SCHOOL OF ENGINEERING
MECHANICAL ENGINEERING
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ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Renewable Energy: exercise 1, solution

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1. CO_2 emissions

   (a) Source: https://webstore.iea.org/download/direct/2831

   In 2018: 4'482 Mt oil (page 12), 3'937 Gm^3 natural gas (p. 14), 7'813 Mt coal (p. 16)

   (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 4'331 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 (7'813 Mt coal $\cdot$ 0.5 = 3'906 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: **14.36 Gt CO_2**
   Total annual emissions from fossil fuels is 12.55 + 7.58 + 14.36 = 34.49 Gt CO_2 (42.6% from coal, 36.6% from oil, 20.8% from gas)
   34.49 Gt CO_2 / 7.55 billion people = **4.568 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 2016. These statistics are shown in Figure 1 for different countries.

   (d) 13'699 Mtoe total primary energy consumption = 574 EJ/yr = **18.2 TW** $\Rightarrow$ **2.49 kW per person** on the planet on average
   CO_2 intensity of energy: 33.17 Gt CO_2 / 13'699 Mtoe $\Rightarrow$ **2.42 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.

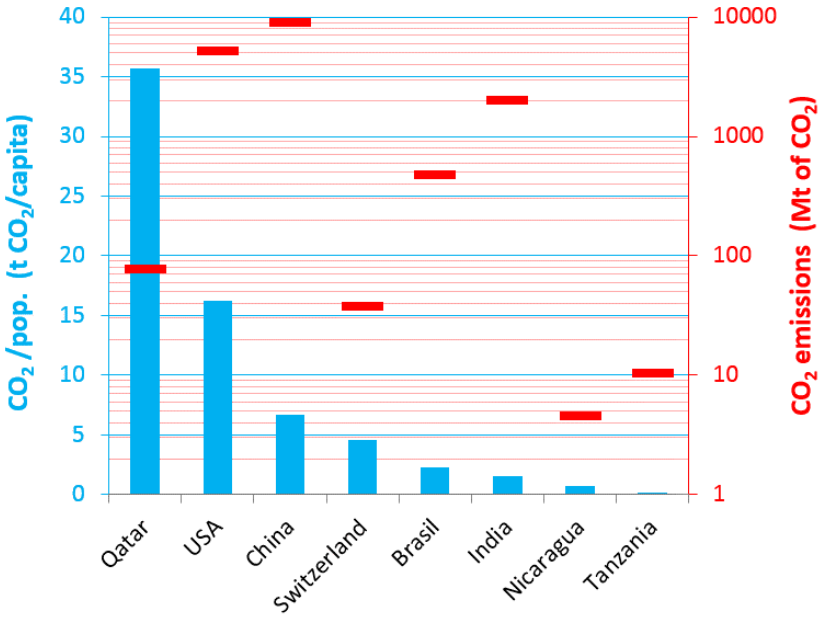

Figure 1: CO_2 emission per capita and CO_2 emissions for different countries

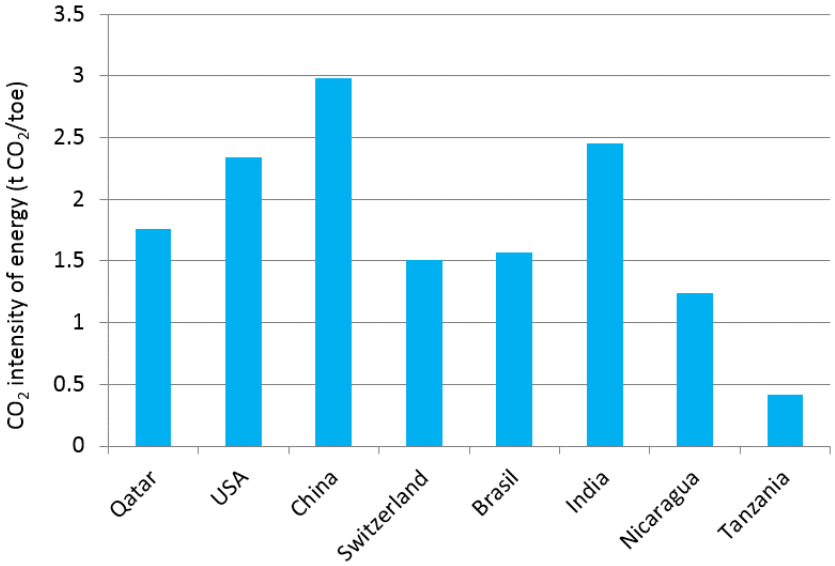

Figure 2: CO_2 emission intensity of countries i) to viii)

2. Replacement - Biomass

(a) 7'709 Mt coal · 20 MJ/kg = 154.2 EJ. We need 2 · 154.2 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%) = 308 EJ = 18.1 Tt of wood. If we can grow 2 kg per m^2 sustainably, the total amount of $18.1 \cdot 10^{12}$ 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 4'331 Mtoe = 181 EJ, 181 EJ / (21 MJ/l) which is $8.63 \cdot 10^{12}$ l. This requires 1 ha / 3'000 l · $8.63 \cdot 10^{12}$ l = $2.88 \cdot 10^9$ **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 3'590 Gm^3 of natural gas per year. By agro-waste digestion we would need 3'590 Gm^3/2000 (m^3/ha) = $1.8 \cdot 10^9$ **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. 188% of the available agricultural area would be needed to replace oil by bioethanol, and 117% to cover the need of gas by biogas. 84% of the total forest on earth would be needed to be transformed into agricultural area or wood harvesting lands to cover all fossil fuels by biomass.

(c) The total biomass energy needed is given by 7'365 Mtoe for wood (24% of yearly biomass production in forest); 4'331 Mtoe for bioethanol and 3'087 Mtoe for biogas (3'590 Gm^3 converted to Mtoe using the heating value), a total of 7'418 Mtoe for bioethanol and biogas (about double of the yearly biomass production in agriculture). All together is 14'783 Mtoe, which corresponds to 46% of the forest biomass.

(d) If the increase is entirely covered by wood, it represents 16.7% of the forest to harvest ($9.36 \cdot 10^6$ km^2). By bioethanol, it represents 330% of available agricultural area and by biogas 289%.

3. Replacement - Solar

(a) The solar irradiance per year is given by 6 kWh/m^2 · 365 = 2'190 kWh/m^2 = 7.88 · 10^{-9} EJ/m^2. To replace coal-produced electricity, we need 0.4/0.18 · 154.18 EJ energy equivalent in solar = 342.6 EJ. The area to produce this energy by solar is 154.18 EJ / 7.88 · 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 · 10^{-9} EJ/m^2 · 0.18 · 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 · 10^{-9} EJ/m^2 · 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 1.48·10^8 km^2 and 3.62·10^8 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:

Integrating the solar irradiation from excel file gives yearly global horizontal solar irradiation of 1'863 kWh/m^2 = 6.71 · 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).