10 times greater than the cost of electric power stations that run on fossil fuels and other renewables.

Example: Gemasolar power plant, Seville, Spain

Heliostat: It consists of 2650 heliostats that focus 95 percent of solar radiation onto a giant receiver.

Temperature: The temperatures as high as 900°C are obtained at the receiver.

Molten salt tanks are heated by concentrated solar heat reaching a temperature of above 500°C.

Water runs through the molten salt tanks in which it is boiled and superheated. The resulting steam is directed to turbines to produce power. Steam leaving the turbine is condensed and pumped back to the molten salt tanks to repeat the heat engine cycle.

Storage: The plant can store solar heat and use it for a period of 15 hours in the absence of daylight.

Capacity: The plant has an installed capacity of 19.9 MW and can produce 110 GWh of electricity per year.



Figure 4-8
A solar-power-tower plant uses large array of mirrors called heliostats that track the sun and reflect solar radiation into a receiver mounted on top of a tower.

Example: Ivanpah solar power plant

Started commercial operation in 2013 after a 3-year construction period, and consists of three separate units. The electricity generated can serve 140,000 homes during the peak hours of the day.

Location and capacity: The plant is located in Mojave desert in California and is the largest solar thermal power plant in the world with a capacity of 377 MW.

It is located at an area of 3500 acres (14.2 km²) with 300,000 concentrated mirrors reflecting solar energy to receivers at the top of three towers in three plants. The towers are 140 m high.

The solar energy is absorbed by water flowing in the pipes of the boiler.

The water turns into superheated vapor, which is directed into a steam turbine located at the bottom of the tower. Electrical output from the turbine is sent to transmission lines.

Condenser type: This plant uses air-cooled condenser, which uses 95 percent less water than wet-cooled solar thermal plants.

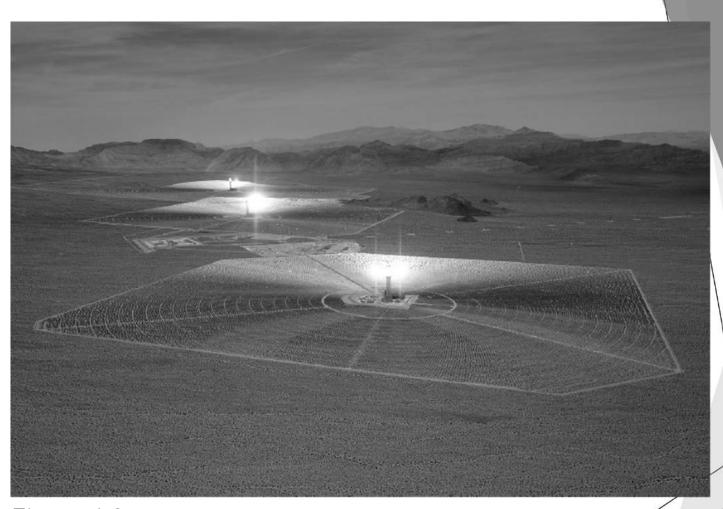


Figure 4-9
Ivanpah solar thermal power plant.

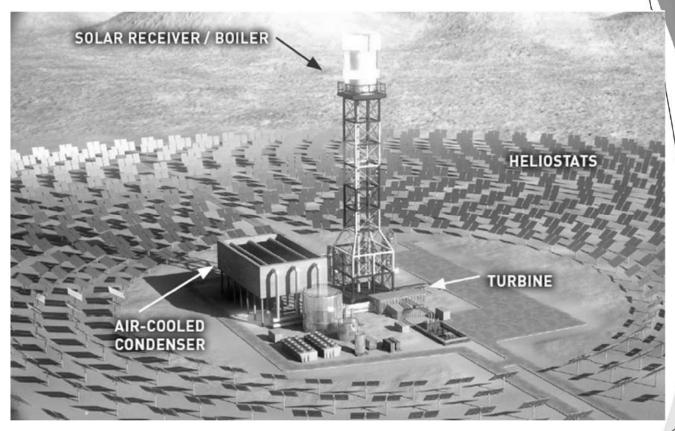
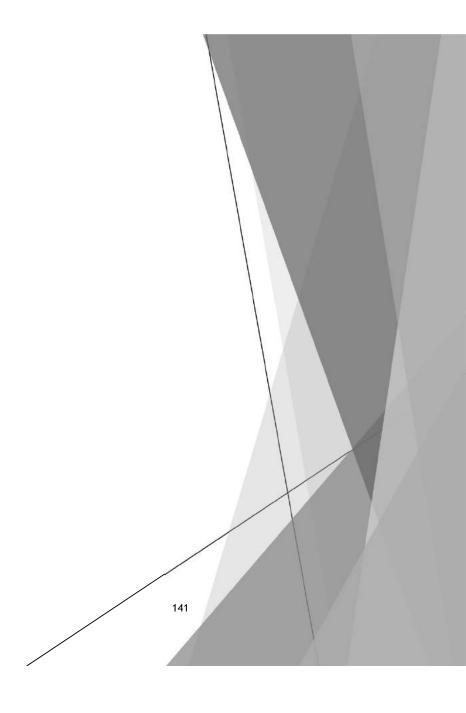


Figure 4-10
One of the three plants of Ivanpah solar system showing main components.

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Solar Pond

A promising method of power generation involves collecting and storing solar energy in large artificial lakes a few meters deep, called solar ponds.

Solar energy is absorbed by all parts of the pond, and the water temperature rises everywhere.

The top part of the pond, however, loses to the atmosphere much of the heat it absorbs, and as a result, its temperature drops.

This cool water serves as insulation for the bottom part of the pond and helps trap the energy there.

Usually, salt is planted at the bottom of the pond to prevent the rise of this hot water to the top.

A power plant that uses an organic fluid, such as alcohol, as the working fluid can be operated between the top and the bottom portions of the pond.

The main disadvantage of a solar pond power plant is the low thermal efficiency. If the water temperature is 35°C near the surface and 80°C near the bottom of the pond, the maximum thermal efficiency can be determined as

$$\eta_{\text{th,max}} = 1 - \frac{T_L}{T_H} = 1 - \frac{(35 + 273) \text{ K}}{(75 + 273) \text{ K}} = 0.115 \text{ or } 11.5\%$$

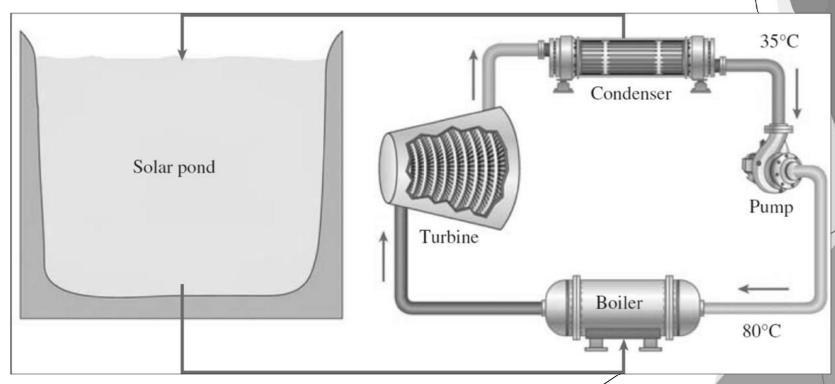


Figure 4-11 Operation of a solar pond power plant.

An **ocean thermal energy converter (OTEC)** system uses the same principle, but in this case the water at the sea or ocean surface is warmer as a result of solar energy absorption.

The water at a deeper location is cooler.

Then, a heat engine can be operated that utilizes the surface warm water as heat source and deep cold water as the heat sink.

Experiments have been performed using the OTEC principle but the results have not been promising due to large installation cost and low thermal efficiency.

4-6 PHOTOVOLTAIC CELL

Electricity can be produced from solar energy by using solar collectors to collect solar heat into a fluid and routing this fluid into a turbine.

This may be viewed as indirect conversion of solar energy into electricity.

Direct conversion of solar radiation into electricity is possible by the use of photovoltaic cell systems. A photovoltaic system consists of an array of solar cells.

An understanding of the operation of solar cells requires physics of atomic theory and semiconductor theory.

The cell involves a p-type semiconductor and an n-type semiconductor.

Silicon is commonly used as a semiconductor material in solar cells.

The silicon is doped with phosphorus to produce the n-type semiconductor while it is doped with boron to produce the p-type semiconductor.

There is a current density flow at the p-n junction of a solar cell.

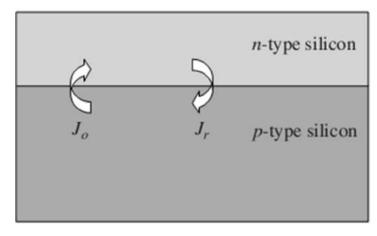


Figure 4-12
A simplified model for current density at p-n junction.

Current density *J***:** The current *I* over the cell surface area *A*.

Light-induced recombination current J_r : The current density flow from n-type semiconductor to p-type semiconductor.

Dark current or reverse saturation current J_o : The current density flow from p-type to n-type.

$$J_r = J_o \exp\!\left(\!rac{e_o V}{kT}
ight)$$
 In an illuminated solar cell

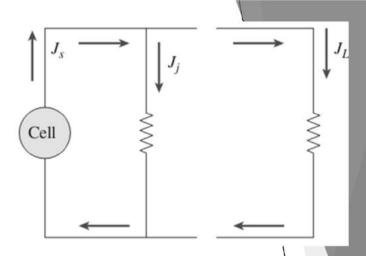


Figure 4-13
Equivalent circuit for solar cell.

where $e_o = 1.6 \times 10^{-19}$ J/V is equal to charge of one electron, $k = 1.381 \times 10^{-23}$ J/K is Boltzmann's constant, V is voltage, and T is the cell temperature. The junction current density J_j is equal to algebraic sum of J_r and J_o :

$$J_j = J_r - J_o = J_o \left[\exp \left(\frac{e_o V}{kT} \right) - 1 \right]$$
 Current output density J_s : The current density flow through the junction or load.

$$J_L = J_s - J_j = J_s - J_o \left[\exp \left(\frac{e_o V}{kT} \right) - 1 \right]$$
 Load current density J_L

The voltage is zero V=0 when the cell is short-circuited and thus $J_s=J_L$ The cell output is through the junction when the circuit is open and $J_L=0$. The voltage in this case is called the open circuit voltage, $V_{\rm oc}$.

$$V_{\rm oc} = \frac{kT}{e_o} \ln \left(\frac{J_s}{J_o} + 1 \right)$$
 Open circuit voltage

$$\frac{J_L}{J_s} = 1 - \frac{J_o}{J_s} \left[\exp \left(\frac{e_o V}{kT} \right) - 1 \right]$$
 An expression for the ratio of the load current density J_L to short circuit current density J_s

$$\dot{W} = J_L V A$$
 $\dot{W} = V A J_s - V A J_o \left[\exp \left(\frac{e_o V}{kT} \right) - 1 \right]$ The power output delivered to the load A : cell area

$$\exp\left(\frac{e_o V_{\text{max}}}{kT}\right) = \frac{1 + J_s/J_o}{1 + \frac{e_o V_{\text{max}}}{kT}}$$
 The maximum load voltage for the maximum power output

The maximum voltage V_{max} is implicit in this equation. A trial-error approach or an equation solver is needed to solve for V_{max} .

$$\dot{W}_{\text{max}} = \frac{AV_{\text{max}}(J_s + J_o)}{1 + \frac{kT}{e_o V_{\text{max}}}}$$
 The maximum power output of the cell

$$\eta_{\text{cell}} = \frac{\dot{W}}{AG}$$
 The conversion efficiency of a solar cell

$$\eta_{\text{cell,max}} = \frac{\dot{W}_{\text{max}}}{AG} = \frac{AV_{\text{max}}(J_{s} + J_{o})}{AG\left(1 + \frac{kT}{e_{o}V_{\text{max}}}\right)} = \frac{V_{\text{max}}(J_{s} + J_{o})}{G\left(1 + \frac{kT}{e_{o}V_{\text{max}}}\right)} \quad \text{The maximum conversion efficiency of a solar cell}$$

We can plot the current density ratio J_L/J_s as a function of load voltage for a specified value of open circuit voltage V_{oc} .

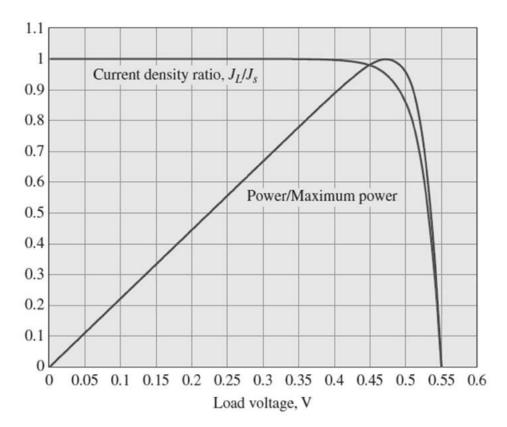
Also, we can plot power output normalized with respect to maximum power against load voltage.

The plots in Fig. 4-14 are obtained with V_{oc} = 0.55 V and T = 300 K.

Note that a high-quality silicon solar cell can produce an open circuit voltage of about 0.6 V.

For short circuit case $(J_L = J_s \text{ or } J_L / J_s = 1)$, the voltage is zero, and the power output is zero.

For open circuit voltage case $(J_L = 0)$, the voltage is 0.55 V, and the power output is also zero.



The maximum power occurs at a voltage close to open circuit voltage, which is 0.47 V in this case.

The current density ratio remains close to unity until the open circuit voltage is approached.

Then, it decreases rapidly before it becomes zero at the open circuit case.

The trends and characteristics shown in the figure are typical of most solar cells.

Figure 4-14 Current density ratio J_L/J_s and power output ratio $\dot{W}/\dot{W}_{\rm max}$ in a solar cell as a function of load voltage.

Solar radiation incident on a solar cell is originated from the sun.

The upper limit for the efficiency of a fuel cell may be determined from the Carnot efficiency relation by using effective surface temperature of the sun (5780 K) and an ambient temperature of 298 K:

$$\eta_{\text{cell,max}} = 1 - \frac{T_L}{T_H} = 1 - \frac{298 \text{ K}}{5780 \text{ K}} = 0.948 \text{ or } 94.8\%$$

Silicon: It has been commonly used in solar cells but the commercial silicon solar cells have a low efficiency (between 15 and 20%).

Other materials have been tested extensively in order to increase solar cell efficiencies including cadmium telluride, cadmium sulfide, copper indium diselenide, gallium arsenide, gallium phosphide, indium phosphide

Copper indium diselenide and gallium arsenide are among the most promising materials.

Gallium arsenide solar cell efficiency: 40% has been approached in laboratory environment.

Using multiple junction design with high solar irradiation has resulted in a research efficiency of 43%.

Cost comparison: The cost of high-efficient solar cells is much greater than silicon solar cells.

Capacity: A single solar cell produces only 1 to 2 W of power.

Multiple cells should be connected to form modules and modules should be connected into arrays so that reasonable amounts of power can be generated.

This way, both small and large photovoltaic systems can be installed depending on the demand.

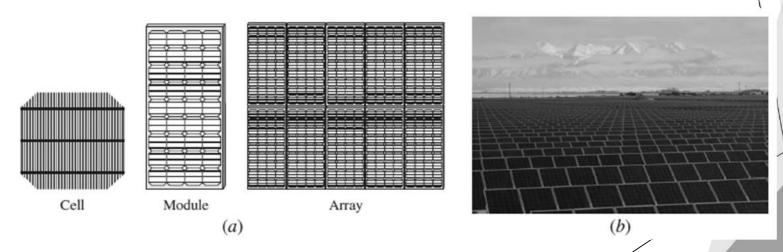


Figure 4-15 (a) A photovoltaic system typically consists of arrays, which are obtained by connecting modules, and modules consist of individual cells. (b) Solar arrays.

Lifespan: The lifespan of a solar cell is about 20 to 35 years.

Dust: Collection of dust on panel surfaces over the time reduces performance of solar panels.

Cost: The cost of solar panels has been decreasing steadily over the years reaching a value of about \$2.5/W.

A solar panel that can provide a peak power of 1000 W costs about \$2500.

Peak power is only realized in summer months during midday hours.

The power output will be less during other times and no power will be produced during nighttime and cloudy periods.

Future cost: The cost of solar power is expected to decrease steadily reaching a value of about \$1.2/W by 2023.

Global solar power capacity: The solar power capacity has increased by 97 GW in 2017 (by 53 GW in China and 11 GW in US) bringing the world total to 400 GW. The capacity nearly quadrupled in the last 5 years.
A steady increase in solar power installations is expected in the coming years. Main reasons for this expected trend are:
☐ Cost of solar panels has been declining.
☐ There is a growing market in Asia particularly in China, India, and Japan especially after Fukushima nuclear disaster.
☐ Cost of financing solar projects is likely to decline.
☐ Public interest and awareness in renewable and particularly in solar energy is growing.
☐ Conversion efficiencies are getting higher due to extensive research and development.
☐ There are growth and improvements in complementary technologies to solar power such as storage and smart grid.

4-7 PASSIVE SOLAR APPLICATIONS

Passive solar: The use of solar energy by means of engineering design without the involvement of mechanical equipment is called passive use of solar energy.

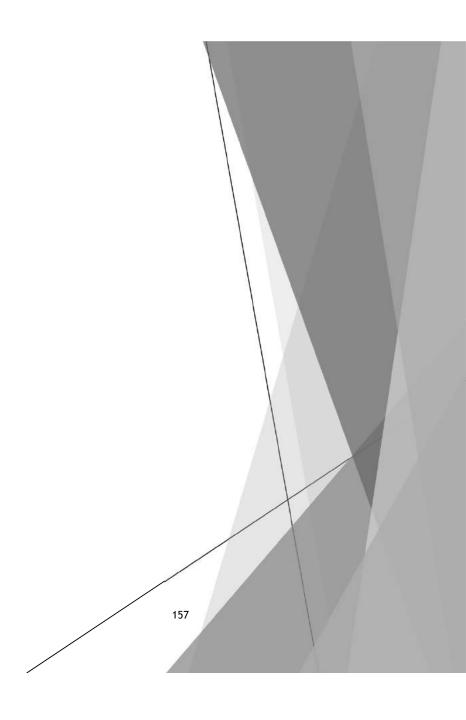
Significant energy savings can be accomplished if a house is designed and built to receive maximum solar heat in winter (to reduce heating energy consumption) and minimum solar heat gain in summer (to reduce cooling energy consumption).

This may include correct selection of orientation of walls and windows, size and type of windows, wall materials, and surface color and finishing of wall surfaces.

Particular preferences in design and construction of buildings will be different in winter-dominated and summer-dominated climates.

The solar heating of swimming pools, food drying, and solar cookers are some other examples of passive solar applications.

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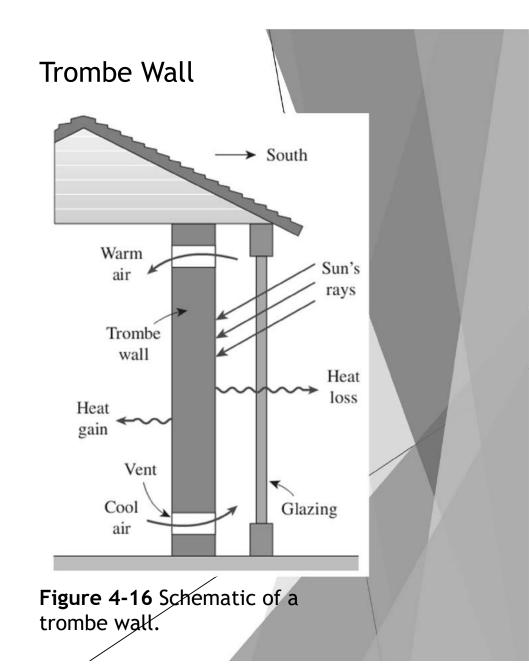


Trombe wall: Dark painted thick masonry walls. They are commonly used on south sides of passive solar homes to absorb solar energy, store it during the day, and release it to the house during the night.

Air vents: Air vents are commonly installed at the bottom and top of the trombe walls so that the room air enters the parallel flow channel between the trombe wall and the glazing, rises as it is heated, and enters the room through the top vent.

Suitable climates: It is particularly effective in reducing heating energy consumption for mild winter climates where solar energy is available during a significant period of time in winter.

Suitable locations: Southern and western United States and southern Europe are well suited for trombe wall applications.



Direct radiation: The part of solar radiation that reaches the earth's surface without being scattered or absorbed.

Diffuse radiation: Solar radiation that is scattered or reemitted by the constituents of the atmosphere.

Direct radiation comes directly from the sun following a straight path, whereas diffuse radiation comes from all directions in the sky.

The entire radiation reaching the ground on an overcast day is diffuse radiation.

The radiation reaching a surface consists of three components: 1 direct radiation, 2 diffuse radiation, and 3 radiation reflected onto the surface from surrounding surfaces.

Solar Heat Gain through Windows

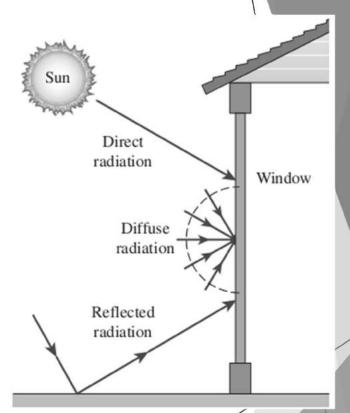


Figure 4-17 Direct, diffuse, and reflected components of solar radiation incident on a window.

When solar radiation strikes a glass surface,

- part of it (about 8 percent for uncoated clear glass) is reflected back to outdoors,
- part of it (5 to 50 percent, depending on composition and thickness) is absorbed within the glass,
- and the remainder is transmitted indoors.

The Standard 3-mm (1/8-in)-thick single-pane double-strength clear window glass

- transmits 86%
- reflects 8%
- absorbs 6%

of the solar energy incident on it.

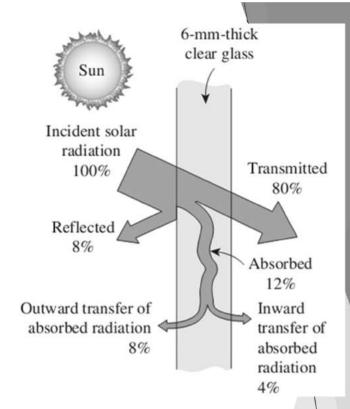


Figure 4-18 Distribution of solar radiation incident on a clear glass.

The solar energy transmitted inside a building represents a heat gain for the building.

Solar heat gain of the building: The sum of the transmitted solar radiation and the portion of the absorbed radiation.

Solar heat gain coefficient (SHGC): The fraction of incident solar radiation that

enters through the glazing. SHGC = 0 - 1

SHGC =
$$\frac{\dot{q}_{\text{solar, gain}}}{G} = \tau_s + f_i \alpha_s$$

 $\alpha_{\rm s}$ solar absorptivity of the glass

 au_{s} solar transmissivity of the glass

 f_i the inward flowing fraction of the solar radiation absorbed by the glass

Total solar heat gain through window

$$\dot{Q}_{\text{solar, gain}} = \text{SHGC} \times A_{\text{glazing}} \times G$$

6-mm-thick clear glass Sun Incident solar radiation Transmitted 100% 80% Reflected 8% Absorbed 12% Outward transfer of Inward absorbed radiation transfer of 8% absorbed radiation

 A_{glazing} glazing area of the window

 \vec{G} solar heat flux incident on the outer surface of the window, $\text{in } W/m^2$

Another way of characterizing the solar transmission characteristics of different kinds of glazing and shading devices is to compare them to a well-known glazing material that can serve as a base case.

This is done by taking the standard 3-mm (1/8-in) thick double-strength clear window glass sheet whose SHGC is 0.87 as the reference glazing and defining a **shading coefficient SC** as

$$SC = \frac{SHGC}{SHGC_{ref}} = \frac{SHGC}{0.87} = 1.15 \times SHGC$$

The shading coefficient of a single-pane clear glass window is

$$SC = 1.0$$

The larger the shading coefficient, the smaller the shading effect, and thus the larger the amount of solar heat gain.

TABLE 4-2 Shading Coefficient SC and Solar Transmissivity $au_{\rm solar}$ for Some Common Glass Types for Summer Design Conditions (ASHRAE, 1993)

Types of Glazing	Nominal Thickness			
	mm	in	$ au_{ ext{solar}}$	SC*
(a) Single glazing				
Clear	3	1/8	0.86	1.0
	6	1/4	0.78	0.95
	10	3/8	0.72	0.92
	13	1/2	0.67	0.88
Heat absorbing	3	1/8	0.64	0.85
	6	1/4	0.46	0.73
	10	3/8	0.33	0.64
	13	1/2	0.24	0.58
(b) Double glazing				
Clear in	3^{\dagger}	1/8	0.71*	0.88
Clear out	6	1/4	0.61	0.82
Clear in, heat absorbing out§	6	1/4	0.36	0.58

^{*}Multiply by 0.87 to obtain SHGC.

[†]The thickness of each pane of glass.

[‡]Combined transmittance for assembled unit.

⁶Refers to gray-, bronze-, and green-tinted heat-absorbing float glass.

Solar heat entering a house through windows is preferable in winter since it reduces heating energy consumption but it should be avoided as much as possible in summer since it increases cooling energy consumption.

Shading devices are used to control solar heat gain through windows.

Shading devices are classified as internal shading and external shading, depending on whether the shading device is placed inside or outside.

External shading devices are more effective in reducing the solar heat gain since they intercept the sun's rays before they reach the glazing.

The sun is high in the horizon in summer and low in winter. A properly sized roof overhang or a horizontal projection blocks off the sun's rays completely in summer while letting in most of them in winter.

A window can also be shaded from outside by vertical or horizontal or architectural projections, insect or shading screens, and sun screens.

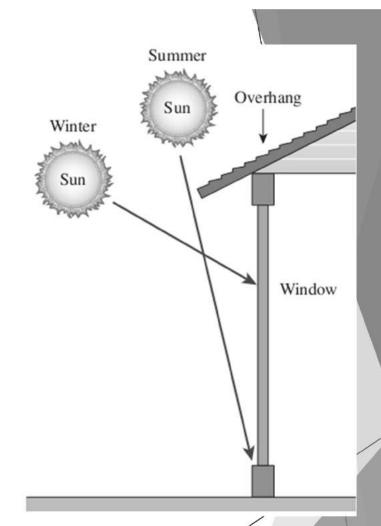


Figure 4-19 A properly sized overhang blocks off the sun rays completely in summer while letting them through in winter.

Internal shading: It is used in most windows to provide privacy and aesthetic effects as well as some control over solar heat gain.

Internal shading devices: They reduce solar heat gain by reflecting transmitted solar radiation back through the glazing before it can be absorbed and converted into heat in the building.

Draperies: They reduce the annual heating and cooling loads of a building by 5 to 20%, depending on the type and the user habits.

In summer, they reduce heat gain primarily by reflecting back direct solar radiation.

The reflectance of the surface of the drapery facing the glazing has a major effect on the amount of solar heat gain.

Light-colored draperies: They maximize the back reflection and thus minimize the solar gain.

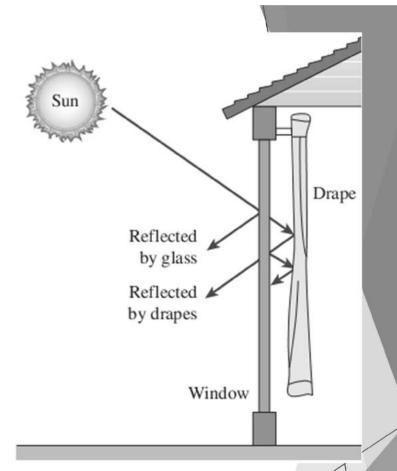


Figure 4-20 Draperies reduce heat gain in summer by reflecting back solar radiation, and reduce heat loss in winter by forming an air space before the window.

The shading coefficients of drapes also depend on the way they are hung.

Usually, the width of drapery used is twice the width of the draped area to allow folding of the drapes and to give them their characteristic "full" or "wavy" appearance.

A flat drape behaves like an ordinary window shade.

A flat drape has a higher reflectance and thus a lower shading coefficient than a full drape.

The primary function of an indoor shading device is to provide thermal comfort for the occupants.

An unshaded window glass allows most of the incident solar radiation in, and also dissipates part of the solar energy it absorbs by emitting infrared radiation to the room.

The emitted radiation and the transmitted direct sunlight may bother the occupants near the window.

The type of climate in an area usually dictates the type of windows to be used in buildings.

In cold climates where the heating load is much larger than the cooling load, the windows should have the highest transmissivity for the entire solar spectrum, and a high reflectivity (or low emissivity) for the far infrared radiation emitted by the walls and furnishings of the room.

In warm climates where the cooling load is much larger than the heating load, the windows should allow the visible solar radiation (light) in, but should block off the infrared solar radiation.

Such windows can reduce the solar heat gain by 60% with no appreciable loss in daylighting.

This behavior is approximated by window glazings that are coated with a heat-absorbing film outside and a low-e film inside.

Properly selected windows can reduce the cooling load by 15 to 30% compared to windows with clear glass.

Tinted glass and glass coated with reflective films reduce solar heat gain in summer and heat loss in winter.

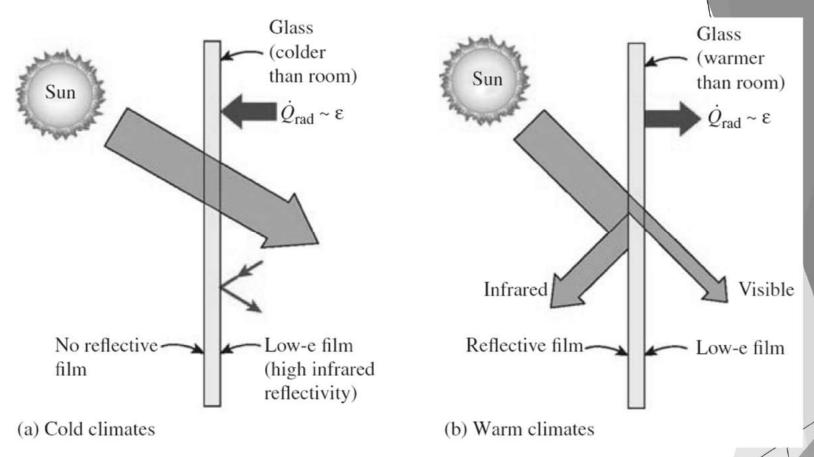
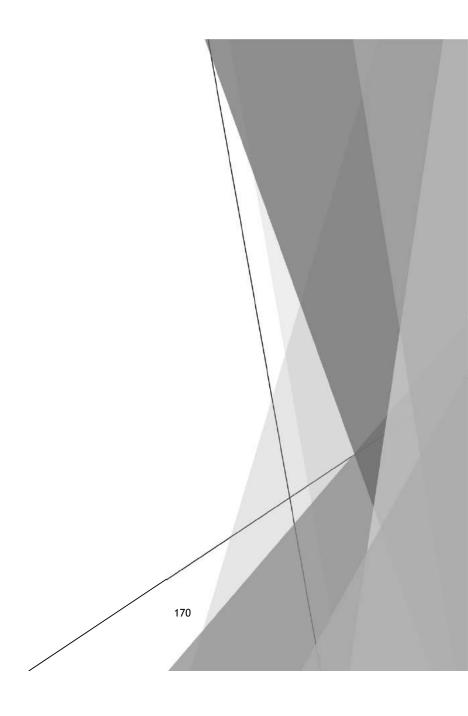


Figure 4-21 Radiation heat transfer between a room and its window is proportional to the emissivity of the glass surface, and low-e coatings on the inner surface of the windows reduce heat loss in winter and heat gain in summer.

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Thanks for the attendance

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