CE 11 Engineered Systems & Sustainability: Midterm 2			Total Score ↓
Date: 11.02.2021,	Total questions: **8**	Total points: **111**	
Name:		Time: 1 hr 10 min	

Question:	1	2	3	4	5	6	7	8	Total
Points:	15	15	5	8	3	30	20	15	111
Score:									

Instructions:

1. **Show your work. When needed, use words to explain your reasoning.**
2. **Use a reasonable number of sig figs in your answers (2-3 will suffice).**
3. **The exam is open-book, open-notes. Important constants and unit conversions are provided on the last page of the exam.**
4. **No use of the internet or communication with other people is allowed while taking the exam.**
5. **Exam will end at 12:20pm to allow for time to upload exams to gradescope. Any exams not uploaded by 12:30pm will receive a zero.**

15 1. **Heat Pumps and Batteries:** Suppose you have an air source heat pump that requires 5 kW when it is running on chilly winter day. You also have a rooftop solar PV system that generates 250 Watts of electricity during 10 hours of daylight (and none at night). Your home (excluding the heat pump) uses 700 kWh per month (assume 1 month = 30 days) of electricity.

(a) How much battery storage capacity (in kWh) would you need to ensure that, during a blackout, you could run your heat pump for a total of 10 hours in the winter? Assume a round trip efficiency of 90%. The battery can be charged with your rooftop system and/or grid electricity. (5 points)

Solution:
All we need to do is multiply the total hours (10) by the power required by the heat pump. Then divide by round trip efficiency:

$$\text{Battery capacity} = \frac{(5\text{ kW})(10\text{ h})}{0.9} = 56\text{ kWh}$$

(b) How much of your monthly electricity use can you supply with your solar PV system over the course of one winter month, assuming your heat pump runs for a total of 300 hours during the month? Report your answer as a percentage. (10 points)

Solution:
Total electricity demand for our home in 1 month:

$$\text{Power demand} = 700 \text{ kWh/month} + (5 \text{ kW})(300 \text{ h/month}) = 2200 \text{ kWh/month}$$

Our PV panels generate:

$$\text{Power generated} = (250 \times 10^{-3} \text{ kW})(10 \text{ h/day})(30 \text{ days/month}) = 75 \text{ kWh/month}$$

$$\text{Fraction supplied by rooftop solar} = \frac{75 \text{ kWh/month}}{2200 \text{ kWh/month}} = 3.4\%$$

$\boxed{15}$ 2. **Emission Footprint of Concrete:** You are asked to find the CO_2 footprint of producing one cubic meter of concrete. As a rule of thumb, you can calculate the process (non-combustion) emissions from making cement and then double them to estimate the total emissions (including fuel combustion, mining, etc.). Use a density of 2,400 kg per cubic meter of concrete. Your concrete mix is 10% cement and the cement is 100% CaO. Assume emissions for all other components of the concrete are negligible. Report your results in kg CO_2 per m^3 concrete.

Solution: We can start by estimating the mass of cement in the mixture.

$$m_{CaO} = (1 \text{ m}^3)(2400 \text{ kg/m}^3)(0.10) = 240 \text{ kg}$$

We also know that making CaO involves driving CO_2 off of $CaCO_3$. So let's find the moles of CaO in our mixture.

$$\text{Moles CaO} = \frac{(240 \text{ kg})(10^3 \text{ g/kg})}{(40 \text{ g/mol} + 16 \text{ g/mol})} = 4286 \text{ mol of CaO}$$

We get one mole of CO_2 emissions per mole of CaO produced. So, our process (non-combustion) emissions are:

$$\text{CO}_2 \text{ emissions} = 4286 \text{ mol}(12 \text{ g/mol} + 2(16 \text{ g/mol})) = 188540\text{g CO}_2$$

But we need to double this to get the approximate total emissions (including combustion and mining):

$$\text{Total CO}_2 = 2(188540 \text{ g CO}_2) = 377 \text{ kg CO}_2/\text{m}^3 \text{ concrete}$$

$\boxed{5}$ 3. **Types of Vehicle Engines:** Which of the following is true about compression-ignited (CI) engines? Select all that apply.

a. Gasoline is an appropriate fuel to use
b. Diesel is an appropriate fuel to use
c. More efficient than spark-ignited (SI) engines
d. Less efficient than SI engines
e. Higher PM emissions than SI engines
f. Lower PM emissions than SI engines
g. Less durable in heavy duty cycles than SI engines
h. More durable in heavy duty cycles than SI engines
i. Easier to achieve complete air-fuel mixing than SI engines
j. More difficult to achieve complete air-fuel mixing than SI engines

Solution: The correct answers are b, c, e, h, j

$\boxed{8}$ 4. **Pairing Similar Technologies:** Select pairs of technologies that are very similar in function, but run in reverse relative to one another.

a. Electrolyzers and Li-ion Batteries
b. Electrolyzers and Hydrogen Fuel Cells
c. Li-ion Batteries and Hydrogen Fuel Cells
d. LEDs and Solar PV Cells
e. Li-ion Batteries and Lead-Acid Batteries
f. UV Disinfection Systems and CFLs
g. LEDs and CFLs
h. Electric Motors and Electric Generators

Solution: The correct answers are b, d, h

$\boxed{3}$ 5. **Lightbulbs:** Mercury vapor is used in some light bulbs to (select only one):

a. Emit visible light
b. Emit UV radiation
c. Generate electricity
d. Emit infrared radiation
e. Emit blackbody radiation

Solution: The correct answer is b.

30 6. **Fuel Needs for Delivery Vehicles:** You own a fleet of delivery trucks driving around the Bay Area. You must calculate the fuel needed for a one-way trip on the route for each truck in MJ (LHV) of diesel. Assume the diesel engines are 35% efficient, the fully loaded trucks weigh 10,000 kg each, frontal area of each truck is 3 m^2, $C_R = 0.005$, and $C_D = 0.5$. You may ignore transmission/drivetrain losses. Use a density of air = 1.225 kg/m^3 and g = 9.8 m/s^2.

(a) Truck A takes a route with an average incline of 1 degree at a constant speed of 40 km/hour. The route is 30 km long. Find the total diesel fuel used (in MJ, LHV) on the trip. (15 points)

Solution: We know that we will need to start by calculating the resistive force (F_{res}). We can zero out the acceleration term because we are traveling at a constant speed. Now we have:

$$\mathrm{F}_{res} = mg\sin\theta + C_R mg + C_D A_F \frac{\rho_A v^2}{2}$$

$$\mathrm{F}_{incline} = mg\sin\theta = (10,000 \text{ kg})(9.8 \text{ m/s}^2)(\sin 1^\circ) = 1710 \text{ N}$$

$$\mathrm{F}_{rolling} = C_R mg = (0.005)(10,000 \text{ kg})(9.8 \text{ m/s}^2) = 490 \text{ N}$$

$$\mathrm{F}_{drag} = C_D A_F \frac{\rho_A v^2}{2} = (0.5)(3 \text{ m}^2)\frac{(1.225 \text{ kg/m}^3)(\frac{1 \text{ h}}{3600 \text{ s}}(40 \times 10^3 \text{ m/h}))^2}{2} = 113 \text{ N}$$

To calculate the total force to be overcome, we also need to

$$F_{res} = 1710 \text{ N} + 490 \text{ N} + 113 \text{ N} = 2310 \text{ N}$$

Energy is equal to force applied over a distance:

$$E = Fd = (2310 \text{ N})(30 \times 10^3 \text{ m}) = 6.93 \times 10^7 \text{ J} = 69.3 \text{ MJ}$$

Then we need to calculate total fuel input using the engine efficiency:

$$E_{diesel} = \frac{69.3 \text{ MJ}}{0.35} = 198 \text{ MJ of diesel}$$

(b) Truck B will take a flat route with a strong headwind blowing in precisely the opposite direction that it would be traveling. How much *additional* drag force would the truck be subject to as a result of a 20 km/hour wind? *Hint:* drag calculations typically use a vehicle velocity relative to still air. If the truck is traveling through air that is blowing in the opposing direction, you must calculate the effective velocity, which will be *higher*. Report your answer in Newtons. (15 points)

Solution: The effective velocity of the vehicle, assuming the wind is blowing in the opposing direction at 20 km/h is:

$$v_{eff} = 20 \text{ km/h} + 40 \text{ km/h} = 60 \text{ km/h}$$

$$\text{F}_{drag-wind} = C_D A_F \frac{\rho_A v^2}{2} = (0.5)(3 \text{ m}^2)\frac{(1.225 \text{ kg/m}^3)(\frac{1 \text{ h}}{3600 \text{ s}}(60 \times 10^3 \text{ m/h}))^2}{2} = 255 \text{ N}$$

From our previous answer, we calculated:

$$\text{F}_{drag-still} = C_D A_F \frac{\rho_A v^2}{2} = (0.5)(3 \text{ m}^2)\frac{(1.225 \text{ kg/m}^3)(\frac{1 \text{ h}}{3600 \text{ s}}(40 \times 10^3 \text{ m/h}))^2}{2} = 113 \text{ N}$$

So the additional drag force is:

$$\text{F}_{drag-extra} = 255 \text{ N} - 113 \text{ N} = 142 \text{ N}$$

(c) **Extra credit question (10 pts):** How fast would the wind need to be blowing for the additional drag force (relative to still air) to be equivalent to the force needed to overcome the incline (1 degree, as described in part a)? Report your answer in km/h.

Solution:
We know that the force needed to overcome the incline is:

$$\text{F}_{incline} = mg\sin\theta = (10,000 \text{ kg})(9.8 \text{ m/s}^2)(\sin 1^\circ) = 1710 \text{ N}$$

From our previous answer, we calculated:

$$\text{F}_{drag-still} = C_D A_F \frac{\rho_A v^2}{2} = (0.5)(3 \text{ m}^2)\frac{(1.225 \text{ kg/m}^3)(\frac{1 \text{ h}}{3600 \text{ s}}(40 \times 10^3 \text{ m/h}))^2}{2} = 113 \text{ N}$$

So we need for the wind speed to be high enough to produce a total drag of:

$$F_{extra} = 1710 \text{ N} + 113 \text{ N} = 1823 \text{ N}$$

This accounts for the 1710 N of "extra" drag that must be set equal to the incline term and the 113 N of drag that the vehicle would experience if the air were still.

$$1823 \text{ N} = (0.5)(3 \text{ m}^2)\frac{(1.225 \text{ kg/m}^3)(\frac{1 \text{ h}}{3600 \text{ s}}((40 + v_w)10^3 \frac{\text{m}}{\text{h}}))^2}{2}$$

$$v_w = 120 \text{ km/h}$$

20 7. **Indoor Air Quality:** You just made a romantic meal to impress your new significant other. You light ten candles which each emit $PM_{2.5}$ at a rate of 0.03 mg/candle/hour, turn on your air purifier, and sit down to eat. Your air purifier has a flow rate of 300 cubic meters per hour but a $PM_{2.5}$ removal efficiency of only 50%. Assume no other ventilation for your apartment. Your house is 100 square meters, with 3 meter ceilings. *Hint:* Treat the air purifier as you would a ventilation system.

(a) What is the steady-state concentration of $PM_{2.5}$, assuming you continue burning the candles? Report your answer in mg/m^3. (10 points)

Solution: We have been reminded that we should treat the air purifier as a "ventilation" system. Let's start with the basic equation:

$$C_{inbound}Q + E = C_{outbound}Q$$

We know that there is a relationship between the "outbound" concentration that is processed by the air purifier and the "inbound" concentration that the air purifier delivers. This is because we were given a 90% efficiency.

$$(1 - 0.5)C_{ss}Q + E = C_{ss}Q$$

$$C_{ss} = \frac{E}{Q(1 - 0.5)}$$

$$C_{ss} = \frac{(0.03 \times 10)\ \text{mg/h}}{(0.5 \times 300)\ \text{m}^3/\text{h}} = 0.002\ \text{mg/m}^3$$

(b) What is the steady-state concentration of $PM_{2.5}$, assuming you continue burning the candles, if your air purifier has a higher removal efficiency (99%)? Report your answer in mg/m^3. (10 points)

Solution: Let's start with the basic equation:

$$C_{inbound}Q + E = C_{outbound}Q$$

We know that there is a relationship between the "outbound" concentration that is processed by the air purifier and the "inbound" concentration that the air purifier delivers. This is because we were given a 90% efficiency.

$$(1 - 0.99)C_{ss}Q + E = C_{ss}Q$$

$$C_{ss} = \frac{E}{Q(1 - 0.01)}$$

$$C_{ss} = \frac{(0.03 \times 10)\ \text{mg/h}}{(0.99 \times 300)\ \text{m}^3/\text{h}} = 0.001\ \text{mg/m}^3$$

15 8. **CO_2 Emissions from People vs. Furnaces:** You are curious approximately how many people it would take to emit the same amount of CO_2 as your gas furnace. Assume 0.01 liters CO_2 emitted per person per second at T = 20°C and P = 1 atm. Your gas furnace uses 85 MJ (LHV) of natural gas per hour. You may approximate natural gas as 100% methane.

Solution: We can convert the volume of CO_2 emitted per person to mass of CO_2 per hour:

$$PV = \eta RT$$

$$(1 \text{ atm})(0.01 \text{ L}) = \eta(0.0821\frac{\text{L atm}}{\text{mol K}})(293.15 \text{ K})$$

$$\eta = 0.000415 \text{ moles CO}_2 \text{ per person per second}$$

$$\eta = 1.5 \text{ moles CO}_2 \text{ per person per hour}$$

Now we can find out how many moles of natural gas are emitted per hour by the furnace:

$$\eta_{gas} = (85 \text{ MJ})(\frac{1}{47.1 \text{ MJ/kg}})(\frac{1}{16 \times 10^{-3}\text{kg/mol}}) = 113 \text{ mol CH}_4\text{/h}$$

Since we know that one mole of natural gas produces one mole of CO_2, the number of moles of gas consumed is equal to the number of moles of CO_2 produced.

$$\eta_{CO2} = 113 \text{ mol CO}_2\text{/h}$$

$$\text{Number of people} = \frac{113 \text{ mol CO}_2\text{/h}}{1.5 \text{ mol CO}_2\text{/person-h}} = 75 \text{ people}$$

Potentially useful constants and conversion factors:

Lower Heating Value of Natural Gas = 47.1 MJ/kg
R = 0.0821 $\frac{\text{L atm}}{\text{mol K}}$
Atomic masses (in g/mol) are:
C = 12.011
H = 1.008
O = 15.999
N = 14.007
Ca = 40.08
Useful unit conversion factors:
1 ton = 0.907185 metric tons
Remember: ton = short ton
Remember: tonne = metric ton
Remember: 1 m^3 = 1000 liters
Temperature in Kelvin = $°C + 273.15$