Tutorial

Calculation of hourly solar radiation on tilted surface considering interaction between radiation and atmosphere

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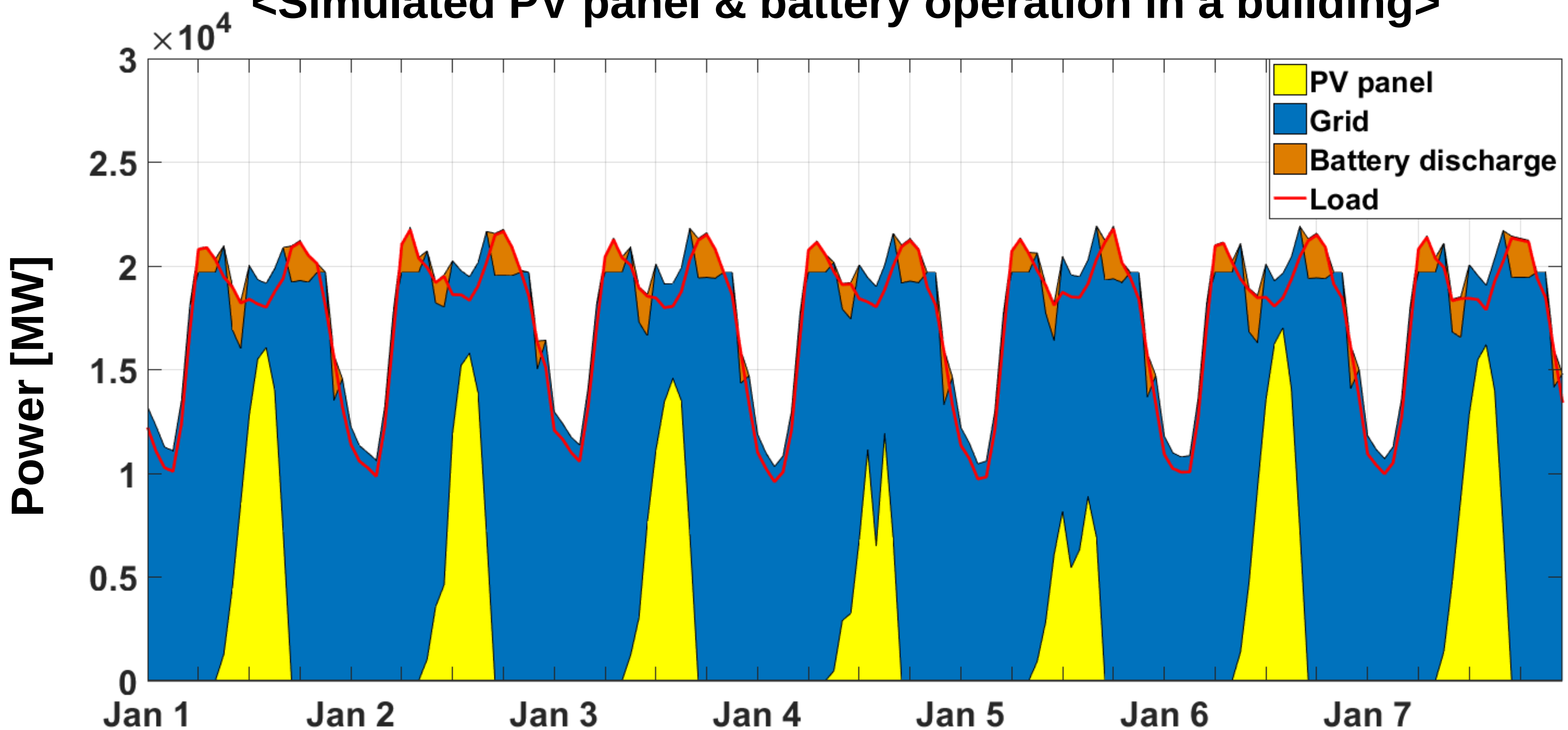
Solar energy conversion: Photovoltaic panel, Solar water heater

- Large solar energy conversion capacity worldwide
  - PV panel: 227 GW, Solar water heater: 435 GW (2015)
    - Nuclear power plant 신고리1호기: 1.4 GW
    - In South Korea, PV panel 3.43 GW (2015)

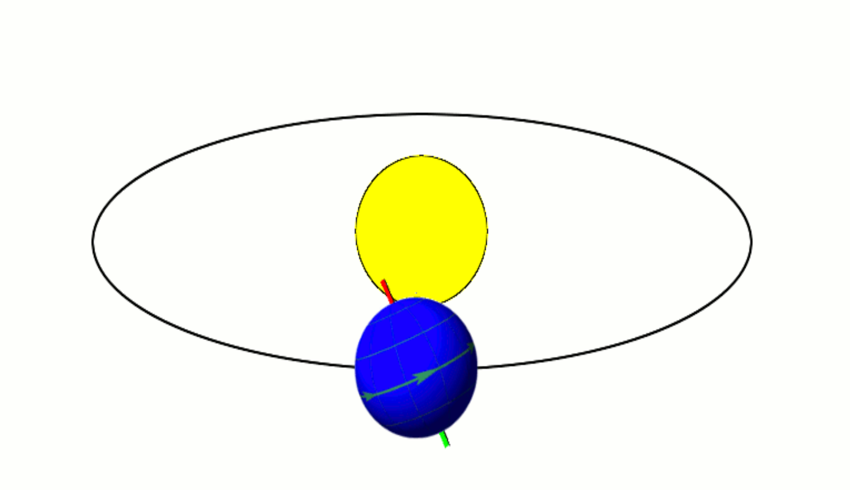
Key of solar energy system analysis: Hourly solar radiation on a tilted plane

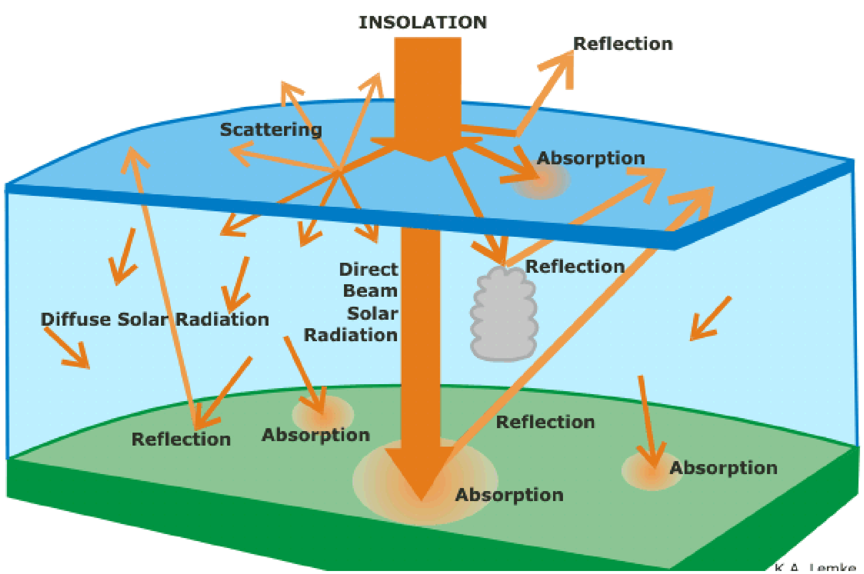
- **Needed for calculating hourly energy production**
  - **Temporal operation of energy system (figure below)**
  - **Economic evaluation of solar energy system, and hybrid system including solar energy and other power sources**

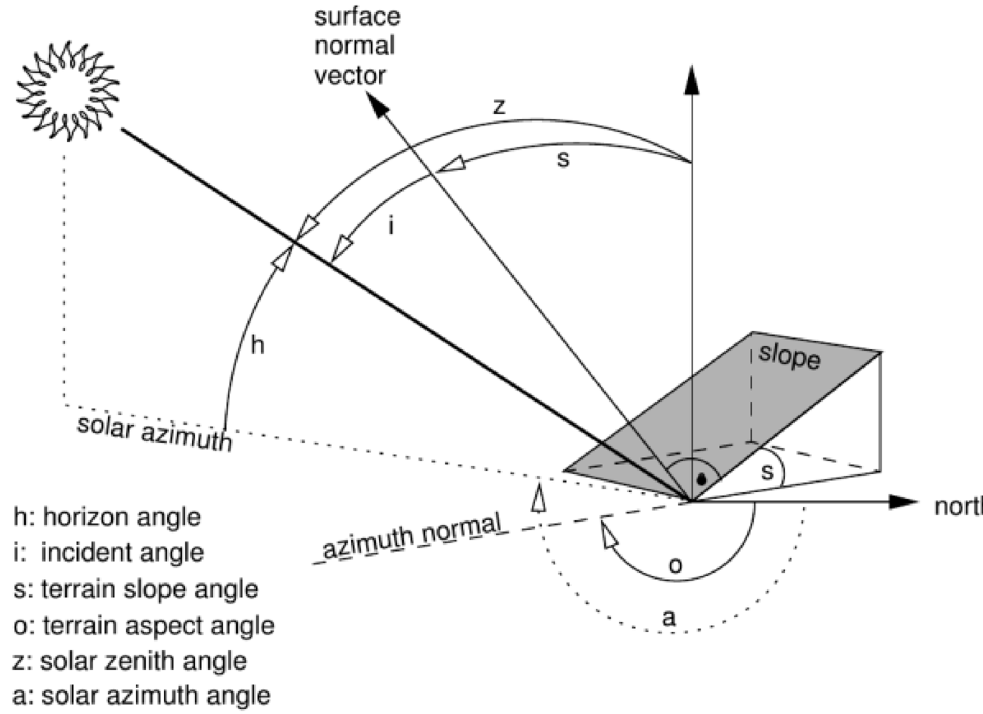
<Simulated PV panel & battery operation in a building>



Complexities: Rotation & revolution, tilt angle, interaction with atmosphere

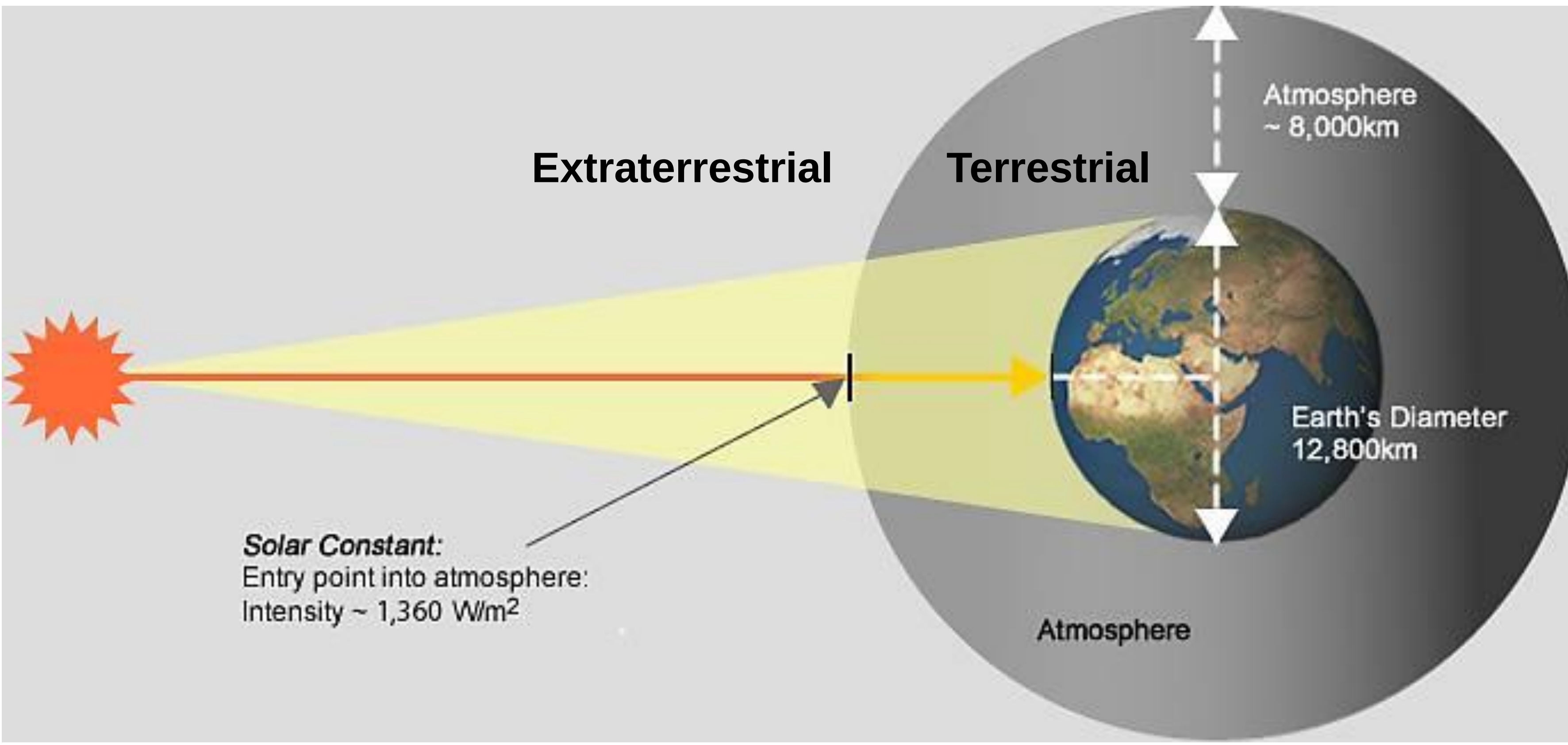






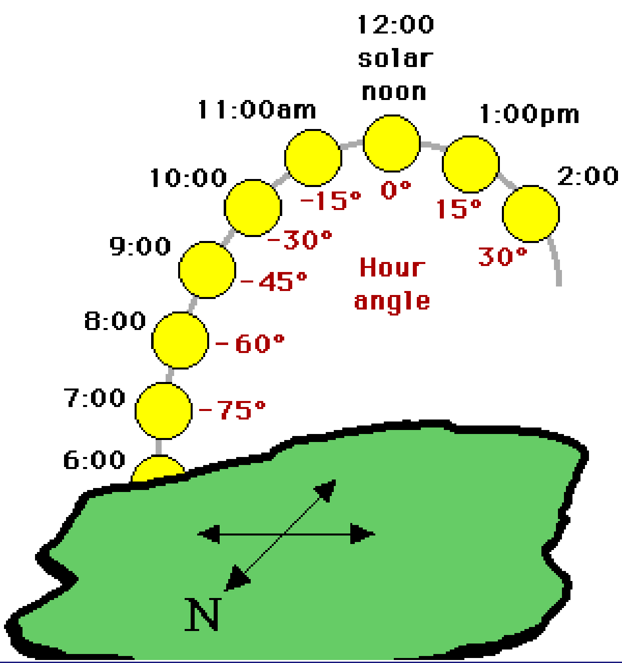
Global solar constant G_{SC}: Flux density of solar radiation on entry point into atmosphere

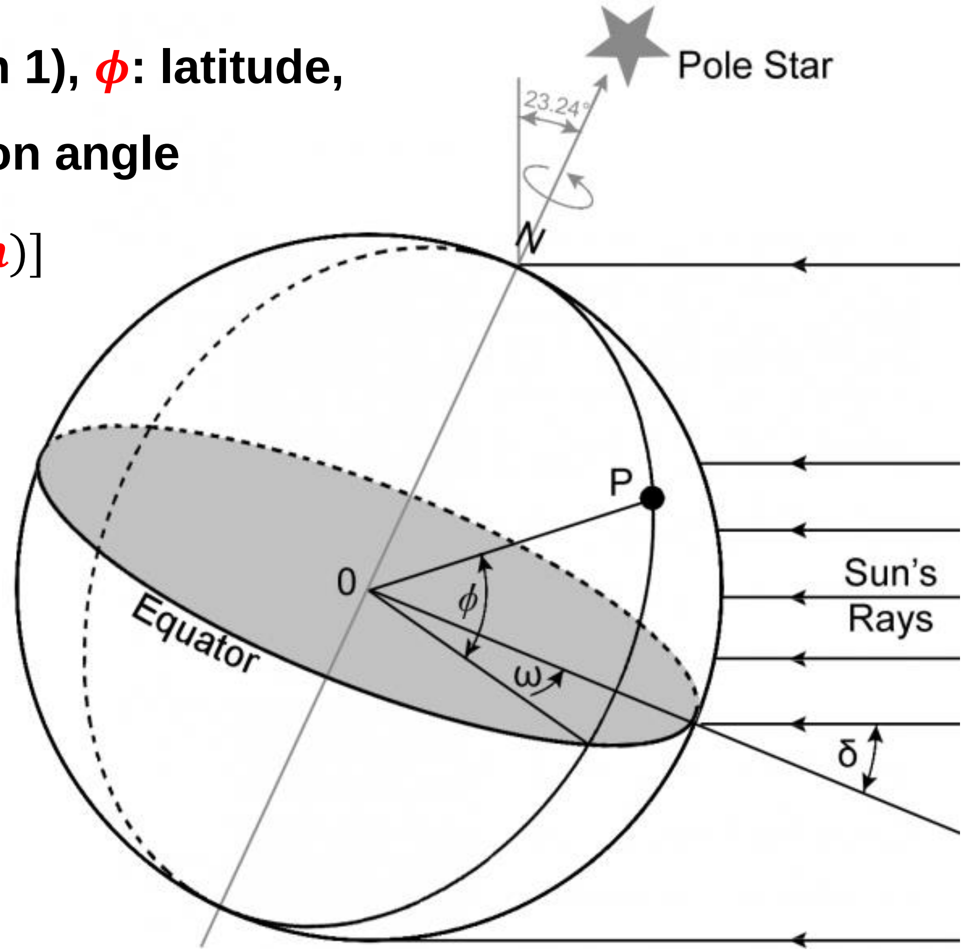
- **About 1,367 W/m^2 with an uncertainty of ~1%**



Extraterrestrial radiation on a horizontal plane at a certain place & a certain time G_o

- Radiation on a plane at the outer edge of atmosphere
  - $G_o = G_{SC}(1 + 0.033cos\frac{360^o n}{365})(cos\phi cos\delta cos\omega + sin\phi sin\delta)$
    - n: number of day (1 for Jan 1), ϕ: latitude, ω: hour angle, δ: declination angle
    - $\delta = 23.45^o sin[\frac{360^o}{365}(284 + n)]$



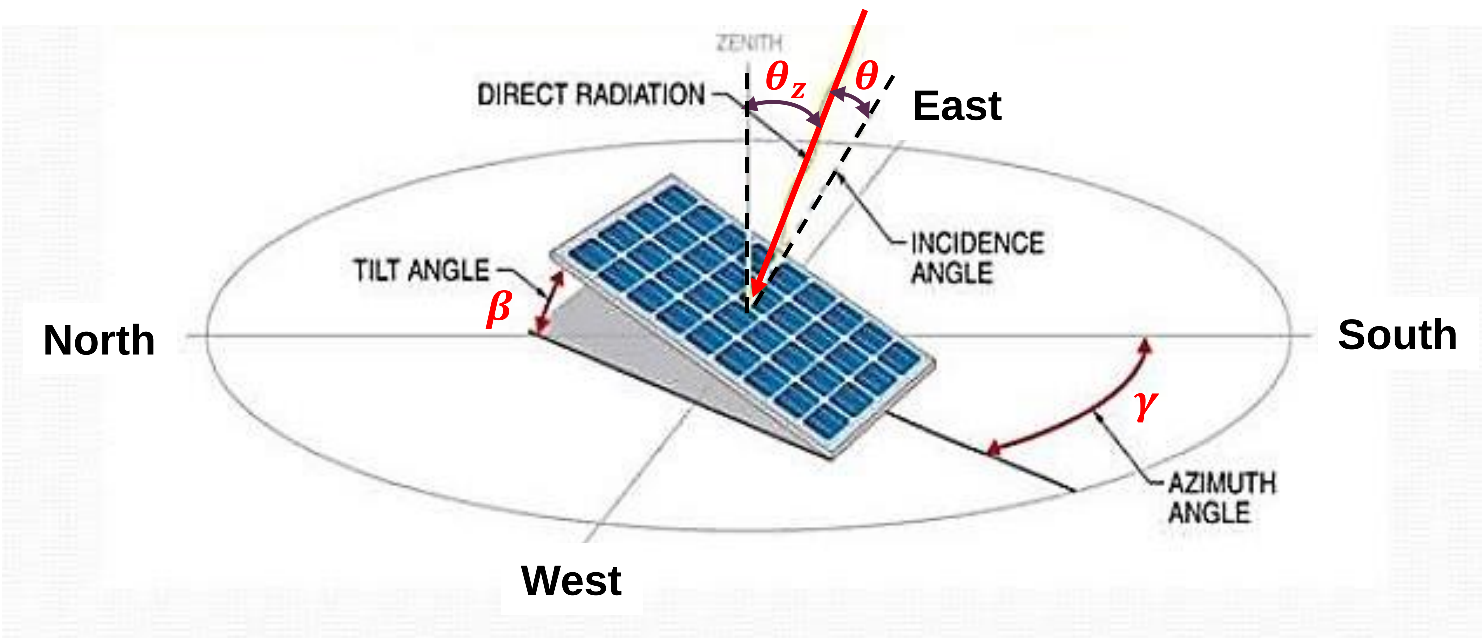


Total extraterrestrial solar energy for an hour on a horizontal plane I_o

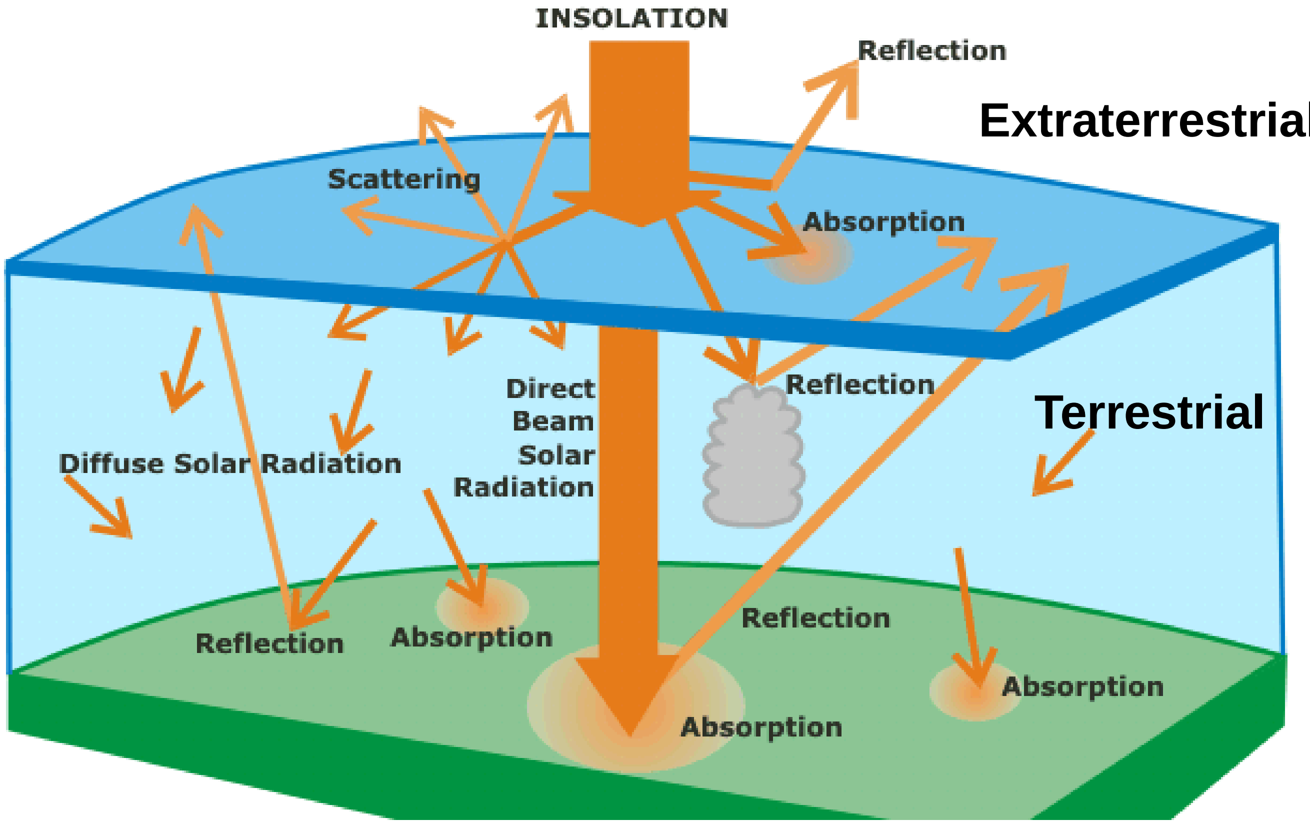
- Integration of G_o from corresponding hour angle ω_1 to $\omega_2 = \omega_1 + 15^{\mathrm{o}}$
  - $I_o = \int_{\omega_1}^{\omega_2} G_o \, d\omega$ (unit: Wh/m²)
  - $I_o = \frac{12}{\pi} G_{SC} \left(1 + 0.033 cos \frac{360^{\mathrm{o}} n}{365}\right)$
    $\times [cos\phi cos\delta (sin\omega_2 - sin\omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180} sin\phi sin\delta]$

From horizontal plane to tilted plane: Angle of incidence θ

- **Angle between the beam on a plane and the normal to the plane**
  - $\cos\theta = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma$
    $+\cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega$
    $+\cos\delta\sin\beta\sin\gamma\sin\omega$
  - $\cos\theta_z = \cos\theta(\beta = 0) = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$



Interaction between radiation and atmosphere: Reflection, direct radiation, diffuse radiation



- **Fraction of reflected energy (albedo)** $\rho_g \approx 0.35$
- **Direct radiation (**I_b**), diffuse radiation (**I_d**)**
  - **Hourly terrestrial total radiation (horizontal surface)** $I = I_b + I_d$

Calculation of hourly terrestrial total radiation on a tilted plane I_T: HDKR model

- **Consideration of beam, isotropic diffuse, ground reflectance, horizon brightening**
  - $$I_T = \left(I_b + \frac{I_d I_b}{I_o}\right)\frac{\cos\theta}{\cos\theta_z} + I_d\left(1 - \frac{I_b}{I_o}\right)\left(\frac{1+\cos\beta}{2}\right)\left[1 + \sqrt{\frac{I_b}{I}}\sin^3\left(\frac{\beta}{2}\right)\right] + I\rho_g\left(\frac{1-\cos\beta}{2}\right)$$
  - **Abbreviation for Hay, Davies, Klucher, Reindl**

Problem of using HDKR model: No values of I_d & I_b in published data

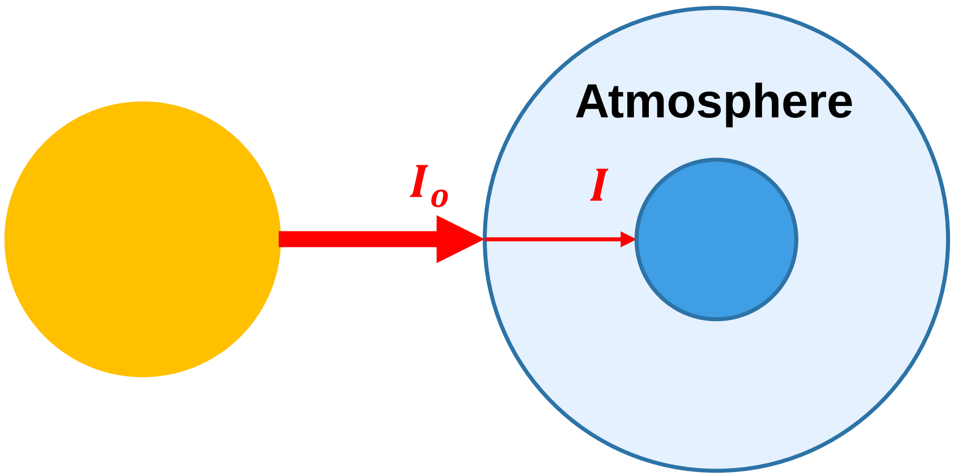
- **Ex> Datasheet published by 기상청**

임의기간(시별): 2017-04-20 00시 ~ 2017-04-20 23시

	지점번호	지점	일시	일사 (MJ/m²)
7	108	서울	2017-04-20 06	0.00
8	108	서울	2017-04-20 07	0.08
9	108	서울	2017-04-20 08	0.32
10	108	서울	2017-04-20 09	0.55
11	108	서울	2017-04-20 10	0.49
12	108	서울	2017-04-20 11	0.59
13	108	서울	2017-04-20 12	1.16
14	108	서울	2017-04-20 13	1.88
15	108	서울	2017-04-20 14	1.74
16	108	서울	2017-04-20 15	1.11
17	108	서울	2017-04-20 16	0.76
18	108	서울	2017-04-20 17	0.90
19	108	서울	2017-04-20 18	0.47
20	108	서울	2017-04-20 19	0.20
21	108	서울	2017-04-20 20	0.02

Value of $I = I_b + I_d$, but values of I_b and I_d are required for obtaining I_T

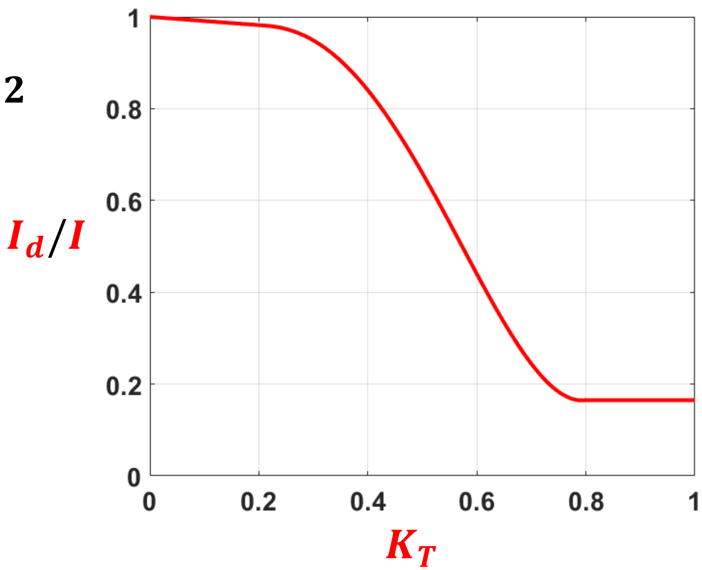
Clearness index & Erbs' correlation: Calculation of I_d with I in published data



Clearness index

$K_T = I/I_o$

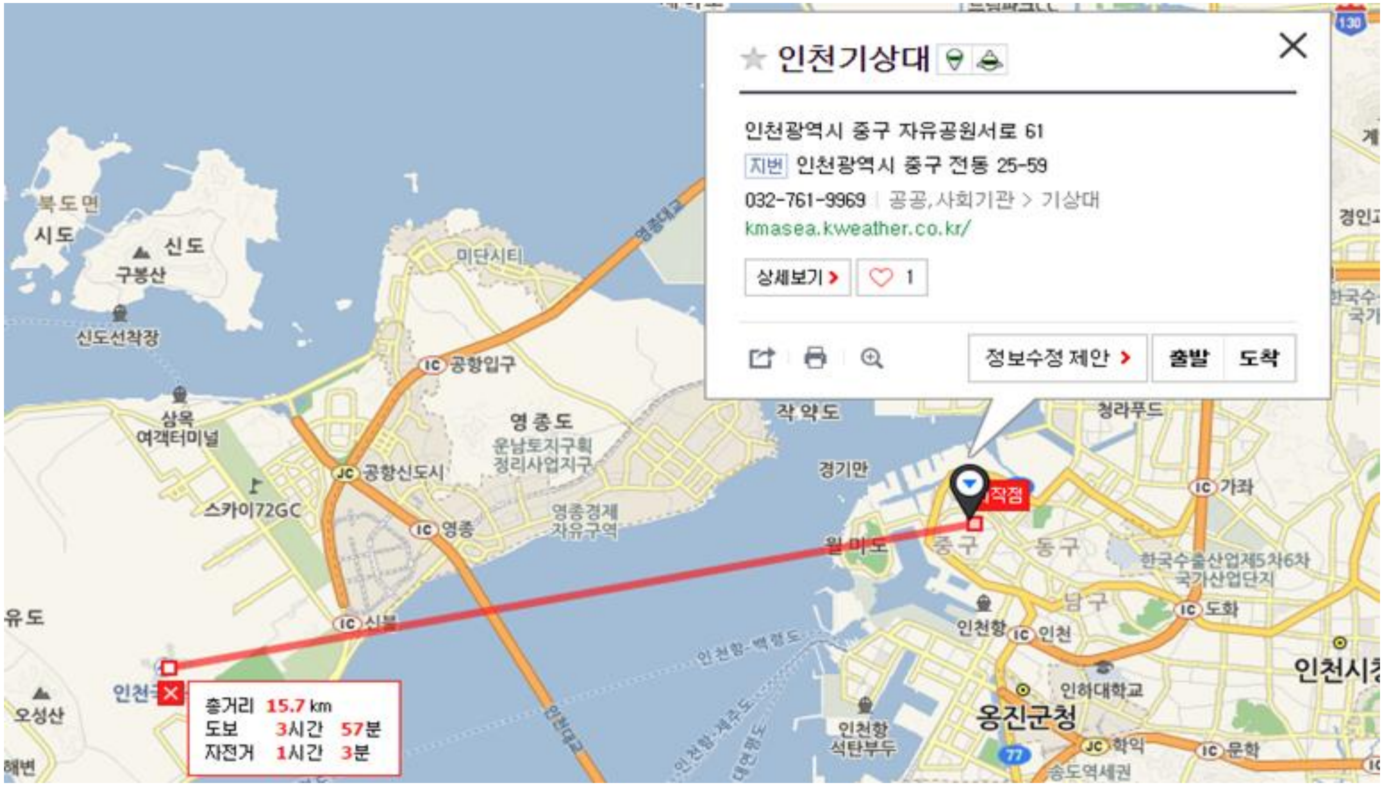
- **Erbs' correlation: I_d/I as a function of K_T**
  - $I_d/I = 1 - 0.09K_T$ for $K_T \leq 0.22$
  - $I_d/I = 0.9511 - 0.1604K_T + 4.388{K_T}^2 - 16.638{K_T}^3 + 12.336{K_T}^4$ for $0.22 < K_T \leq 0.80$
  - $I_d/I = 0.165$ for $K_T > 0.80$



- **$I_b = I - I_d$, able to obtain I_T**

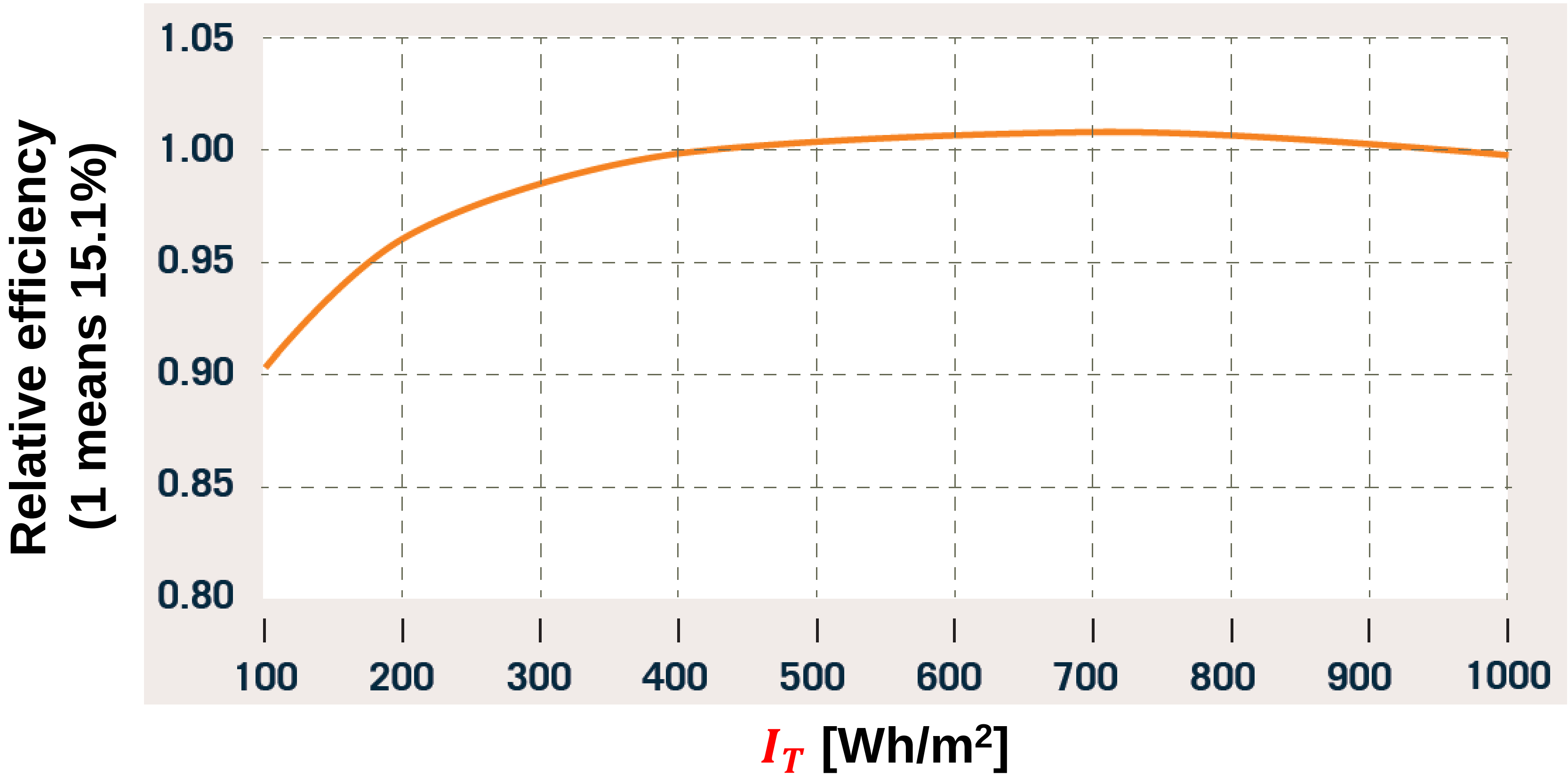
Validation with measured data: PV panel in Incheon airport

- **Measured hourly power generation of the PV panel**
  - **Comparison with simulation data**
  - **Calculation of hourly power with calculated I_T**
  - **Calculation of hourly I_T with published I in Incheon**



Conversion of solar radiation to electricity: Performance curve of a PV panel

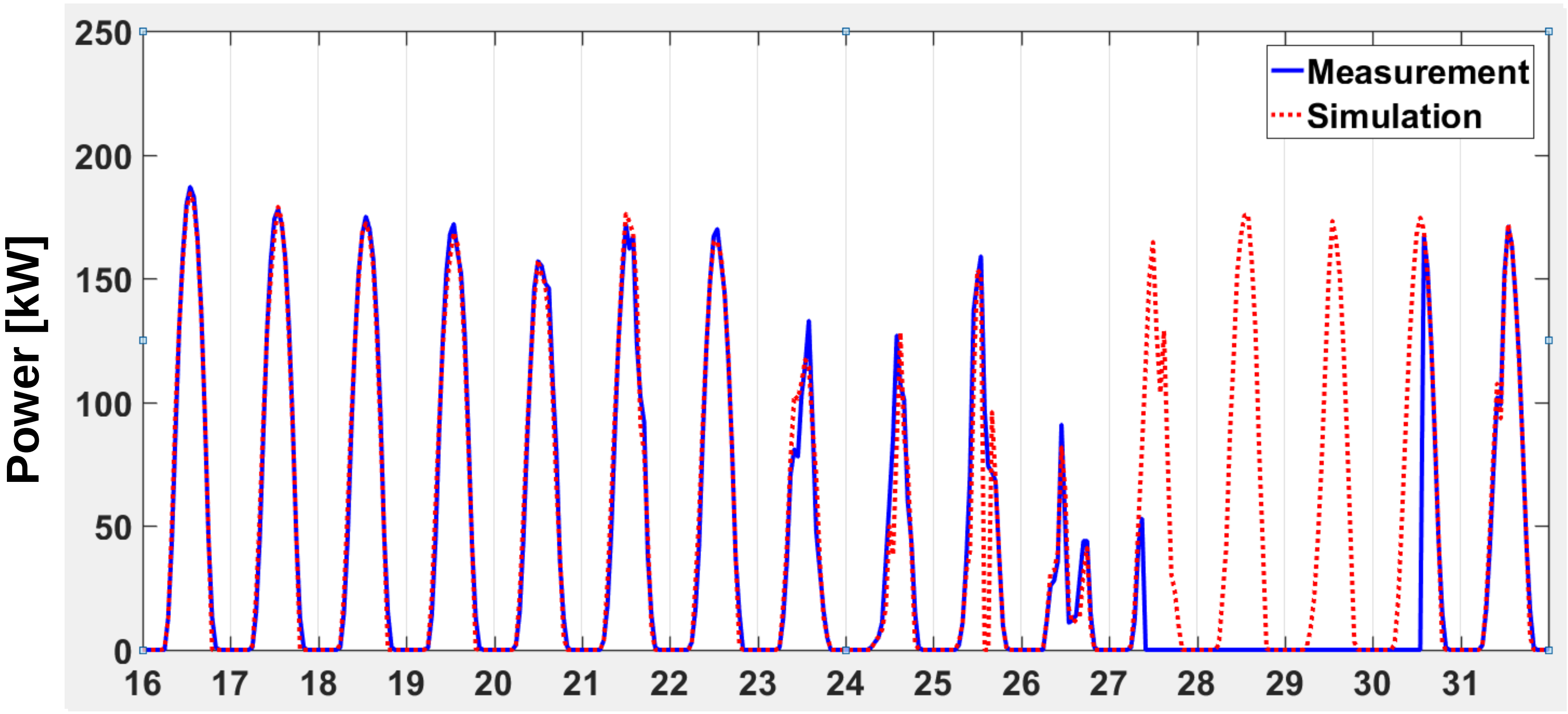
- **Ex> A module of Hanhwa Q-Cell**
  - **300 W per module (1.97m^2), conversion efficiency 15.1%**



  - **Calculation of I_T with $\beta = 20^o, \gamma = 0$**

Simulated data and measured data: Good match

- **Ex> May 2016**
  - **27th~30th day: under maintenance**



Summary: Calculation process

$$I_T = f_1(\underbrace{I_b, I_d}, \underbrace{I_o}, \underbrace{\theta, \theta_z}, \beta)$$

$$\theta = f_2(\delta, \phi, \omega, \beta, \gamma)$$

$$\theta_z = f_2(\delta, \phi, \omega, 0, 0)$$

$$G_o = f_3(n, \delta, \phi, \omega)$$

$$I_o = \int_{\omega_1}^{\omega_2} G_o \, d\omega$$

I **from published data**

$$I_d = I f_4(K_T = I/I_o)$$

$$I_b = I - I_d$$

References

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- **Shyam S, C., & Rajeev K, A. (2011). Estimation of hourly solar radiation on horizontal and inclined surfaces in Western Himalayas. Smart grid and renewable energy, 2011.**
- **Erbs, D. G., Klein, S. A., & Duffie, J. A. (1982). Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. Solar energy, 28(4), 293-302.**