Unit 2 : Energy Meteorology

Solar Constant : $\dot{G}_0 = \dot{G}_s \cdot \frac{4\pi R_s^2}{4\pi (AU)^2}$; $\left[\frac{W}{m^2}\right]$;

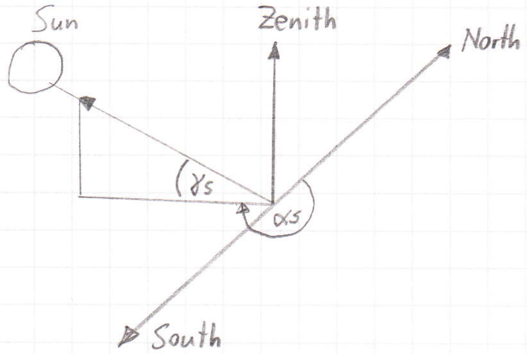
$\dot{G}_s = 63,15 \frac{MW}{m^2}$; $R_s = 0,6963 \cdot 10^6$ km ; $AU = 1,496 \cdot 10^8$ km

↑ Irradiation Sun ; ↑ Radius Sun ; ↑ Astronomic Unit

Distance Sun - Earth : – Winter : $0,983 \cdot AU$

– Summer : $1,017 \cdot AU$

Altitude γ_s (Sun height) Azimuth α_s (North → South)



Air Mass : $AM = \frac{1}{\sin \gamma_s}$ [Unit 2, page 8]

Irradiation Tilted : $G_{total,tilted} = G_{dir,tilted} + G_{dif,tilted} + G_{ref,tilted}$

↑ direct ; ↑ diffuse ; ↑ reflected

Direct Radiation : $G_{dir,tilted} = G_{dir,horizontal} \cdot \frac{\cos \Theta}{\sin \gamma_s}$

Angle Θ sunbeam → normal vector : [Unit 2 page 12]

$$\cos \Theta = \frac{\vec{s} \cdot \vec{n}}{|\vec{s}| \cdot |\vec{n}|} \Rightarrow \Theta = \arccos\left[\frac{\vec{s} \cdot \vec{n}}{|\vec{s}| \cdot |\vec{n}|}\right]$$

$$\vec{s} = \begin{bmatrix} r \cdot \sin(90° - \gamma_s) \cdot \cos(\alpha_s) \\ r \cdot \sin(90° - \gamma_s) \cdot \sin(\alpha_s) \\ r \cdot \cos(90° - \gamma_s) \end{bmatrix}$$

z.B. $|\vec{s}| = \sqrt{x^2 + y^2 + z^2}$; $\vec{s} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}$

r = sunbeam length (not required ⇒ $r = 1$)

$$\vec{n} = \begin{bmatrix} \sin(90° - \gamma_s) \cdot \cos(\alpha_s) \\ \sin(90° - \gamma_s) \cdot \sin(\alpha_s) \\ \cos(90° - \gamma_s) \end{bmatrix}$$

with $\gamma_s = 90° - \gamma_p$

Diffuse Radiation :

$$G_{diff,\,tilted} = \frac{1}{2} \cdot G_{diff,\,hor} \cdot (1 + \cos(\gamma_P)) \cdot \left(1 + F \cdot \sin^3\left(\frac{\gamma_P}{2}\right)\right) \cdot (1 + F \cdot \cos^2 \theta \cdot \cos^3 \gamma_S)$$

Cloudness Function :

$$F = 1 - \left[\frac{G_{diff,\,hor}}{G_{total,\,hor}}\right]^2$$

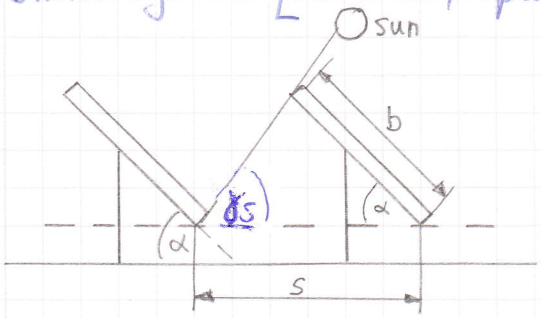
Ground Reflection or Albedo A : [Unit 2 page 13]

$$G_{ref,\,tilted} = G_{total,\,hor} \cdot A \cdot \frac{1}{2} \cdot (1 - \cos \gamma_P)$$

Irradiation Total horizontal :

$$\hat{G}_{total,\,hor} = \hat{G}_{dir,\,hor} + G_{diff,\,hor} \quad \text{(no Albedo !)}$$

Shading : [Unit 2, page 14]



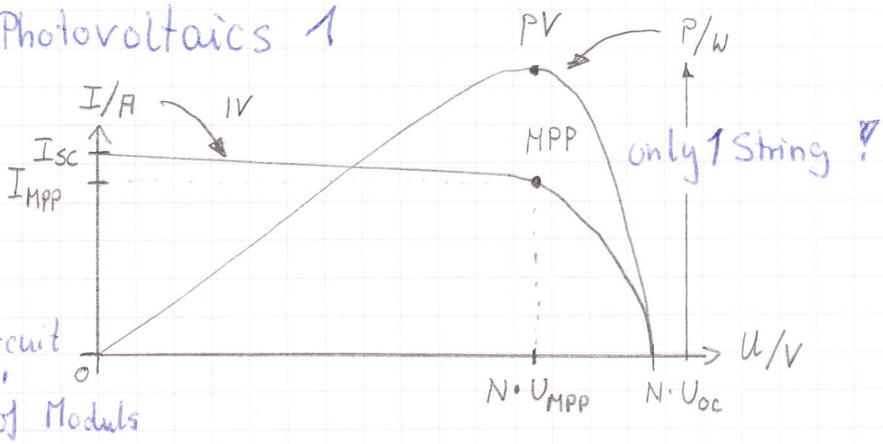
$$s = b \cdot \frac{\sin[180 - (\alpha + \gamma_S)]}{\sin \gamma_S}$$

Tilted roof with tilt angle β [Unit 2, page 19]

$$s = b \cdot \frac{\sin[180 - (\alpha + \gamma_S + \beta)]}{\sin(\gamma_S + \beta)}$$

Unit3 : Photovoltaics 1

IV-Courve :



sc ≙ short circuit
oc ≙ open "
N ≙ Numbers of Moduls

STC : Standard Test Condition : $T_{Pr} = 25°C$

$AM = 1{,}5$

$\dot{G} = 1000 \ W/m^2$

NOCT : Nominal Operation Cell Temperature : $\dot{G} = 800 \ W/m^2$

$T_{NOCT} = 40-45°C$

$$U_{oc(T)} = U_{oc(25°C)} + \Delta U_{oc} \qquad \Delta U_{oc} = \alpha \cdot U_{oc(25°C)} \cdot (T - 25°C)$$

$$I_{sc(T)} = I_{sc(25°C)} + \Delta I_{sc} \qquad \Delta I_{sc} = \beta \cdot I_{sc(25°)} \cdot (T - 25°C)$$

Fill Factor : $FF = \left(\frac{U_{MPP} \cdot I_{MPP}}{U_{oc} \cdot I_{sc}} \right)$ in %

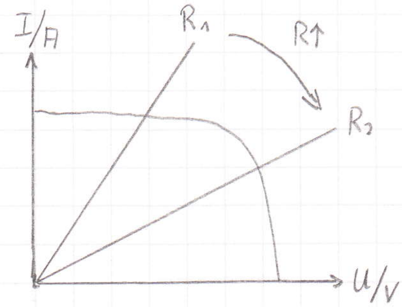
Rated efficiency under STC : $\eta = \frac{P_{MPP}}{\dot{G} \cdot A_{Modul}}$

Power - ~~deg~~ decrease : $\Delta P = \gamma \cdot \Delta T$ in %

↖ Temperature Coefficient P_{MPP}

Unit 4 : Photovoltaics 2

MPP - Tracking :



$R_1 < R_2$

European Efficiency :

$$\eta_{EU} = 0{,}03 \cdot \eta_5 + 0{,}06 \cdot \eta_{10} + 0{,}13 \cdot \eta_{20} + 0{,}1\, \eta_{30} + 0{,}48 \cdot \eta_{50} + 0{,}2 \cdot \eta_{100}$$

Efficiency : $\eta_{Pr-Gen} = \frac{W_{DC}}{G \cdot A}$

$\eta_{invert} = \frac{W_{AC}}{W_{DC}}$ $\qquad \eta_{invert} = \eta_{WR}$

$\eta_{STC} = \frac{P_r}{\dot{G}_{STC} \cdot A}$

Performance Ratio : $PR = \frac{W_{AC}}{W_{AC\,(opt)}} = \frac{W_{AC}}{G \cdot A \cdot \eta_{STC}}$ $[\%]$

Final Yield : $Y_F = \frac{W_{AC}}{P_r} = \frac{PR \cdot G}{\dot{G}_{STC}}$ $[kWh/kW]$

Output Energy : $W_{AC} = G \cdot A \cdot \eta_{STC} \cdot PR$ $[kWh]$

Rated Power : $P_r = \dot{G}_{STC} \cdot A \cdot \eta_{STC}$ $[kW]$

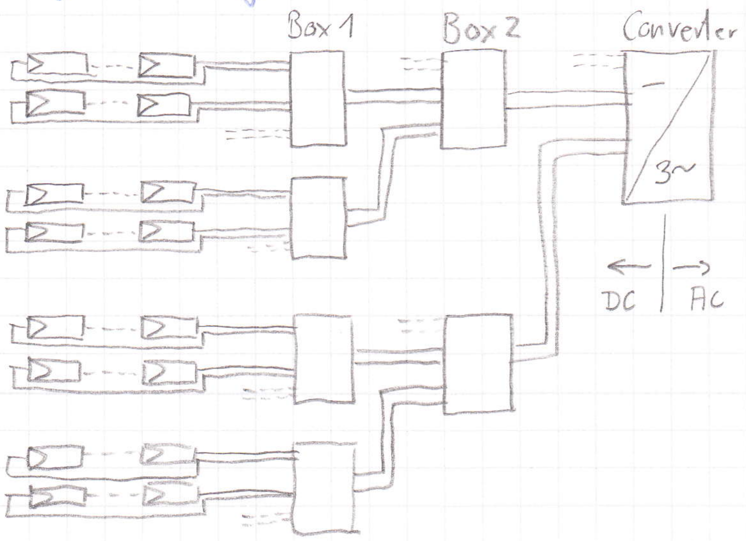
~~Pow~~ Performance Ratio Transformed : $PR = \frac{Y_F \cdot \dot{G}_{STC}}{G}$

Rough Determination of Yield :

$W_{AC} = G_{Modul} \cdot A \cdot \eta_{WR} \cdot \eta_{Pr-Gen}$ $\qquad G_{Modul} = G_{Hor} \cdot Tiltfactor$ (Horizontal ↓ G_{Hor})

Special : $\eta_{WR} \cdot \eta_{Pr-Gen} \approx 10\,\%$

Wiring / Cabling

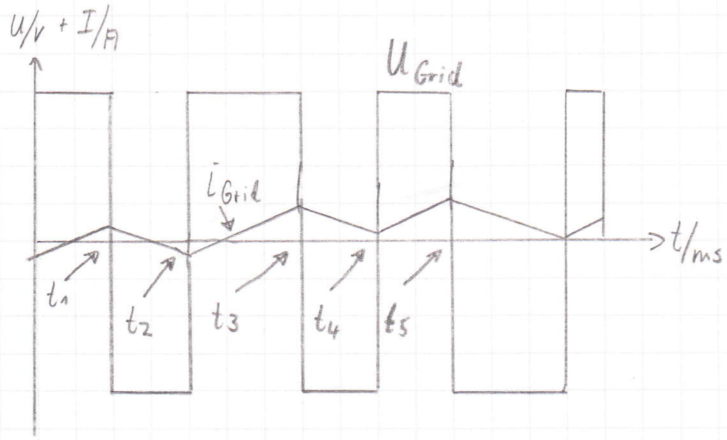


Voltage Drop : $\Delta U = 2 \cdot I \cdot R$; $R = \frac{l}{\kappa \cdot A}$; $\kappa_{Cu} = 56 \frac{m}{\Omega \cdot mm^2}$

Power losses : $P_v = 2 \cdot I^2 \cdot R$ (single AC or DC)

Power losses 3 Phase : $P_{v_{3\sim}} = 3 \cdot I^2 \cdot R$

PWM - Converter DC → AC :



$\Delta i_{Grid} = \frac{U}{L} \cdot \Delta t$ $\left[\frac{A}{sec} \cdot \Delta t\right]$

$i_{Grid\, t_3} = i_{Grid\, t_2} + \Delta i_{(t_2 \to t_3)}$ usw.

Formelsammlung Solar & Wind

Unit 5 (Standalone Systems)

- $DOD = \frac{Q_{Out}}{Q_{in}}$ (Depth of Discharge)

  i.e. 100 Ah into battery, 40 Ah out

  $\Rightarrow DOD = 40\%$

- $SOC = \frac{Q_{Batt}}{Q_{in}} = 1 - DOD$ (State of Charge)

  i.e. 100 Ah into battery, 40 Ah out

  $\Rightarrow SOC = 60\%$

Seite 5

- $\eta_{Ah} = \frac{Q_{Out}}{Q_{in}}$ (Ampere-Hour Efficiency)

  Q_{Out} = entnommene Ladungsmenge vom Ladezustand 1 zu Ladezustand 2

  Q_{in} = zugeführte Ladungsmenge um Ladezustand 1 wieder herzustellen

- $\eta_{Wh} = \eta_{Batt} = \eta_{BattIn} \cdot \eta_{BattOut}$

- $Turnover = \frac{\int |I_{-}| \cdot dt}{C_{rated}}$; C_{rated} = Capacity of Batt.

- $W_{day} = \int_0^{24h} P(t) \cdot dt = \underbrace{\Delta t}_{=1h} \sum_1^{24h} P(t)$ (Consumer-Load) [kWh]

irradiation {
- $G_{day} = \Delta t \sum_1^{24h} G(t)$ (auf $1\,m^2$) $\left[\frac{kWh}{m^2}\right]$
- $G_{daytotal} = G_{day} \cdot A_{PV}$ (auf gesamten PV-Generator) [kWh]

}

- $$W_{BattUse} = \frac{W_{required}\ (z.B.: 2 \cdot W_{day})}{\eta_{System}\ (z.B.: \eta_{BattOut} \cdot \eta_{DC/AC})}$$

- $$W_{Batttotal} = \frac{W_{BattUse}}{max.\ DOD}$$

- $$C_{rated} = \frac{W_{Batt\,total}}{U_{Battrated}}$$

Änderung Ladezustand von t1 nach t2:

- $W_{t1} = U_{Battrated} \cdot C_{rated} \cdot SOC_{t1}$

$W_{in} = W_{PV\,t1-t2} = G_{t1-t2} \cdot A_{PV} \cdot (t_2 - t_1) \cdot \eta_{PV} \cdot \eta_{DC/DC}$

$W_{out} = W_{L\,t1-t2} = \frac{L_{t1-t2}}{\eta_{AC/DC}}$

$W_{in} > W_{out}$ (Ladung)

$W_{Batt\,t2} = W_{Batt\,t1} + [(W_{in} - W_{out}) \cdot \eta_{Battin}]$

weiter auf nächster Seite

③

$$W_{out} > W_{in} \quad \text{(Entladung)}$$

$$W_{Batt\,t2} = W_{Batt\,t1} + \frac{(W_{in} - W_{out})}{\eta_{Batt\,out}}$$

$$\Rightarrow SOC_{t2} = \frac{W_{t2}}{C_{rated} \cdot U_{Batt\,rated}}$$

<u>erforderliche Systemgröße:</u>

- $U_{System} = n_{Reihe} \cdot U_{Batt}$
- $C_{System} = n_{Parallel} \cdot C_{Batt}$
- $I_{Strang} = I_{Batt} = \frac{I_{System}}{n_{Strang}}$

$C_{real} = C_{rated} \cdot C_{\%}$; $C_{\%}$ = Tabelle S. 7: abhängig von Strangstrom erreichbare Kapazität in %

<u>Dichte abhängig von SOC:</u> (Tabelle Seite 7)

- $U_{Batt\,SOC} = U_{System\,SOC} / n_{Reihe}$; / ≙ geteilt

$\Rightarrow$ Dichte siehe Tabelle Seite 7

Unit 6 (Solar Thermal Systems)

Kollektor:

- τ_{Cor} = Transmission coefficient of cover

  α_{Abs} = Absorption coefficient of absorber

  $\dot{G}$ = Power of irradiation

  $\dot{Q}_N = \dot{Q}_{Use}$ = Useful power tranferred to heat fluid

  $\dot{Q}_S$ = Reflection Losses of the glass cover

  $\dot{Q}_R$ = Reflection losses of the absorber

  $\dot{Q}_{Loss}$ = Power emitted in the long wave area + Losses due to convection

siehe Seite 6

- $Q_{Use} = \dot{G} \cdot A \cdot \delta \cdot t$

- $\dot{Q}_{Use} = \dot{G} \cdot A \cdot \tau_{Cov} \cdot \alpha_{Abs} - a_1 A (T_{Abs} - T_{Amb}) - a_2 A (T_{Abs} - T_{Amb})^2$

  $\eta_{Coll} = \frac{Q_N}{\dot{G} \cdot A} = \underbrace{\alpha_{Abs} \cdot \tau_{Cov}}_{a_0} - \frac{a_1}{\dot{G}} \cdot (T_{Abs} - T_{Amb}) - \frac{a_2}{\dot{G}} (T_{Abs} - T_{Amb})^2$

  $\eta_{Coll} = a_0 - \frac{a_1}{\dot{G}} \cdot (T_{Abs} - T_{Amb}) - \frac{a_2}{\dot{G}} \cdot (T_{Abs} - T_{Amb})^2$

Deckungsfaktor

- Jahr: $f_{S_{Jahr}} = \frac{Q_{Use\,Jahr}}{Q_{Load\,Jahr}}$

- Monat: $f_{S_{Monat}} = \frac{G_{Tilt} \cdot 30d \cdot \delta \cdot A}{Q_{Load\,Monat}}$; $Q_{Load\,Monat} = B$

Thermal Store:

- $Q = c \cdot m \cdot (T_{Store} - T_{Amb})$

$Q_{Loss} = U_{Store} \cdot A_{Store} \, (T_{Store} - T_{Amb})$

$A_{Store} = \underbrace{d \cdot \pi \cdot h}_{\text{Mantel}} + \underbrace{1 \cdot \frac{d^2 \cdot \pi}{4}}_{\text{Deckel}}$ (Oberfläche Speicher)

Pipe:

- $U_{Pipe} = \frac{\pi}{\frac{1}{2 \cdot \lambda} \cdot \ln\left(\frac{d_o}{d_i}\right) + \frac{1}{\alpha_o \cdot d_o}}$

d_i = inner diameter

d_o = outer diameter

α_o = Heat tranfer coefficient from outer side of insulation to air

λ = Heat conductivity of heat insulation

$\dot{Q}_{Pipe} = l \cdot U_{Pipe} \cdot (T_{Fluid} - T_{Amb})$; l: Hin- und Rückweg für Rücktemp. nicht gegeben

Operational behaviour:

- $\dot{Q}_{Heat} = \dot{Q}_{Solar} - \dot{Q}_{Pipe} - \dot{Q}_{Loss}$; $\dot{Q}_{Solar} = \dot{G} \cdot A_{Coll} \cdot \eta_{Coll}$

- $dQ_{Heat} = c_p \cdot m \cdot dT_{Store}$

- $\Delta T_{Store} = \frac{\Delta t}{c_p \cdot m} \left(\dot{G} \cdot A_{Coll} \cdot \eta_{Coll} - \dot{Q}_{Pipe} - \dot{Q}_{Loss} - \dot{Q}_{Use} \right)$

Rough design of solar thermal systems:

- $W = m \cdot c \cdot \Delta T$
- $A = \frac{W}{G \cdot \delta}$

Details siehe Seite 13

Unit 7 (Konzentrierende Solarthermie)

Concentration factor

- $C = \frac{A_R}{F}$; A_R = area emitting radiation
  F = area receiving radiation (Absorber)

- $T_A = 5777\,K \cdot \sqrt[4]{\frac{C}{46211}}$; T_A = maximum absorber temp.

Output Power Collector = Q_N

- $\eta = \frac{\dot{Q}_N}{\dot{G} \cdot A_R} = \rho_R \left(1 - \rho_{Abs}\right) - \frac{U_A}{\dot{G} \cdot C} \left(T_{Abs} - T_{Amb}\right) - \frac{\varepsilon_{Abs} \cdot \sigma}{\dot{G} \cdot C} \left(T_{Abs}^4 - T_{Amb}^4\right)$

  ρ_R = Reflection coefficient ; ρ_{Abs} = Reflection coeff. Absorber

  U_A = Heat transmission coeff. Absorber ; ε = Emissio coeff Absorber

  σ = Boltzmann - constant

- $\dot{m} = \frac{\dot{Q}_N}{c_{p\,oil} \cdot \Delta T}$

Solar Power Plant without store

- $\eta_{total} = \frac{P_{Grid}}{\dot{Q}_N} = \eta_{Abs} \cdot \eta_{HeatExchanger} \cdot \eta_{Therm} \cdot \eta_{Generator}$

- $\eta_{total} = \frac{P_{Grid}}{\dot{G}_N \cdot A_R}$

Unit 8 (Wind Energy Converters)

Windgeschwindigkeit:

- $v_H = v_{10} \left(\frac{H}{10m}\right)^a$ (Hellmann)
- $v_2(h_2) = v_1(h_1) \cdot \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)}$ z_0 siehe Seite 5

Leistungen:

- $P = P_{el} = \frac{1}{2} \rho \cdot v^3 \cdot A \cdot c_p \cdot \eta$
- $P_{Wind} = \frac{1}{2} \cdot \dot{m} \cdot v^2 = \frac{1}{2} \cdot \rho \cdot A \cdot v^3$ (Seite 9)
- $\eta = \frac{P_{el}}{P_{Welle}}$

Speed coefficient:

siehe Diagramm Seite 10

- $\lambda = \frac{2 \cdot \pi \cdot r \cdot n}{v}$; v = Wind speed in front of WEC at hub height

Weibull distribution:

$$f(v) = \frac{c}{A} \cdot \left(\frac{v}{A}\right)^{(c-1)} \cdot e^{-\left(\frac{v}{A}\right)^c}$$

$$v_m = A \cdot \left(0{,}568 + \frac{0{,}434}{c}\right)^{(1/c)}$$

Rayleigh distribution:

$$f(v) = \frac{\pi}{2} \cdot \left(\frac{v}{v_m^2}\right) \cdot e^{-\left(\frac{\pi}{4}\right) \cdot \left(\frac{v}{v_m}\right)^2}$$

Betriebsstunden:

- $T_m = \frac{W_m}{P_{el\,rated}}$ (full load hours)
- $T_{Class} = f(v) \cdot 8760\,h \cdot \Delta v$