MAE 119 Final Exam
Winter 2013
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Open Book/Notes/WiFi
All problems of equal value
<u>SOLVE ANY SIX (6) PROBLEMS</u>

1. *Fundamentals of Energy and Power:* A large industrial manufacturer needs to heat up 1000 Tonnes of material by 250 deg K in a time period of 1000 seconds. The material has a specific heat of 1 kJ/kG-deg K. Using your knowledge of the first law of thermodynamics, what heating power must be applied to do the job if the rate of heating is constant? If this heat comes from burning natural gas, what is the mass flow-rate of gas that must be supplied to the heating system? The heat content of natural gas is about 50 MJ/kg.

2. *Human Quality of Life and Energy Access:* If the entire human population of 7 Billion people were to consume energy at the per-capita energy consumption rate of the developed world, estimate the resulting total global energy consumption rate. Roughly how much of a relative increase from current rates of energy consumption does this represent? If this energy is all from burning natural gas, estimate the resulting rate of C injection into the atmosphere. If the effective timescale of CO_2 transfer out of the atmosphere is 100 years, what will be the final steady-state atmopheric CO_2 concentration? State any assumptions.

3. *Climate Change Basics:* Suppose the mass of CO_2 in the Earth's atmosphere is eventually doubled from it's preindustrial value due to the combustion of fossil fuels, but the CO_2 concentration then stops increasing. If the effective timescale of CO_2 transfer out of the atmosphere is 100 years, what is the final rate of CO_2 emissions in this scenario? What will the minimum value of IR transmission coefficient be? When is this minimum value reached? Justify your answers using the 0-D mathematical models developed in class.

4. *What does (and doesn't) scale to meet demand?:* How much electrical power could California conceivably generate from wave energy? Assume that the waves have a height 1 m, a wavelength of 50 m, the coastline is 1000 km long, and we agree that we could cover 10% of that coastline with wave energy conversion systems. Estimate what relative fraction California's peak electrical power demand could be provided by wave power.

5. *Solar thermal:* You have been asked to design a solar thermal power plant that could produce 2GW of electricity *continuously* to replace the San Onofre nuclear power station. Estimate the mirror collecting area and amount of overnight energy storage necessary to accomplish this design goal.

6. *Solar PV:* You have been asked to design a solar PV power plant that could produce 2GW of electricity *continuously* to replace the San Onofre nuclear power station. Estimate the PV panel collecting necessary to accomplish this design goal. If the sun shines for 50% of the time, and the other 50% is night, how much energy must be stored overnight to accomplish this goal.
7. *Wind:* You wish to design a wind farm capable of producing 1 GW of electricity when operated at the maximum design wind-speed of 10 m/sec. Wind turbine manufacturers can provide you with 150m diameter turbines. How many turbines must you purchase and install to meet this design goal? If the turbines can only be placed no closer than 1 km apart, what is the minimum land area required for the wind farm? When the wind-speed is only 3 m/sec, what will be the power output of the wind farm?

3/20/13

MAE 119 W 2013 FINAL EXAM SOLUTION

[signature]

100% P_{heat} is assumed to be applied to the mass in question. Thus 1st law gives

$$P_{heat} = m C_p \frac{dT}{dt}$$

$$\frac{dT}{dt} \simeq \frac{\Delta T}{\Delta t} = \text{const} \quad \Delta T = 250\,°K \quad \Delta t = 10^3\,\text{sec}$$

thus

$$P_{heat} = m C_p \frac{\Delta T}{\Delta t} = 10^6\,KG\; 10^3 \frac{J}{KG\,°K}\; \frac{250\,°K}{10^3\,sec}$$

$= 250$ MW of thermal power

If all heat is from Natural gas Combustion, and heat of combustion is $h_{CH_4} = 50$ MJ/KG

we have

$$P_{heat} = \dot{m}\, h_{CH_4} \Rightarrow \dot{m} = \frac{P_{heat}}{h} = \frac{250\,10^6\,J/sec}{50\,10^6\,J/KG}$$

$\dot{m} = 5$ KG/sec

2. Population, $P = 7 \times 10^9$ individuals

Let p denote per-capita annual energy usage in developed world

From Class Notes we have p in the range
(Electrical Power Consumption) → p

$p \doteq 3-10$ ~~kW-hr~~ $\times 10^3$ kW-hr person/year in developed world.

We can express in in units of Watts by noting 1 year $\doteq$ 8760 hours $\doteq 10^4$ hours and thus

$$p \doteq 300-1000 \text{ Watts/person}$$

Total electrical power consumption would then be

$$P^{elec}_{tot} = P \cdot p = 7\,10^9 \; 300-1000$$

$$\doteq 21\,10^{11} - 7\,10^{12}$$

$$= 2-7 \text{ TW}$$

but this is only electrical power, which is about 1/3 of total power. thus total power (electricity + heat + transport) is $\approx 3\times$ higher,

$$P_{tot} \doteq 6-21 \text{ TW}$$

2. (cont'd)

Current Global Power Demand is $\simeq$ 15 TW
thus there is range of 50% lower to 50% higher
than current demand

From problem #1 above, $h_{CH_4} \simeq 50$ MJ/kG

$$\therefore \quad \dot{m}_{CH_4} = \frac{P_{tot}}{h_{CH_4}} = \frac{6-21 \; 10^{12} \; W}{50 \; 10^6 \; J/kG}$$

$$= \frac{6-21}{50} \cdot 10^6 \; \frac{kG}{sec} \; CH_4$$

Carbon Mass Rate would then be

$$\dot{m}_C = \frac{12}{16} \dot{m}_{CH_4} = \frac{12}{16} \frac{6-21}{50 \; 4 \; 64} 10^6 \simeq \frac{1}{3} \cdot \frac{1}{10} 10^6 \frac{kG}{sec}$$

in 1 yr have $\simeq 3 \, 10^7$ sec

$$\text{then } \Delta \bar{m}_C \Big|_{1yr} = \dot{m}_C \Delta t = \frac{1}{3} \frac{1}{10} 10^6 \, 10^7 \text{ kGs}$$

$\simeq 3 \times 0.3$ or $1 - 0.3 \; 10^{13}$ kG

$\simeq 3 \times 1 - 3 \; 10^{12}$ kG

$= \frac{1-3 \;\; 3-9 \text{ GTonnes}}{\text{yr}}$

2. (cont'd)

For Steady State C Balance We had

$$\delta M_c = Q_{c_0} \tau_{net}$$

if $Q_{co} = 3-9 \frac{\text{GTonnes}}{\text{yr}}$ $\tau_{net} = 100 \text{yrs}$

[N.B. Currently $Q_{co} \simeq 8$ GTonnes/year]

$\delta M_c \simeq 300 - 900$ GTonnes

original carbon mass in Atmosphere is about

$M_c \simeq 790$ GTonnes (w/ CO_2 @ 350 ppm)

then $M_c \Rightarrow M_c + \delta M_c \simeq 1100 - 1700$ GTonnes

This will give CO_2 concentration in range.

$$\frac{1100-1700}{790} \cdot 380 \text{ ppm} \simeq \underline{550 \rightarrow 800 \text{ ppm}}$$

(3.) $M_c \rightarrow 2M_c$

$M_c \hat{=} 600$ GTonnes (pre-industrial)

$\therefore \delta M_c = 2M_c - M_c \hat{=} 600$ GTonnes

for steady state C-balance we know

$$Q_c = \frac{\delta M_c}{\tau_{at}} = \frac{600 \text{ GTonnes}}{100 \text{ yr}} = 6 \text{ GTonnes/yr}$$

From our homework problems we know if $M_{CO_2} \rightarrow 2M_{CO_2}$

then $\beta_{IR} \rightarrow \beta_{IR}^2$

initial $\beta_{IR} \hat{=} 0.05 \rightarrow$ final $\beta_{IR} \hat{=} (5 \cdot 10^{-2})^2 = 25 \cdot 10^{-4}$
$= 0.0025$

β_{IR} minimum reached when δM_c is doubled

4 Wave Power

$h = 1m \quad \lambda = 50m \qquad L_{coast} = 10\% \cdot 10^3 km = 10^2 km$

$$P = \frac{\rho g^{3/2} \lambda^{1/2} a^2}{4\sqrt{2\pi}}$$

$$\simeq \frac{10^3 \; 10^{3/2} \; \sqrt{50} \; 1}{4\sqrt{2\pi}}$$

$4\sqrt{2\pi} \simeq 2.5 \to \simeq 10$

$$\simeq \frac{10^2 \; 10^{3/2} \; 7 \; 1}{10} \simeq 7 \, kW/m$$

$\therefore P_{tot} = 7 \, 10^3 \, W/m \cdot 10^5 m = 7 \times 10^8 W = 0.7 \, GW$

total Ca Power Demand Ranges from $\simeq 20$ GW (winter night time) to $\simeq 40$ GW (peak in summer)

thus this represents $\frac{0.7}{20-40} \simeq 1-3\%$ of total Ca demand

5. Solar Thermal

$P_{tot} = 2\,GW$

Q! Minim Area, A, & Energy Storage, E_{st}?

E_{st} is just $P_{tot} \cdot \Delta t$, $\Delta t = \frac{1}{2}$ day = 12 hours

$\therefore E_{ST} = 2\,10^9 \cdot 12 \cdot 3600 = 2 \cdot 48\,10^{11}$

$\simeq 10^{13}\,J$

$= 10^4\,GJ$

Collecting A?

I_{ave}, Average Solar Intensity in Day Time $\simeq 300\,W/m^2$

Power Balance gives

$$P = \eta_{th} A\, I_{ave}$$

$\eta_{th} \simeq 0.3$ for typ heat cycle

thus $A = \dfrac{P}{\eta I_{ave}}$

5. (cont'd)

but we must produce 4 GW in daytime, & store 1/2 of it (if overall storage efficiency is 100%). Thus

$$A = \frac{4\ 10^9\ W}{0.4 \cdot 300} \qquad \frac{10^{10}}{300} \simeq 3\ 10^7\ m^2$$

$\simeq 30\, km^2$

(6.) Same Storage Requirement as in #5,

$E_{ST} = 10^4\ GJ$

but $\eta \simeq 10\%$ for PV

thus Area is 4 (x) larger

i.e. $120\ km^2$

7. **Wind**

$V = 10\ m/sec \qquad d = 150m$

$P = N_{turbine} \cdot \eta \frac{1}{2}\rho V^3 \cdot \frac{\pi d^2}{4}$

$\eta \le \eta_{max} \simeq 59\%$ take $\eta \simeq 40\%$

$$N_{turb} = \frac{P}{\eta \frac{1}{2}\rho V^3 \cdot \frac{\pi}{4}(150)^2}$$

$$= \frac{10^{10}\ \cancel{10^9}\ W}{0.4\ \frac{1}{2}\ 1 \cdot 10^3\ \frac{3}{4}(1.5)^2 10^4}$$

($(1.5)^2 \simeq 2$)

$= 0.3\ 10^3$

$\simeq 300$ Turbines !

if min separation is $l = 1km$, land area/turbine

then is $l^2 = 1km^2/turbine \rightarrow$ <u>$300\ km^2$ Needed</u>

7 (cont'd)

if $V \rightarrow 3^{m}/sec$ this is a drop of

$$\left(\frac{V}{3} \right)^3 \quad \frac{10^3}{3^3} = \frac{1000}{27} = 37 \text{ (x) drop}$$

Power Production will then be <u>27 MW</u>