Solutions lecture 1

1.1 Joule's test setup

a) A load of $50kg$ is displaced over a distance of $20m$. All the mechanical energy is converted into thermal energy, which increases the temperature of $5.0L$ water. First, the energy gained by this displacement of the load can be calculated:

$$\begin{aligned}\Delta E_{mech} &= F \cdot \Delta h = m \cdot g \cdot \Delta h \\ &= 50 \cdot 9.81 \cdot 20 \\ &= 9810J\end{aligned} \tag{1.1}$$

All the mechanical energy is converted into thermal energy:

$$\Delta E_{mech} = Q = m_{water} \cdot c_v \cdot \Delta T \tag{1.2}$$

From this, the temperature increase can be calculated, as the mass of the water ($\approx 5.0kg$) and the specific heat capacity ($= 4186J \cdot kg^{-1} \cdot K^{-1}$) are known:

$$\Delta T = \frac{\Delta E_{mech}}{m_{water} \cdot c_p} = \frac{9810}{5.0 \cdot 4186} = 0.47°C \tag{1.3}$$

b) First, some data from diesel has to be found online. The values that should be found online are the density of diesel and the price per liter: $0.85\ \mathrm{kg\,L^{-1}}$ and €1.21 respectively.

With a budget of €1, the amount of liters diesel you can buy is equal to:

$$V_{diesel} = \frac{1}{1.21} = 0.8264L \tag{1.4}$$

The amount of energy in this diesel volume is equal to:

$$E_{diesel} = V_{diesel} \cdot \rho_{diesel} \cdot \hat{E}_{diesel} = 0.8264 \cdot 0.85 \cdot 45.5 = 31.96\mathrm{MJ} \tag{1.5}$$

In the equation, $\hat{E}$ is the given specific calorific value of (or chemical energy in) diesel. Now, we can calculate the number of times the load can be lifted:

$$N_{lifts} = \frac{31.96 \cdot 10^6}{9.810 \cdot 10^3} = 3258\ times \tag{1.6}$$

So, the load can be lifted 3258 times.

c) First, the power is converted to W ($1hp = 746W$):

$$P = 2.5 \cdot 746 = 1865W \tag{1.7}$$

Now, the time it takes to lift this load using the maximum amount of power can be calculated:

$$t = \frac{\Delta E_{mech}}{P} = \frac{9810}{1865} = 5.26s \tag{1.8}$$

It takes longer than 5 seconds to lift the load, which means that the engine is not suitable.

d) The energy in a chocolate bar can be found online, which is equal to approximately $530kcal$ per $100g$. One kcal is equal to $4184J$, so the total energy in 900 g chocolate can be calculated:

$$E_{chocolate} = m_{choc} \cdot \hat{E}_{choc} = 0.9 \cdot 5300 \cdot 4184 = 19.96MJ \tag{1.9}$$

The energy required per lift was already calculated: $9810J$. The number of days that the engine can run on chocolate then becomes:

$$t = \frac{19.96 \cdot 10^6}{9810 \cdot 120} = 16.96 \; days \tag{1.10}$$

The engine can run for almost 17 days on the chocolate.

e) The electricity costs are given: €0.17 per kWh. One kWh is equal to $3.6MJ$. Now, we can calculate how much energy we can get with a budget of €1:

$$E = \frac{1}{0.17} \cdot 3.6 = 21.18MJ \tag{1.11}$$

Comparing this answer to the answer obtained in question 1b, we see that the amount of energy from diesel is higher with the same budget. This means that the diesel engine is the cheaper option.

1.2 Transport by car and bus

a) In both cases the distance to be travelled is $2 \cdot 75 = 150$ km. The car has a consumption of 7.2 liters per 100 kilometers, so the fuel used per car is

$$150\text{km} \cdot \frac{7.2\text{L}}{100\text{km}} = 10.8\text{L}$$

Thus, for six cars a total of $6 \cdot 10.8 = 64.8$L of fuel is needed.

The consumption of the bus is 35 liters per 100 kilometers, so

$$150\text{km} \cdot \frac{35\text{L}}{100\text{km}} = 52.5\text{L}$$

So for the bus, 52.5 L of fuel is needed.

b) The total amount of energy E_{total} is the mass of the fuel m multiplied by the caloric value (chemical energy released when combusted) of the fuel. The mass of the fuel needed is the needed amount of liters V multiplied by the specific mass m_{spec} of the fuel:

$$E_{total} = m \cdot E = m_{spec} \cdot V \cdot E$$

For the car, the above equation becomes:

$$E_{total,car} = 64.8\text{L} \cdot 0.70\text{kg}\,\text{L}^{-1} \cdot 42\text{MJ}\,\text{kg}^{-1} = 1905\text{MJ}$$

Per person this comes down to 79.4 MJ. For the bus:

$$E_{total,bus} = 52.5\text{L} \cdot 0.85\text{kg}\,\text{L}^{-1} \cdot 43\text{MJ}\,\text{kg}^{-1} = 1919\text{MJ}$$

Per person this comes down to 79.9 MJ.

c) For the car, the fuel costs are

$$\text{Price fuel car} = 64.8 \cdot €1.49 = €96.55$$

For the bus, the fuel costs are:

$$\text{Price fuel bus} = 52.5 \cdot €1.14 = €59.85$$

The total costs for the bus is €59.85+ €200=€259.85. This means that the going by car is the cheapest option.

d) The minimum amount of kilometers can be calculated by equating the costs of the cars per kilometer to the costs of the bus per kilometer:

$$\text{Costs car} = \text{Costs bus}$$

In order to do so, we need to calculate the costs per kilometer. For the car:

$$\text{Costs per kilometer car} = \frac{96.55}{150} = €0.64$$

And for the bus:

$$\text{Costs per kilometer bus} = \frac{59.85}{150} = €0.40$$

Equating the costs of the car to the costs of the bus:

$$€0.64 \cdot x = €0.40 \cdot x + €200$$

where x is the distance in kilometers. Solving this gives a distance of 833 km.

e) In the lecture sheets, you can find that one hour of cycling at 15 km/h costs a person 1600 kJ of energy. The time needed to travel will be 150 km/15 km/h=10 hours. The amount of energy needed per person is thus $10\text{h} \cdot 1600\text{kJ}\,\text{h}^{-1} = 16\text{MJ}$. Note that this is much less than by car or bus!

The lecture slides also give the definition of the Calvé: 1 Calvé = 200 kcal= $200 \cdot 4.184$kJ = 0.8368MJ. For the 150 kilometers of cycling, all students needs

$$\frac{16\text{MJ}}{0.8368\text{MJ}\text{Calvé}^{-1}} = 19,1\text{Calvé}$$

f) Which travel option is the most efficient, depends on the energy conversions included in the analysis. While cars use less energy than the bus when transporting 24 people, the production of bus fuel might be more efficient than the production of car fuel. The same principle applies to cycling; the energy used while cycling may be five times less than using cars, but to produce, distribute and digest the sandwiches with peanut butter also costs a considerable amount of energy. Cycling is the most efficient, using only the energy conversions in the assignment, followed by cars and then the bus. In reality, factors including the environment, travel time, and costs play an essential role.

1.3 Boiling water - Hand in

a) In the first lecture material, the definition of one kilocalory is given: one kilocalory is the amount of energy needed to heat 1 kg of water 1 °C; 1 kcal = 4.184 kJ. In this exercise 1 L of water with a mass of approximately 1 kg needs to be heated $\Delta T = 100 - 20 = 80$ °C. This will cost:

$$80 \text{ kcal} = 80 \cdot 4.184 \text{ kJ} = 334.7 \text{ kJ}$$

b) First determine the total amount of energy that needs to be delivered. The 334.7 kJ from answer a is the useful 40% of this total amount.

$$E_{\text{total}} = \frac{E_{\text{useful}}}{\eta} = \frac{334.7 \text{ kJ}}{0.40} = 836 \text{ kJ}$$

With η being the efficiency of 40%

Next, determine the amount of mass needed:

$$m_{\text{gas}} = \frac{E_{\text{total}}}{E_{\text{gas}}} = \frac{836 \cdot 10^5 \text{ J}}{50 \cdot 10^6 \text{ J/kg}} = 0.017 \text{ kg}$$

With E_{gas} being the calorific value of the gas.

Using the density of the gas $\rho_{\text{gas}} = 0.7 \text{ kg/m}^3$, calculate the gas volume needed:

$$\rho_{\text{gas}} = \frac{m_{\text{gas}}}{V_{\text{gas}}} \Rightarrow V_{\text{gas}} = \frac{m_{\text{gas}}}{\rho_{\text{gas}}} = \frac{0.017 \text{ kg}}{0.7 \text{ kg/m}^3} = 0.024 \text{ m}^3 = 24 \text{ L}$$

Conclusion: we need 24 litres of gas to heat 1 liter of water from 20 °C to 100 °C.

c) An amount of 2000 W = 2000 J/s of power P is added to the water. The total energy change ΔE of the water during heating is 334.7 kJ (consider the answer at a). The amount of time Δt needed can be estimated as follows:

$$\Delta t = \frac{\Delta E}{P} = \frac{334.7 \cdot 10^3 \text{ J}}{2000 \text{ J/s}} = 167 \text{ s} = 2 \text{ min } 47 \text{ s}$$

d) See the lecture notes: 1 kWh = 3.6 MJ. An amount of 334.7 kJ is needed, so this is equal to:

$$\frac{334.7 \cdot 10^3 \text{ J}}{3.6 \cdot 10^6 \text{ J/kWh}} = 0.093 \text{ kWh}$$

e) Heating with gas costs more energy than heating with electricity. This conclusion could have been made straight away, since the energy use of the gas has an efficiency of only 40%, while the efficiency of electricity is 100%.
For an exhaustive and fair comparison, all the energy conversions of the gas and the electricity should be taken into consideration. An electricity plant of course also uses (fossil)fuels, and it is reasonable to consider whether these conversions and the transportation across the electricity network have a greater energy loss than the transportation of the gas.

f) Costs of gas:

$$0.024 \text{ m}^3 \cdot €0.67 \cdot m^{-3} = €0.016$$

Costs of electricity:

$$0.093 \text{ kWh} \cdot €0.22 \cdot kWh^{-1} = €0.020$$

Conclusion: heating with gas is the cheaper solution, but it costs more energy (disregarding energy conversions outside the household).