MAE 119 WINTER 2015 PROFESSOR G.R. TYNAN
QUIZ 5: SOLAR THERMAL POWER TECHNOLOGY

CLOSED BOOK CLOSED NOTES.
One significant figure will suffice for your answers.

A solar thermal power plant is to be built in a region that has on average a Direct Normal Incidence (DNI) of 500 W/m^2 and a Diffuse Horizontal Irradiance (DHI) of 500 W/m^2 for 10 hours per day. These values then go to zero for the other 14 hours per day. The plant will use a heat engine that has a conversion efficiency of 40%. It is desired that the plant produce 100 MW of electricity continuously.

(a) What is the minimum light collecting area required for these specifications? 10 points.

(b) How much energy needs to be stored for subsequent use in producing electricity at night? 10 points.

(c) Assuming that a thermal energy storage system is used with a thermal storage medium having a specific heat C_p = 1 kJ/kG-deg K and a density ρ=3000 kG/m^3 estimate the volume of the thermal storage system so that the characteristic stored energy decay time exceeding 24 hours? 10 points.

Hint: Recall that the power balance for the thermal storage system is given as $\rho C_p V \frac{\partial T}{\partial t} = P_{in} - \frac{1}{\eta_{th}} P_{out}$

(d) Explain in words why it would be useful to have such a long thermal energy decay time.

Quiz 5 Solution

a) Need 100 MW

In steady state : $P_{in} = \frac{P_{out}}{\eta}$

$P_{in} = I_{DNI} A$

$$\therefore A = \frac{P_{out}}{\eta I} = \frac{100 \times 10^6 \, W}{500 \, W (0.4)} m^2$$

$$\boxed{= 0.5 \times 10^6 \, m^2 = 0.5 \, Km^2}$$

b) to get 100 MW at $\eta = 40\%$

we need $\frac{100 \times 10^6 \, W}{0.4} = \frac{100 \times 10^6 \, W}{40 \times 10^{-2}} = 2.5 \times 10^8 \, W$

which, sustained for the entire night is

$(14 \text{ hrs} \cdot 2.5 \times 10^8 \, W) = 35 \times 10^8 \, Whr = \boxed{3.5 \, GWhr}$

$\boxed{\leq 4 \, GWhr}$ okay

c) $\rho C_p V \frac{dT}{dt} = P_{in} - \frac{1}{\eta} P_{out}$

$$\rho C_p V dT = - \frac{P_{out}}{\eta} dt$$

$$\int_{T(t=0)}^{T(t)} dT = \frac{-P_{out}}{\eta \rho C_p V} \int_{t=0}^{t} dt$$

$$\Delta T = \frac{-P_{out}}{\eta C_p \rho V} \Delta t$$

P_{in} can be assumed zero at night with no mention of another generator.

P_{out} is a constant 100 MW.

c) cont...

$$\Delta t = \underbrace{\frac{-\eta\, C_p\, \rho\, V\, \Delta T}{P_{out}}}_{\equiv \tau \text{ characteristic time}}$$

$$\tau = 24\,h \cdot 3600\,\frac{s}{h} = 8 \times 10^4\, s$$

$$V^* = \frac{P_{out}\, \tau}{\eta\, C_p\, \rho\, V\, \Delta T}$$

* Either solve for V in terms of °K (i.e. for 1°K of temperature difference) or assume $\Delta T \simeq 100 - 300$ °K.

$$V = \frac{(100 \times 10^6\, W)(8 \times 10^4\, s)}{(0.4)(1000\, J/kgK)(3000\, kg/m^3)(\Delta T\, K)}$$

$$= \frac{800 \times 10^{10}}{12 \times 10^5 (\Delta T)} \simeq \boxed{8 \times 10^6\, m^3 \cdot {}^\circ K \Delta T}$$

$$\boxed{V = 3 \times 10^4 - 8 \times 10^4\, m^3}$$

D) The long decay time is useful for providing power at night (14 hrs), during intermittent days with low DNI, and in case of unforseen contrails or clouds. This added storage effectively boosts the capacity factor of the system and provides flexibility with added dispatchability.