SCHOOL OF ENGINEERING
MECHANICAL ENGINEERING
LRESE - Laboratory of Renewable Energy Sciences and Engineering

Renewable Energy: exercise 1, solution

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1. CO_2 emissions

   (a) Source: Key World Energy Statistics 2019.pdf
   In 2018: 4'482 Mt oil (p. 10), 3'937 Gm^3 natural gas (p. 12), 7'831 Mt coal (p. 14)

   (b) The chemical composition of oil is given by its empirical formula: $C_7H_{14}N_{0.1}O_{0.1}S_{0.3}$. Thus, burning 1 mol of oil (M_{oil}=110 g/mol) emits 7 mole of CO_2 ($M_{CO_2} = 44$ g/mol). The weight ratio CO_2-to-oil is $(7 \cdot 44)/110 = 2.8$ or in other words, burning 4'482 Mt oil will emit 2.8 times the amount in CO_2: **12.55 Gt CO_2**
   Per 1 mol of CH_4 1 mol of CO_2 is emitted, therefore the molar mass ratio $44/16 = 2.75$ multiplied by the amount of gas burnt 3'937 $Gm^3 \cdot 0.7$ kg/m^3 = 2'756 Mt gives the mass of CO_2 emitted: **7.58 Gt CO_2**
   With 1 mol of CO_2 emitted from burning 1 mol of C and a carbon content of approx. 50 wt-% in coal (7'831 Mt coal · 0.5 = 3'916 Mt C), the molar mass ratio of 44/12 = 3.67 again determines the mass of emitted CO_2 when multiplied with the mass of burnt carbon: **14.37 Gt CO_2**
   Total annual emissions from fossil fuels is 12.55 + 7.58 + 14.37 = 34.5 Gt CO_2 (36.4% from coal, 22% from oil, 41.6% from gas)
   34.5 Gt CO_2 / 7.55 billion people = **4.57 t CO_2 / person**

   (c) Statistics of CO_2 emission per capita compared to CO_2 emissions for different countries can be found starting from page 48 of Keyword World Energy Statistics. These statistics are shown in Figure 1 for different countries.

   (d) 13'972 Mtoe total primary energy consumption = 585 EJ/yr = **18.5 TW ⇒ 2.5 kW per person** on the planet on average
   CO_2 intensity of energy: 34.5 Gt CO_2 / 13'972 Mtoe ⇒ **2.5 t CO_2/toe**

   (e) CO_2 emission intensity of countries i) to viii) compare to each other and to the average value of d) in Figure 2.

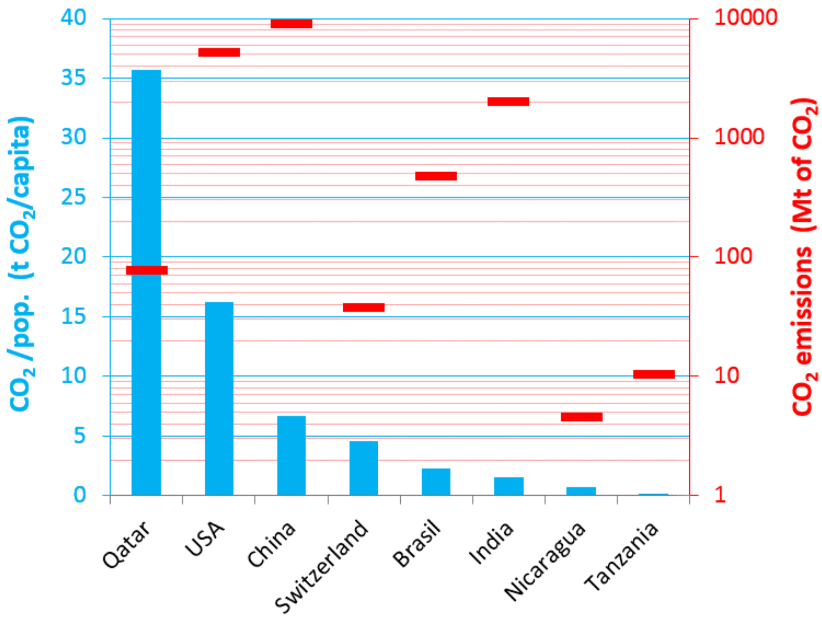

Figure 1: CO_2 emission per capita and CO_2 emissions for different countries

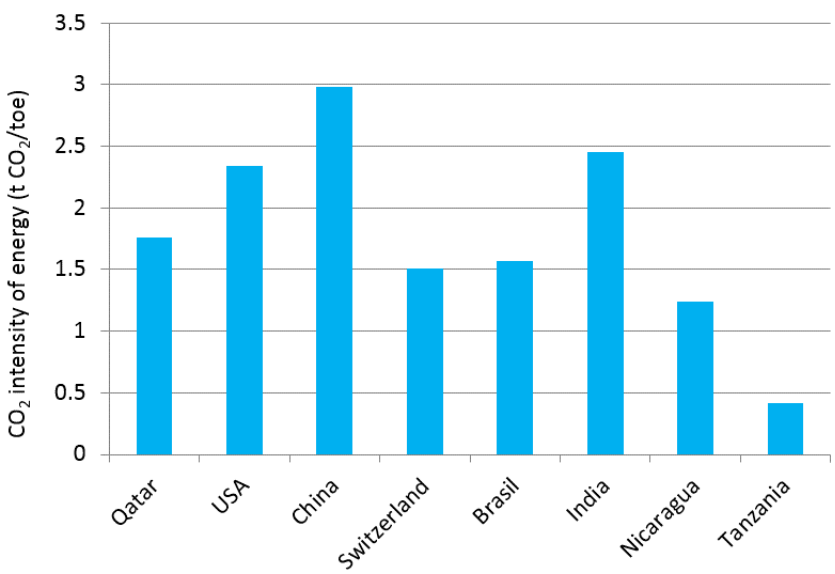

Figure 2: CO_2 emission intensity of countries i) to viii)

2. Replacement - Biomass

   (a) 7'831 Mt coal · 20 MJ/kg = 156.6 EJ. We need 2 · 156.6 EJ energy equivalent in wood to replace coal for the electricity production (factor 2 to account for only half the electrical conversion efficiency, 20% instead of 40%) = 313 EJ = 18.4 Tt of wood. If we can grow 2 kg per m^2 sustainably, the total amount of $18.4 \cdot 10^{12}$ kg grows in $9.07 \cdot 10^{12}$ m^2 = $9.07 \cdot 10^8$ **ha forest to replace coal**.

   For replacement of oil: We need 4'482 Mtoe = 187 EJ, 187 EJ / (21 MJ/L) which is $8.91 \cdot 10^{12}$ L. This requires 1 ha / 3'000 L · $8.91 \cdot 10^{12}$ L = $2.91 \cdot 10^9$ **ha crop land to replace oil**. We would almost need to double the now used agricultural land only to replace oil by ethanol.

   We need 3'937 Gm^3 of natural gas per year. By agro-waste digestion we would need 3'937 Gm^3/2000 (m^3/ha) = $1.96 \cdot 10^9$ **ha of land to replace gas**.

   (b) The forest surface is $5.61 \cdot 10^7$ km^2 and the agricultural area $1.53 \cdot 10^7$ km^2. 16.2% of earth's forest area would be needed to replace coal by wood for electricity. 190% of the available agricultural area would be needed to replace oil by bioethanol, and 128% to cover the need of gas by biogas.

   (c) The total biomass energy needed is given by 7'476 Mtoe for wood (23% of yearly biomass production in forest); 4'482 Mtoe for bioethanol and 3'385 Mtoe for biogas (3'937 Gm^3 converted to Mtoe using the heating value), a total of 7'867 Mtoe for bioethanol and biogas (about double of the yearly biomass production in agriculture). All together is 15'343 Mtoe, which corresponds to 48% of the forest biomass.

   (d) If the increase is entirely covered by forest, it represents 24% of the forest to harvest. If the increase is entirely covered by agriculture area, it represents 219% of the agriculture area to harvest.

3. Replacement - Solar

   (a) The solar irradiance per year is given by 6 $kWh/m^2 \cdot 365 = 2'190\ kWh/m^2 = 7.88 \cdot 10^{-9}\ EJ/m^2$. To replace coal-produced electricity, we need $0.4/0.18 \cdot 154.18$ EJ energy equivalent in solar = 342.6 EJ. The area to produce this energy by solar is 154.18 EJ / $7.88 \cdot 10^{-9}\ EJ/m^2 = 43'458\ km^2$.
   The area to replace oil by solar fuels is 4'331 Mtoe = 181 EJ / $(7.88 \cdot 10^{-9}\ EJ/m^2 \cdot 0.18 \cdot 0.75) = 170'369\ km^2$.
   The area to replace gas by solar heat is 129 EJ (3'590 Gm^3 converted to EJ using the heating value) / $(7.88 \cdot 10^{-9}\ EJ/m^2 \cdot 0.65) = 25'220\ km^2$.
   Total area of 239'046 km^2 is required.

   (b) The area of land and ocean on Earth are respectively $1.48 \cdot 10^8\ km^2$ and $3.62 \cdot 10^8\ km^2$. The total PV/absorber area needed to replace all fossil fuels by solar energy represents only 0.16% of land or 0.07% of water area. In other words, this PV/absorber area represents around 5.8 times the area of Switzerland.

   (c) Solar irradiance data of Almeria, Spain can be found here:
   http://geomodelsolar.eu/data/typical-meteorological-year
   Integrating the solar irradiation from excel file gives yearly global horizontal solar irradiation of 1'863 $kWh/m^2 = 6.71 \cdot 10^{-9}\ EJ/m^2$. The area to replace coal-produced electricity is 51'079 km^2. Similarly, the area to replace oil by solar fuels is 200'244 km^2 and gas by solar heat 29'642 km^2. A total PV/absorber area of 280'965 km^2 is required (6.8 times Switzerland).