

04-Solar Resource Part 1

ECEGR 4530

Renewable Energy Systems



Overview

- Solar Characteristics
- Extraterrestrial Solar Irradiance
- Angle of Incidence
- Solar Irradiance



Introduction

- Most renewable energy systems convert energy whose source is ultimately the sun
 - 3.8 YJ (1×10^{24})/yr pass through the atmosphere
 - approx. 10,000 the amount of energy used by fossil fuels and nuclear per year
- In this lecture we investigate the nature of solar energy



Solar Characteristics

- Solar energy originates from the sun
- Driven by nuclear fusion of hydrogen into helium
- Surface temperature approximately 5500°C



Solar Characteristics

- Heat is transferred from the sun to the Earth via electromagnetic radiation
 - also called solar radiation
- Nature of the electromagnetic radiation is a function of the temperature and emissivity



Solar Characteristics

- Solar radiation from a blackbody (the sun can be approximated by a blackbody) is related to temperature from the Stefan-Boltzmann Law

$$G = \sigma T^4$$

- where
 - G: irradiance or solar irradiance (W/m^2)
 - σ : Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8} \text{ J}/(\text{sm}^2\text{K}^4)$



Exercise

- Calculate the irradiance of the sun (approximate as a blackbody at a temperature of 5500°C) at its surface

$$G = \sigma T^4$$

$$\sigma = 5.67 \times 10^{-8} \text{ J}/(\text{sm}^2\text{K}^4)$$



Exercise

- Calculate the irradiance of the sun (approximate as a blackbody at a temperature of 5500°C) at its surface

$$G = \sigma T^4$$

$$\sigma = 5.67 \times 10^{-8} \text{ J}/(\text{sm}^2\text{K}^4)$$

$$G = (5.67 \times 10^{-8})(5500 + 273)^4 = 6.3 \times 10^7 \text{ W}/\text{m}^2$$

- If the sun was the temperature of a candle it would be:

$$G = (5.67 \times 10^{-8})(1000 + 273)^4 = 1.50 \times 10^5 \text{ W}/\text{m}^2$$



Solar Irradiance

- Unit of G (W/m^2) is power density
- Integrate G over time to find irradiation, the energy density (J/m^2 or kwh/m^2)
- Insolation (not insulation): irradiation whose source is the sun



Extraterrestrial Irradiance

- What is the irradiance that arrives at the top of Earth's atmosphere (extraterrestrial irradiance)?
- Irradiance will decrease as the distance from the sun increases
 - decrease is in proportion to the square of the distance



Extraterrestrial Irradiance

- Irradiance at the surface of the sun
 - $G_{sun} = 6.3 \times 10^7 \text{ W/m}^2$ (63 MW/m²)
- As we move away from the sun, the irradiance decreases
- Surface area of a sphere $A = 4\pi r^2$
 - r : radius of the sphere (m)
- Radius of the sun: $R_{sun} = 695,000 \text{ km}$
- G at any distance R from the sun is:

$$G = G_{sun} \left(\frac{4\pi R_{sun}^2}{4\pi R^2} \right) = G_{sun} \left(\frac{R_{sun}^2}{R^2} \right)$$

↑
Ratio of surface areas



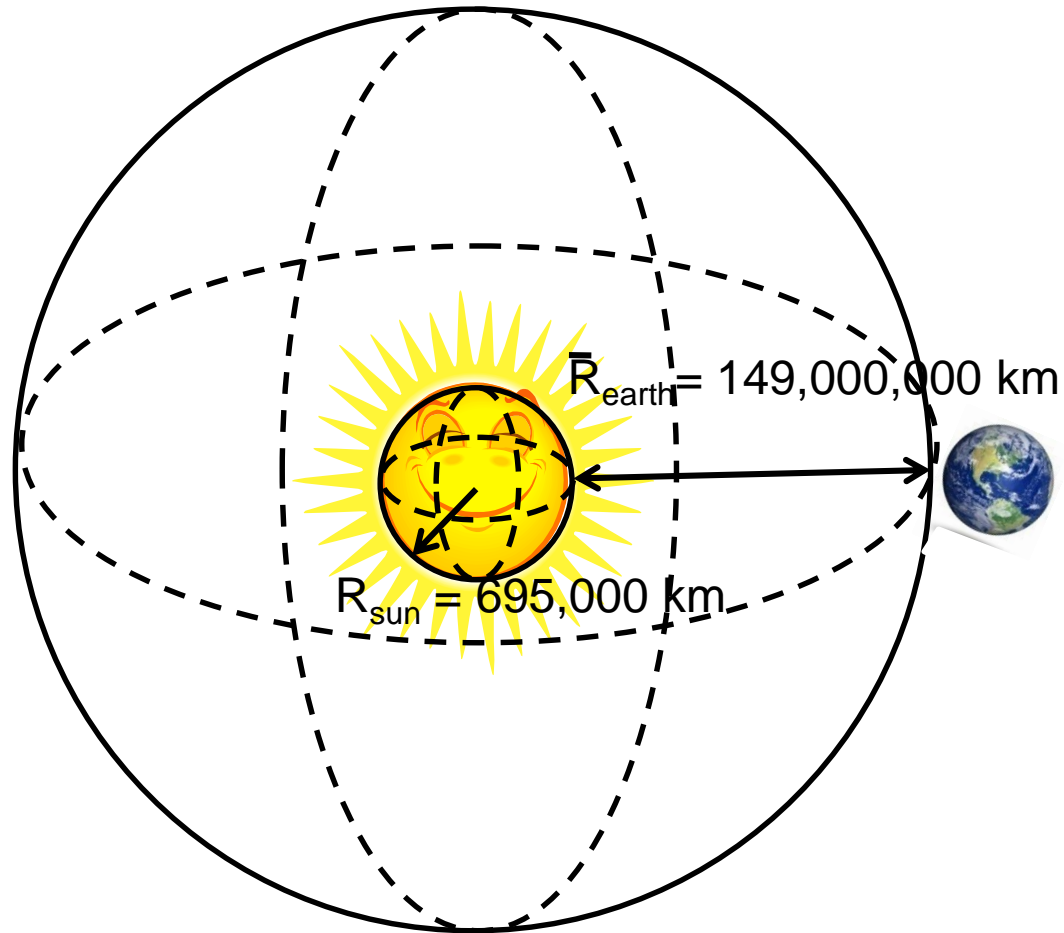
Extraterrestrial Irradiance

- What is the extraterrestrial irradiance at the Earth?
- Average distance from Earth to sun:
 - $\bar{R}_{\text{earth}} = 149,000,000 \text{ km}$
- Solving:

$$G = G_{\text{sun}} \left(\frac{4\pi R_{\text{sun}}^2}{4\pi \bar{R}_{\text{earth}}^2} \right) = 1370 \text{ W/m}^2$$



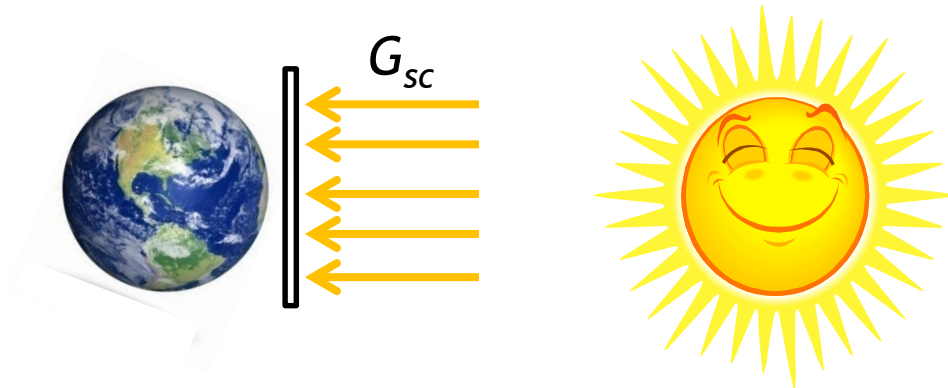
Extraterrestrial Irradiance





Solar Irradiance

- The accepted average solar irradiance value for the top of the Earth's atmosphere (extraterrestrial) is 1367 W/m^2
 - based on satellite data
 - plane normal to the sun
 - $G_{sc} = 1367 \text{ W/m}^2$ defined as a *Solar Constant*





Solar Astronomy

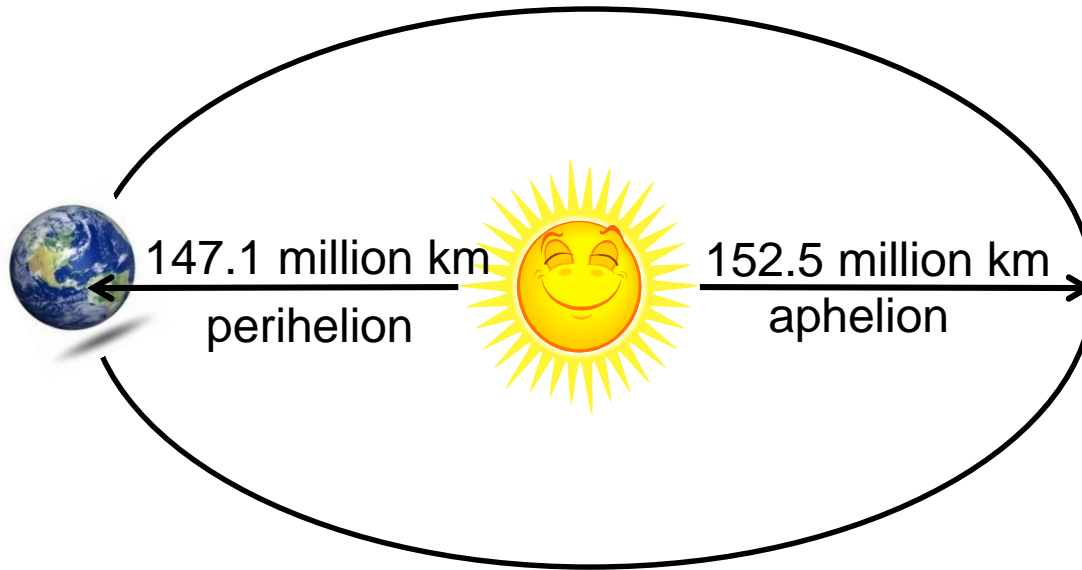
- G_0 : extraterrestrial irradiance on horizontal surface (W/m^2)
- G_{0n} : extraterrestrial irradiance on a plane normal to the radiation
- G_{0T} : total extraterrestrial irradiance on a surface, accounting for surface tilt, if any (W/m^2)
- Subscript 0 means extraterrestrial (top of the atmosphere)

See Lecture 0X-Solar Nomenclature



Extraterrestrial Irradiance

Earth's orbit is nearly circular



a "tilted" view is shown



Astronomy Trivia

- What day of the year is the Earth closest to the Sun (perihelion)?
 - A. December 21st
 - B. June 21st
 - C. September 21st
 - D. March 21st
 - E. January 4th
 - F. June 4th
 - G. October 18th

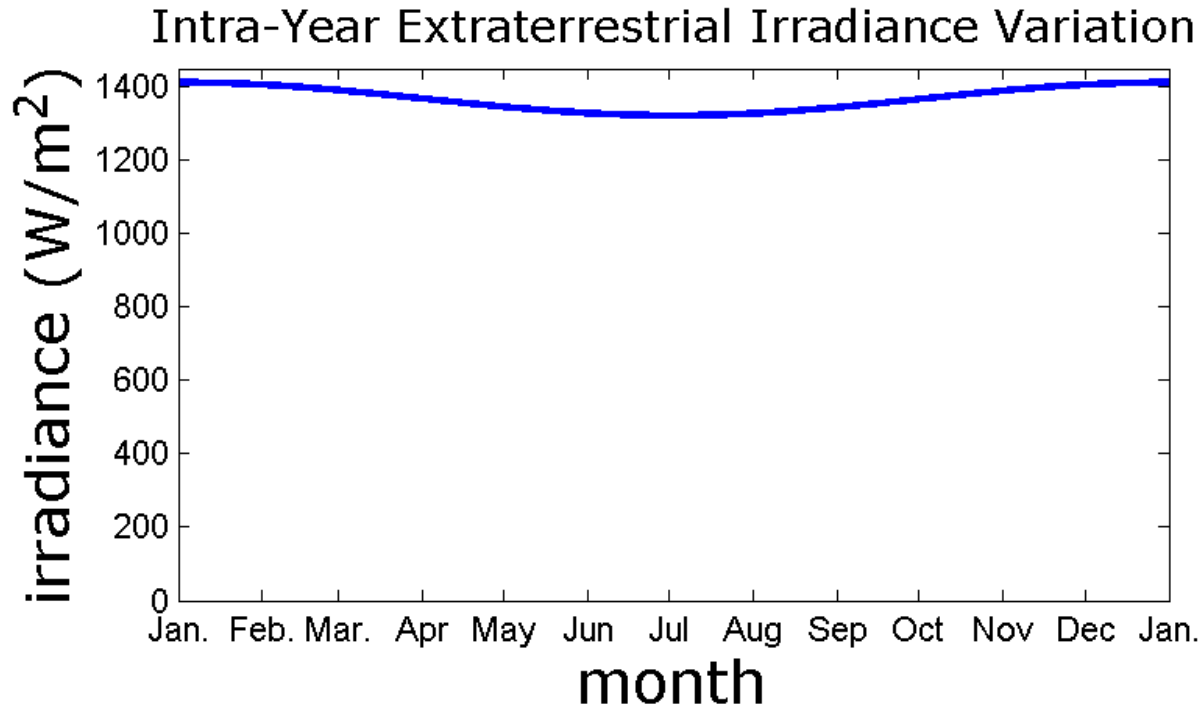


Astronomy Trivia

- What day of the year is the Earth closest to the Sun (perihelion)?
 - A. December 21st
 - B. June 21st
 - C. September 21st
 - D. March 21st
 - E. January 4th**
 - F. June 4th
 - G. October 18th
- Seasons have nothing to do with the distance from the sun



Extraterrestrial Irradiance





Extraterrestrial Irradiance

- We can account for the distance from the sun:

$$G_{on}(d) = G_{sc} \left[1 + 0.033 \cos \left(2\pi \left(\frac{d}{365} \right) \right) \right]$$

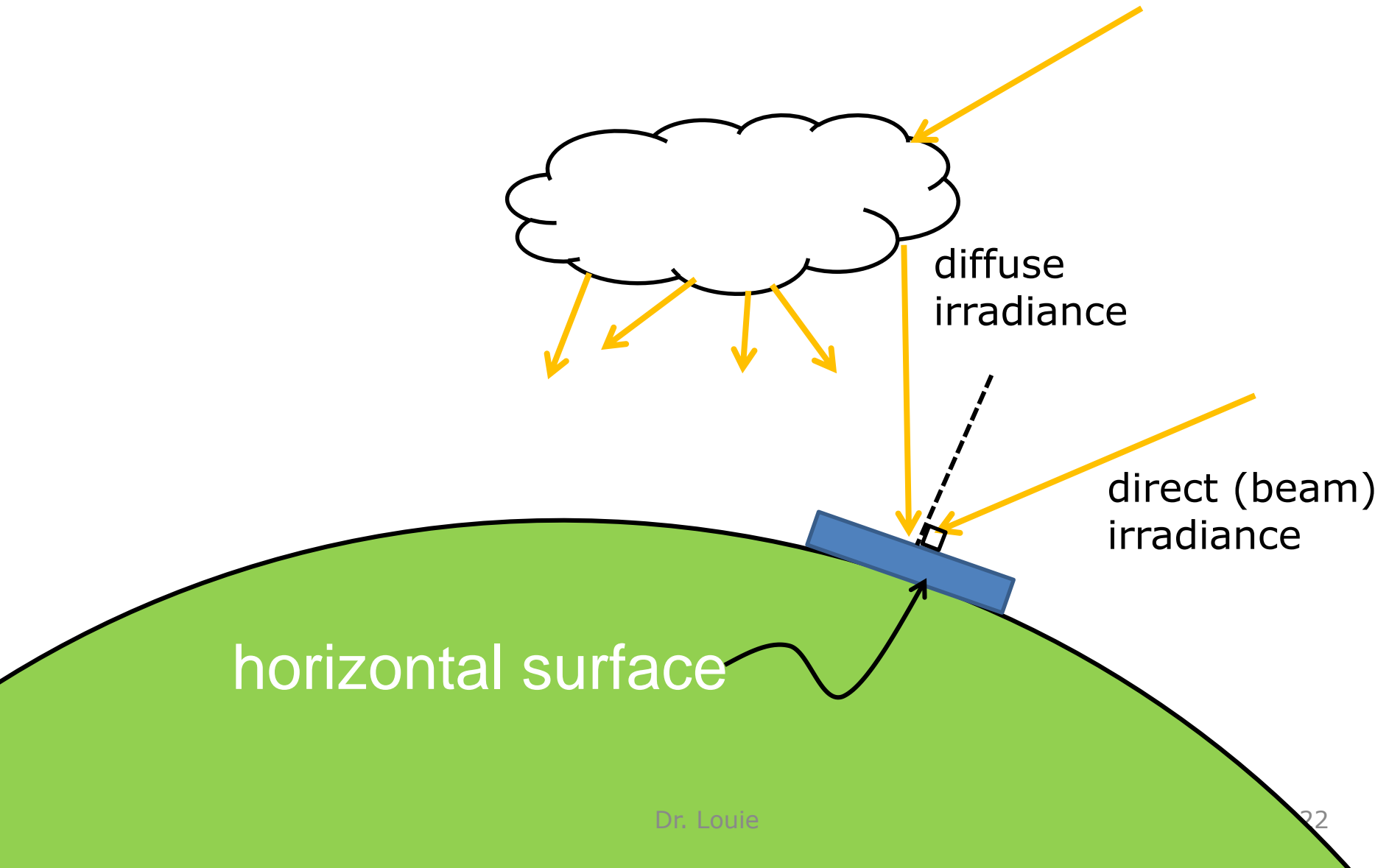
- d is the day of year ($d = 1$ on January 1)
- This is an **approximate** equation
- Peak-to-peak variation is small ($<7\%$)



Solar Irradiance

- Design of solar renewable energy systems requires knowing:
 - Irradiance, insolation
 - Direction of sunlight
 - If the sunlight is diffuse or direct
- We want to be able to quantify the nature of the solar irradiance on a given **surface** on the Earth
- First consider horizontal surfaces

Solar Irradiance





Solar Irradiance

- Direct (beam) irradiance: solar irradiance received from the sun directly. It has not been scattered by the atmosphere.
 - Subscript b is used
- Diffuse irradiance: solar irradiance received from the sun after it has been scattered by the atmosphere
 - Implies change in direction
 - Subscript d is used
- Unless specified elsewhere, assume G_b and G_d are referenced to a horizontal surface



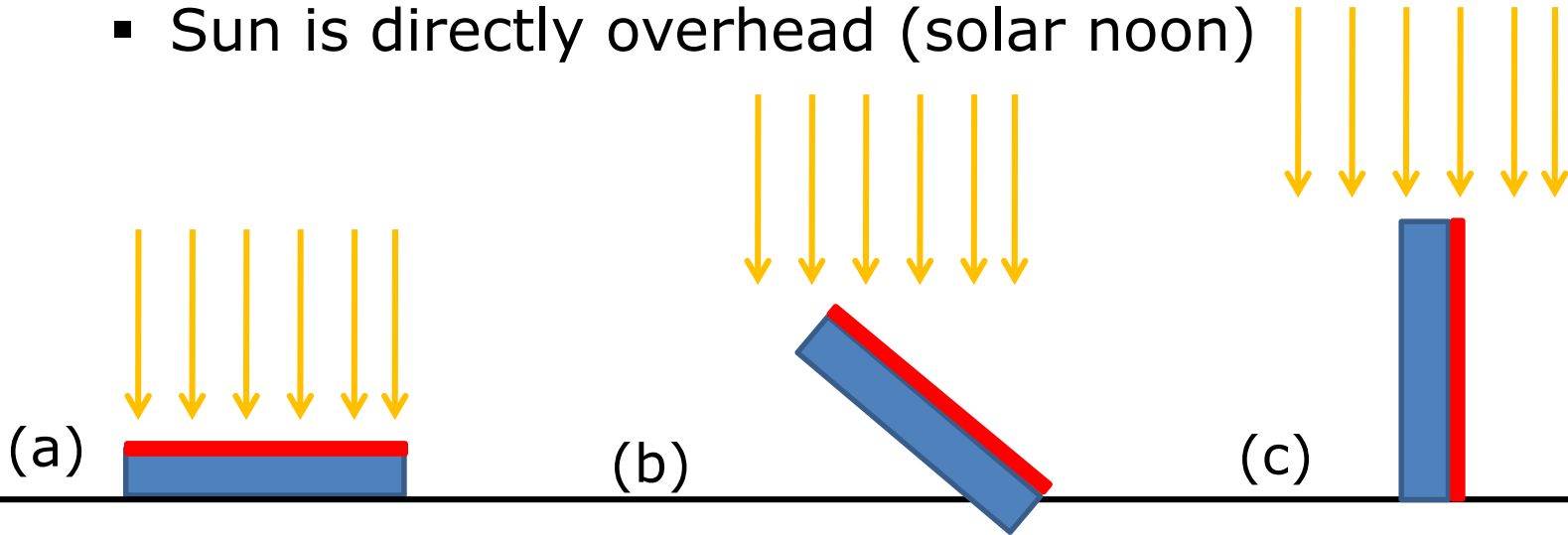
Solar Irradiance

- Global irradiance: sum of beam and diffuse irradiance
 - $G_{\text{GHI}} = G_b + G_d$
- Global Horizontal Irradiance (GHI): global irradiance on a horizontal surface
- GHI is a commonly measured quantity, from which G_b and G_d are estimated (more on this in a later lecture)



Accounting for Angle of Incidence

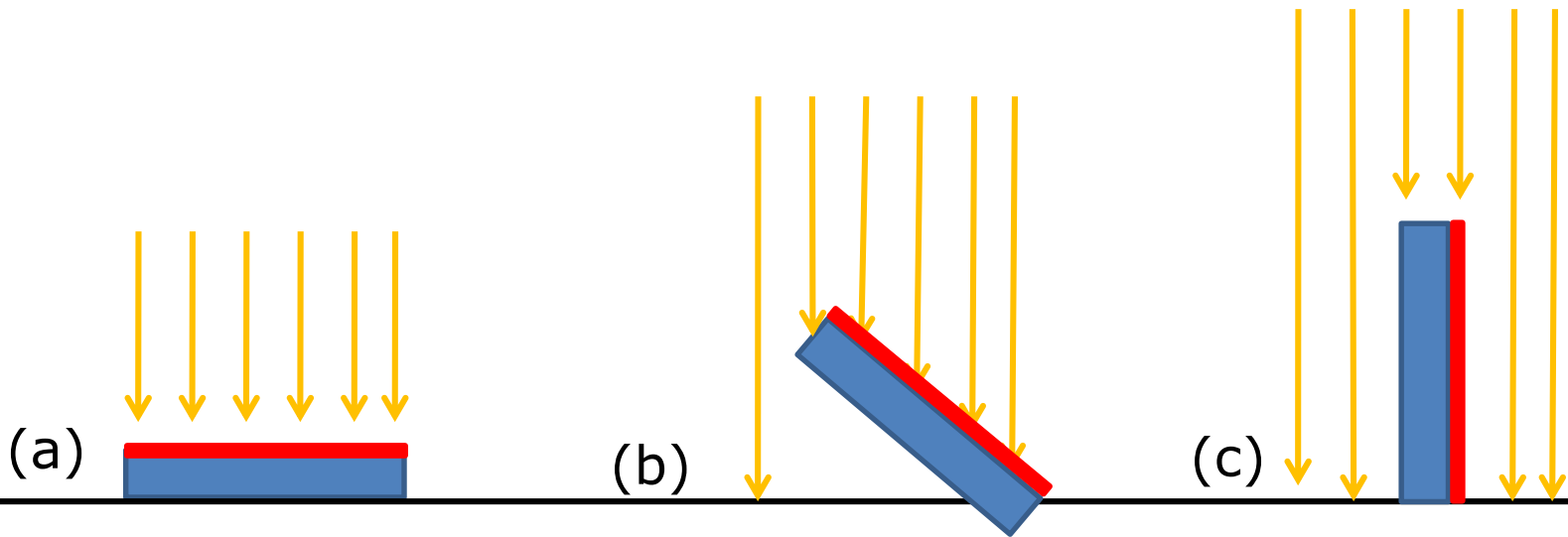
- Which surface receives the most irradiance, G ?
- Assume:
 - No atmosphere, no ground reflectance
 - Only irradiance on the face counts
 - Sun is directly overhead (solar noon)





Accounting for Angle of Incidence

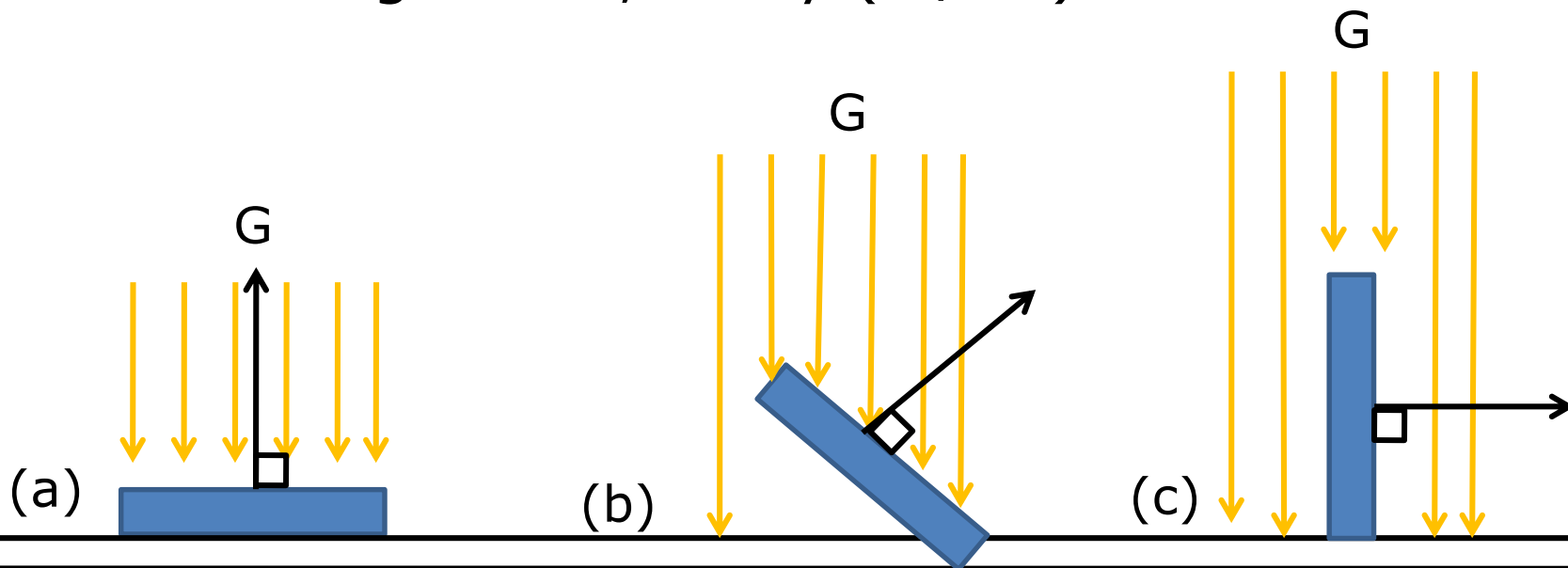
- Surface (a): receives all irradiance
- Surface (b): receives a portion of the irradiance
- Surface (c): receives no irradiance





Accounting for Angle of Incidence

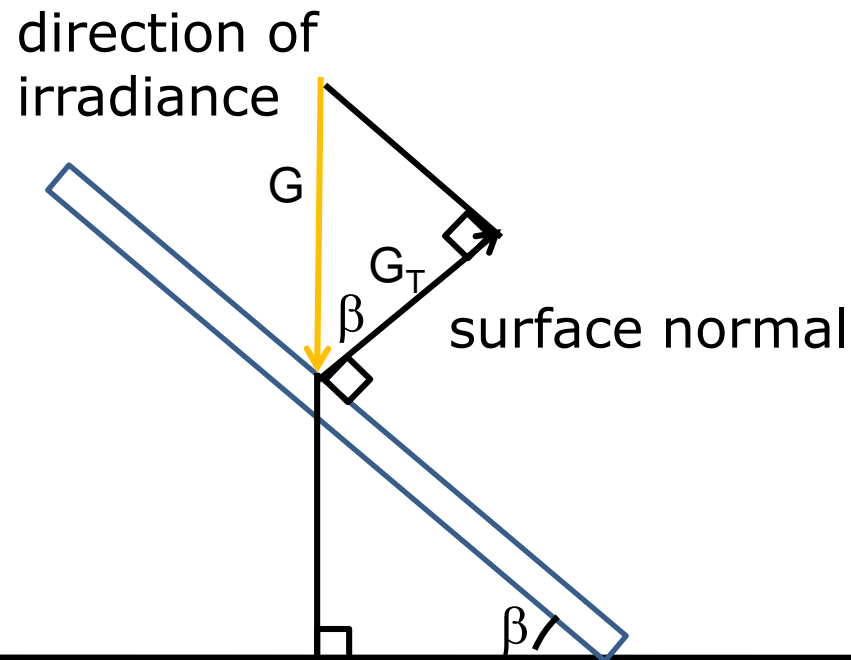
- Compute the projection of G onto the normal of the surface
- θ : angle of incidence, degrees
- G_T : total irradiance received on a surface, accounting for tilt, if any (W/m^2)





Accounting for Angle of Incidence

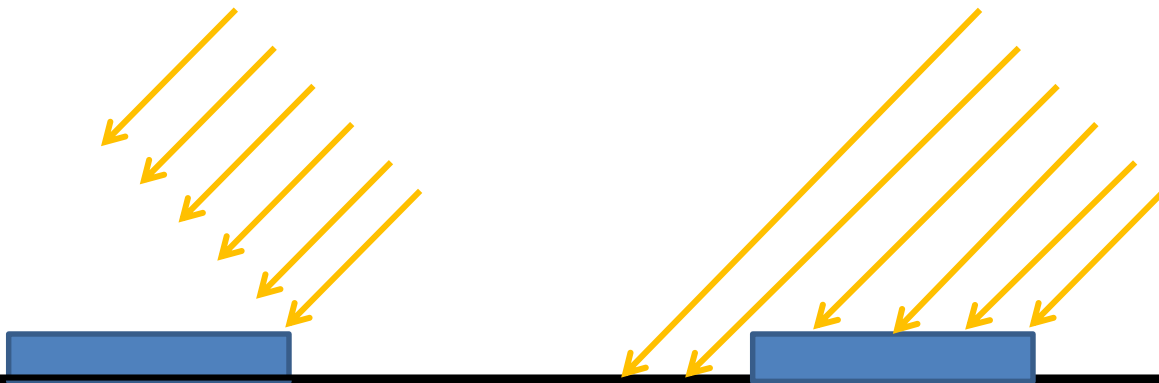
- Let β : tilt of the surface, degrees
- Under assumptions given $\theta = \beta$
 - $G_T = G \cos(\theta)$





Accounting for Angle of Incidence

- Similar derivation if the surface is horizontal, but the irradiance is at an angle





Accounting for Angle of Incidence

- The angle between the sun and a horizontal surface is the zenith angle, θ_z
- VERY IMPORTANT!!!
- Zenith angle is the angle of incidence for a horizontal surface (special case)





Accounting for Angle of Incidence

- Top of the atmosphere irradiance for horizontal surfaces:
 - $G_0 = G_{0n} \cos(\theta_z)$
- Accounting for surface tilt, if any:
 - $G_{0T} = G_{0n} \cos(\theta)$



Accounting for Angle of Incidence

- Compute the extraterrestrial irradiance on a horizontal surface on October 18 when the Zenith angle is 60° , accounting for intra-year irradiance variability. [hint: October 18 is the 291st day of the year]



Accounting for Angle of Incidence

- Compute the extraterrestrial irradiance on a surface on October 18 when the Zenith angle is 60° .

- $G_0 = G_{0n} \cos(\theta_z)$

$$G_{on}(d) = G_{sc} \left[1 + 0.033 \cos \left(2\pi \left(\frac{291}{365} \right) \right) \right] = 1380$$

$$G_0 = 1380 \cos(60) = 690 \text{ W/m}^2$$



Accounting for Angle of Incidence

- Angle of incidence is implicitly accounted for when GHI is measured
 - G_b and G_d must also account for angle of incidence

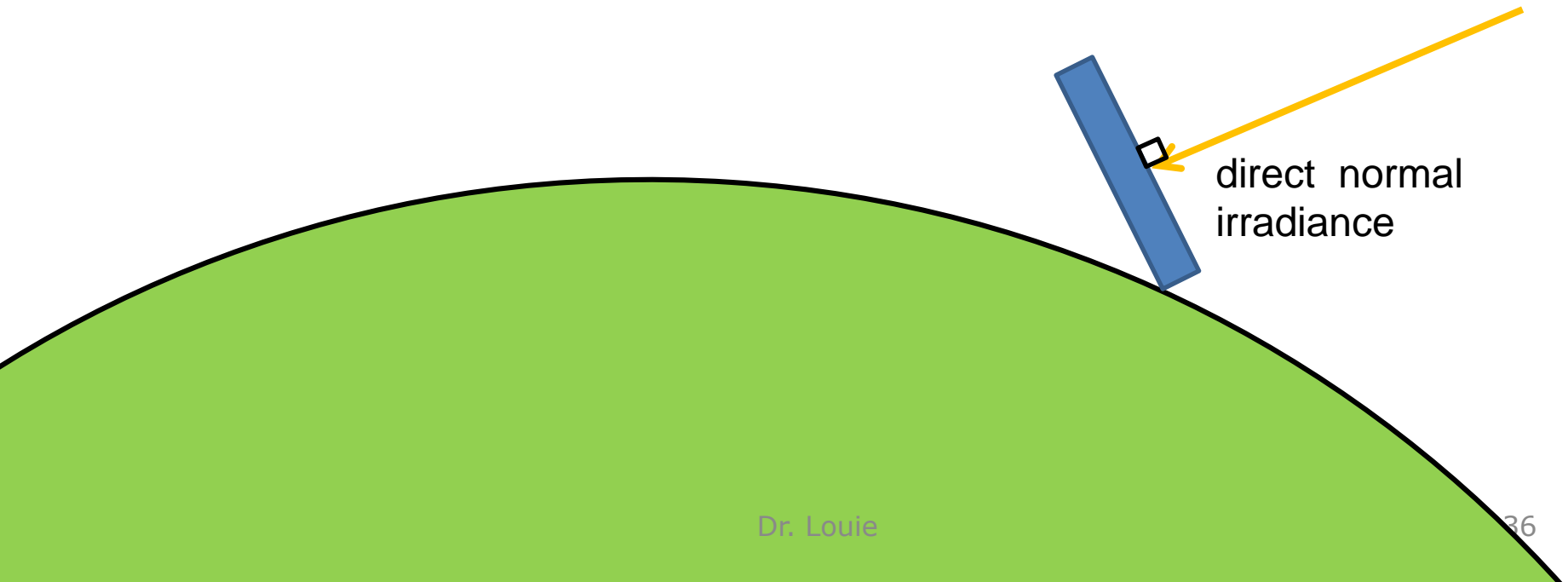


Solar Irradiance

- Concentrating Solar Power (CSP) systems can only utilize beam irradiance
- CSP receivers also track the sun to maximize energy
 - Receiver face stays normal to the sun for most hours
 - Direct Normal Irradiance (DNI): beam irradiance received by a surface normal to the irradiance (G_{DNI})
- Possible (but cumbersome) to estimate DNI from GHI

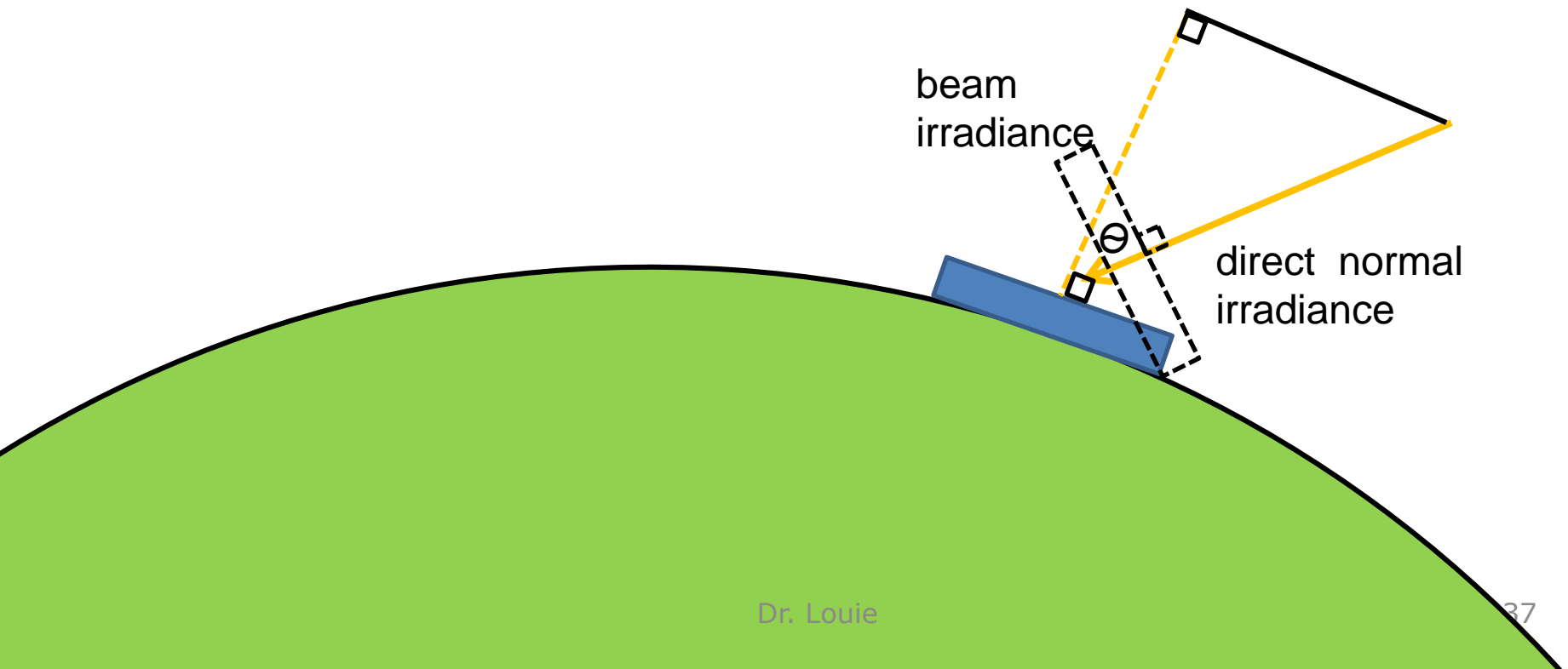
Solar Irradiance

Direct Normal Irradiance: beam irradiance on a surface that is normal to the beam



Solar Irradiance

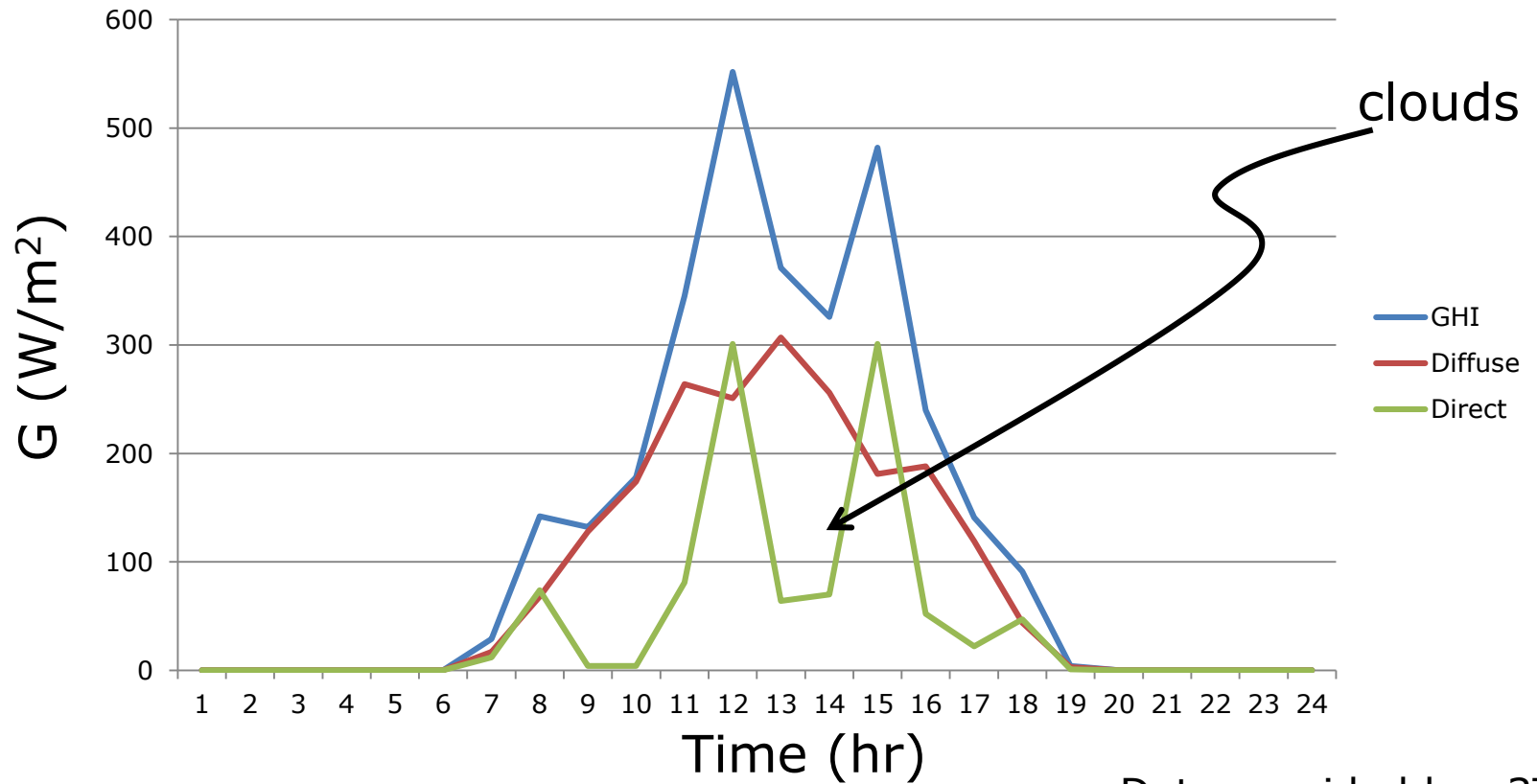
- DNI is related to beam irradiance by:
 - $G_b = G_{\text{DNI}} \cos(\theta)$





Solar Irradiance

Irradiance on 3/21/1997
in Renton, WA



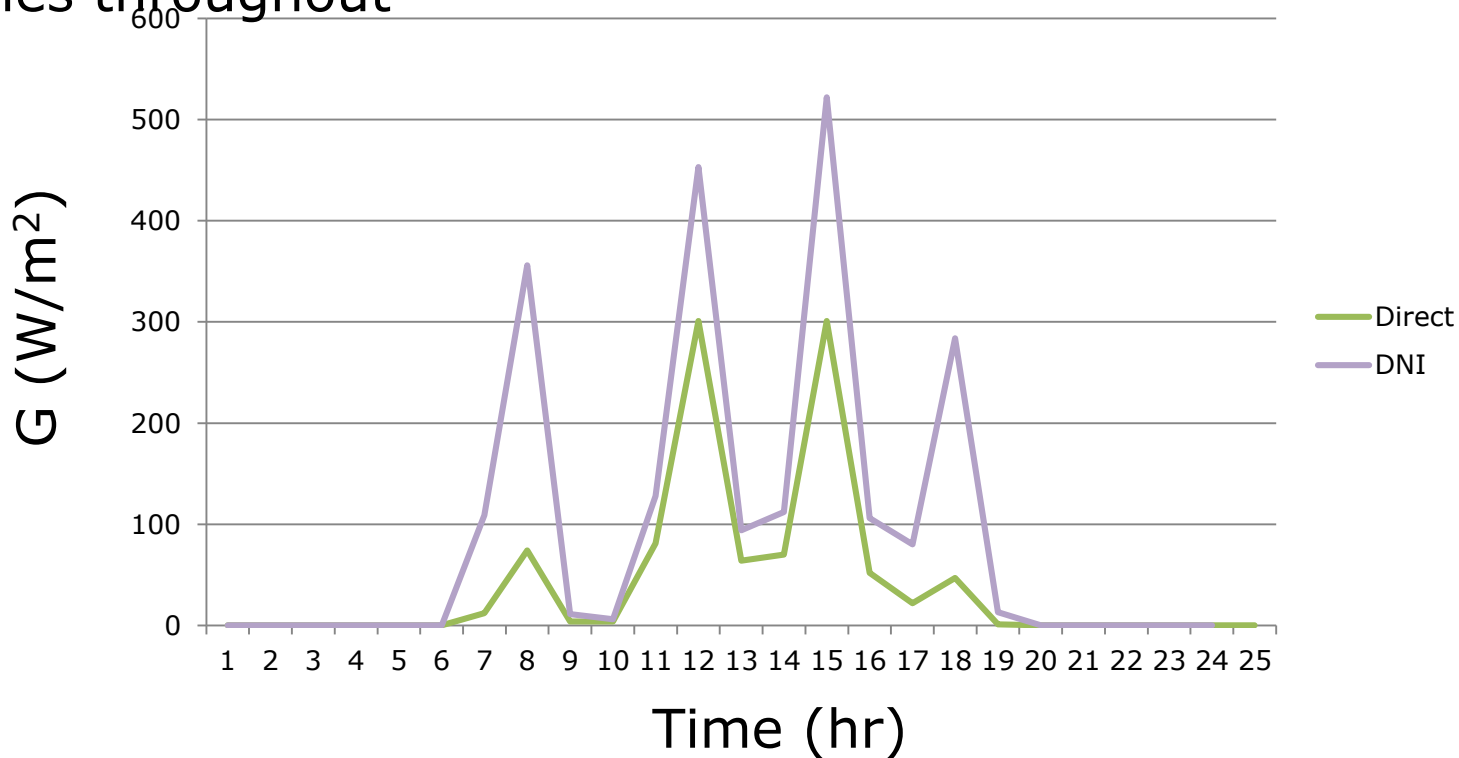
Data provided by: 3TIER



Solar Irradiance

Irradiance on 3/21/1997
in Renton, WA

Not a constant scaling.
 $\cos(\theta)$ varies throughout
the day



Data provided by: 3TIER



Solar Irradiance

- For a given surface
 - $G_{\text{GHI}} = 240 \text{ W/m}^2$
 - $G_{\text{d}} = 188 \text{ W/m}^2$
- What is G_{b} ?



Solar Irradiance

- For a given surface
 - $G_{\text{GHI}} = 240 \text{ W/m}^2$
 - $G_{\text{d}} = 188 \text{ W/m}^2$
- What is G_{b} ?
 - $G_{\text{b}} = G_{\text{GHI}} - G_{\text{d}} = 52 \text{ W/m}^2$



Solar Irradiance

- GHI will always be greater than or equal to DNI
 - True
 - False

- GHI will always be less than or equal to DNI
 - True
 - False



Solar Irradiance

- GHI will always be greater than or equal to DNI
 - True
 - False
 - On clear days and with certain angles of incidence, $DNI > GHI$
- GHI will always be less than or equal to DNI
 - True
 - False
 - On cloudy days and with certain angles of incidence, $GHI > DNI$



Readings

- C. Whitlock, "Cloudy Germany a Powerhouse in Solar Energy", Washington Post, May 2007.
 - [<http://www.washingtonpost.com/wp-dyn/content/article/2007/05/04/AR2007050402466.html>]
- E. Kirschbaum and C. Steitz, "Germany to cut solar subsidies faster than expected", Reuters, Feb 2012.
 - <http://www.reuters.com/article/2012/02/23/us-germany-solar-incentives-idUSTRE81M1EG20120223>