PHYS-310 Heat Transfer, Efficiency, Electricity, Problem Set #3:

1) We learned this week about carbon intensity: 15, 20, 25, (MJ/g_{carbon}) for NG, Petroleum, and coal. We also learned about efficiency of energy conversion. On the street, you're not going to be able to use these values for many relevant calculations because it takes too much time and the people you're talking to will get bored. I want you to become comfortable using the following estimations:
   a) Burning a gallon of gas emits about 10 kg of CO_2 into the atmosphere. A liter of water is 1 kg, and is slightly more than one quarter. Hence a gallon of water is just under 4 kg.. but gasoline is about ¾ the density of water, so a gallon of gasoline is about 3 kg. Gasoline is a long alkane chain, which burns to CO_2, so you're essentially changing a methyl group, CH_3 of mass 14 AMU to CO_2 mass 44. Thus, the mass of CO_2 emitted from burning 1 gallon of gasoline should be: 3 kg * 44/14 = 9.4 kg… close to 10 kg. However, this is an underestimate because the extraction and refinement of gasoline has a considerable carbon footprint. Thus you should really add between 5% and 40% depending on whether you use sweet, light crude oil or tar sands oil, respectively. More on this later.
   b) Using electricity emits about 1 $kg_{(CO2)}/kWh$ for coal, and a third as much for NGCC. Please prove that these estimates are pretty good.
   I think that the video set this up pretty well… let's see we start with NG carbon intensity and then multiply by "1" several times:

$$I_{coal} = \frac{25\ g_{(C)}}{MJ} \cdot \frac{44\ g_{(CO2)}}{12\ g_{(C)}} \cdot \frac{3.6\ MJ}{kWh_{th}} \cdot \frac{kWh_{th}}{\frac{1}{3}kWh_{(e)}} \sim 1\text{ kg}$$

$$I_{NGCC} = \frac{15\ g_{(C)}}{MJ} \cdot \frac{44\ g_{(CO2)}}{12\ g_{(C)}} \cdot \frac{3.6\ MJ}{kWh_{th}} \cdot \frac{kWh_{th}}{\frac{2}{3}kWh_{(e)}} \sim 1/3\text{ kg}$$

   Or, between the two, we recognize that the combined cycle has about twice the efficiency of coal's SC Rankine, and NG has 3/5 of coal's thermal carbon intensity, so between the two:

$$I_{NGCC} = I_{coal}\frac{15}{25} \cdot \frac{\frac{1}{3}}{\frac{2}{3}} = I_{coal}\frac{3}{10} \sim \frac{I_{coal}}{3}$$

2) Using the above estimations like you will on the street talking with folks about energy, please estimate:
   a) Your driving-related CO_2 emissions for the road trip to SF and back, in your friend's F-150.
   b) The extra CO_2 emissions for your mistake for leaving the 100 W bulb for the 4 days you were gone (refer to first assessment).

(2) a) ~250 miles, ~20 mpg → ~12 gallons
×2 = 24 gallons × $\frac{10\text{ kg } CO_2}{\text{gallon}}$ = 240 kg CO_2

b) 10 kWh → ~~10 kg CO_2~~ Nope
⇒ you live in Lovely Ca where the marginal Electricity is Produced by NGCC. ans: 3 kg

(3) a) a: increase

3) Running a Natural Gas Combined Cycle

Let's say you're in charge of a NGCC for Southern LA. You control the flow of NG to the Brayton Cycle turbine and you can monitor the (a) electrical current, (b) the torque (how hard the turbine has to push the generator to keep it going), (c) the spinning frequency of the turbine, and the (d) output voltage. At 5:30 PM, everyone gets home and turns on their electrical appliances – especially air conditioners..

a) When this happens, what do you notice about measurements in (a) – (d) above? As you noticed when you turned the hand generators and the electrical load increases (a) the current goes up, (b) increasing the torque because of the increased current pushing backwards on the rotating coils. If you don't increase the fuel into the generator, (c) the rate of turning will slow, lowering the frequency, and (d) the output voltage decreases because of the reduction of the rate of change of magnetic flux through the rotating coils. BROWN OUT!

b) How do you respond with the flow of NG to the Brayton Cycle Turbine? What does this do? You slam in some additional fuel. This increases the power in and the torque you provide to the generator, reestablishing the speed and voltage at a higher current.! All is well, you have responded so that your generation facility "met load"!

c) After your action, how do measurements (a) – (b) compare to how they were before everyone came home? Explained above. The spinning frequency is now the same as it was before, and with that the voltage is also the same. However, now there is a greater load, so there is more current going out to the homes, there is more current going through the generator. This greater current puts more torque on the generator, resisting the motion… hence the need for the extra amount of NG injection.

4) Transmission

Why do we need Transformers?

a) Please explain how transformers reduce transmission losses, and include consideration of High Voltage, AC/DC, and resistive heat losses in a wire. Using the transmission video please be able to explain each step in this answer: power loss is proportional to I^2 and power transmitted = IV, so we want to transmit power at very high voltages and lower current. We need to raise and lower voltages, and a transformer does this well with AC because it's a *changing* magnetic field that induces voltage in a coil.

Let's say you're on a task force to address the power loss to Bakersfield from Diablo. The power lines were made a long time ago and since then, Bakersfield's demand for electricity during peak hours has doubled.

b) If the power use has doubled, by what factor will the amount of heat loss in the cables increase? Doubling power means that you will draw twice the current. Thus the power loss (I^2R) will increase by a factor of 4.

c) On extra hot days, there will be an extra thermal load on the wires because of the heat. What problem occurs when the wires heat up? How would this change the transmission losses? Two things happen… both are bad: the wire expands, so the wires get longer, and the resistivity of the metal wire increases. Both cause increase in the resistive losses, which increases the temperature of the wires, further exacerbating the losses. Additionally, the expansion causes the wires to sag more, bringing the high voltage wires closer to the ground.

d) Long wires have considerable inductance and capacitance. How does this affect heating loses? This causes reactive power… or sloshing of current around in the wires not powering the load. This "imaginary" load is still real current, and has real power loss associated with it.

e) You find a way to increase the transmission voltage by a factor of 5. By what factor will this change the transmission losses? You can then reduce transmission current by 5, and thus reduce power loss (I^2R) by a factor of 25.

Please read more about what transmission lines are made of at
http://en.wikipedia.org/wiki/Electric_power_transmission

5) A few years ago, the fastest, most expensive production car in the world was the Bugatti Veyron. Here's the video: http://www.youtube.com/watch?v=LO0PgyPWE3o Then you can read about it in Wikipedia, or any place else you can find that interests you. You can skip down to the statistics if you like. At its maximum speed we can presume that it puts out its maximum power, find the efficiency:

a) Look up the maximum power that the engine puts out (please give answer in HP and Watts). What form of energy is this?
b) How does this power compare to a regular car? What is the max power (in HP and Watts) of your car?
c) What is the rate of consumption of petroleum at maximum power output?
d) What is the (chemical potential) energy consumption rate? Please put answer in Watts.
e) What is the efficiency of the gasoline engine at maximum power?
f) What rate (in Watts) does the engine dissipate heat? How many 100W light bulbs would this be? Why would this car need 10 radiators?
g) How much CO_2 does the car put into the atmosphere in the 12 minutes it can drive at top speed before running out of gas? Please put answers in kg of CO_2.

Demographics: You may not be able to find the exact information you are looking for below. Don't sweat it… Please innovate an answer that makes sense to you.

h) If a group of people in the following countries wanted to buy a Veyron, and saved half of their salary for a year, how many people would they have to get together?: USA, Guatemala, DR Congo.

1. a) 1200 hp, 883 kW (Super-sport)

Mostly mechanical energy

b) My car: 2000 Nissan Maxima

222 hp, 166 kW

$\frac{1200\text{ hp}}{222\text{ hp}} = 540\%$

c) 1.4 gal/min

d) $\left(1.4 \frac{\text{gal}}{\text{min}}\right)\left(\frac{33.41\text{ kWh}}{1\text{ gal}}\right)\left(\frac{3600\text{ s}}{1\text{ h}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right) = 2806\text{ kW}$

$= 2.81\text{E}6\text{ W}$

e) $\frac{883\text{ kW}}{2806\text{ kW}} = 31\%$ efficiency @ max engine power

f) $2806\text{ kW} - 883\text{ kW} = 1923\text{ kW} = 1.923\text{E}6\text{ W}$

$1.923\text{E}6\text{ W} \cdot \left(\frac{1\text{ bulb}}{100\text{ W}}\right) = 1.923\text{E}4$ bulbs

This is a lot of heat to dissipate!

g) $CO_2 = 12 + 2(16) = 44$ amu

$C = 12$ amu

$\frac{CO_2}{C} = \frac{44}{12} = 3\frac{2}{3}$

$\left(1.4 \frac{\text{gal}}{\text{min}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right)\left(\frac{6.2\text{ lbs gas}}{1\text{ gal}}\right)\left(\frac{3\text{ lbs } CO_2}{1\text{ lb gas}}\right)\left(\frac{1\text{ kg}}{2.2\text{ lbs}}\right)$

$= 0.197 \frac{\text{kg } CO_2}{\text{s}}$ → $\left(\frac{0.197\text{ kg } CO_2}{1\text{ s}}\right)\left(\frac{12\text{ amu C}}{44\text{ amu } CO_2}\right)$

$= 0.0537 \frac{\text{kg C}}{\text{s}}$

$\left(0.197 \frac{\text{kg } CO_2}{\text{s}}\right)\left(\frac{720\text{ sec}}{12\text{ min}}\right)$

$= 142 \frac{\text{kg } CO_2}{12\text{ min}}$ → $\left(\frac{142\text{ kg } CO_2}{12\text{ min}}\right)\left(\frac{12\text{ amu C}}{44\text{ amu } CO_2}\right)$

$= 39 \frac{\text{kg C}}{12\text{ min}}$

In e) above, you calculated the *first law efficiency*, the *actual* efficiency: energy in (gasoline) vs physical work out. Please look up the engine temperature and estimate the maximum possible efficiency given these temperature extremes (Carnot Efficiency). I wasn't able to find it for a Veyron. You could look it up for the general Otto Cycle.) from this website: https://www.ohio.edu/mechanical/thermo/Intro/Chapt.1_6/Chapter3d.html, I find a combustion temperature of 1800 K. If the outside air is 300 K, the Carnot efficiency is $(T_H - T_C)/T_H \sim 5/6 \sim 83\%$

i) What portion of this maximum theoretical efficiency did you achieve? This portion is called the "second law efficiency" because the Carnot Efficiency comes from adhering the second law of thermal physics.
   a) Even a perfect, frictionless Otto Cycle doesn't achieve the Carnot Efficiency. Please see: http://web.mit.edu/16.unified/www/SPRING/propulsion/notes/node25.html and investigate the efficiency of the Otto Cycle – what is the key factor? Why are diesel engines a little more efficient than the Otto Cycle? Well, there are a few reasons we will touch on later, but please find one of them now.
   b) What is the second law efficiency for a perfect Otto Cycle (achieving perfect Otto Cycle efficiency for the temperatures and compression ratios you find)?
   Otto cycle: automobiles The Otto cycle is the name for the cycle used in spark-ignition internal combustion engines such as gasoline and hydrogen fuelled automobile engines. Its theoretical efficiency depends on the compression ratio *r* of the engine and the specific heat ratio *γ* of the gas in the combustion chamber

$$\eta_{\mathrm{th}} = 1 - \frac{1}{r^{\gamma-1}}$$

   Thus, the efficiency increases with the compression ratio. However the compression ratio of Otto cycle engines is limited by the need to prevent the uncontrolled combustion known as knocking. Modern engines have compression ratios in the range 8 to 11, resulting in ideal cycle efficiencies of 56% to 61%.

   c) What portion of the maximum possible Otto Cycle efficiency does your Veyron actually achieve? We can see that frictional losses claim about half of our efficiency, reducing efficiency from 60% to our actual efficiency of about 30%.