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

Renewable Energy: Introduction Solution

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1. CO_2 emissions

   (a) Source: Key World Energy Statistics 2021.pdf
   In 2020: 4141 Mt oil (p. 12), 4014 Gm^3 natural gas (p. 14), 7575 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 4'141 Mt oil will emit 2.8 times the amount in CO_2: **11.59 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 4'014 $Gm^3 \cdot 0.7$ kg/m^3 = 2'809 Mt gives the mass of CO_2 emitted: **7.73 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 (7'575 Mt coal $\cdot$ 0.5 = 3'788 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: **13.89 Gt CO_2**
   Total annual emissions from fossil fuels is 33.21 Gt CO_2 (41.8% from coal, 23.3% from oil, 34.9% from gas)
   33.21 Gt CO_2 / 7.82 billion people = **4.25 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 60 to 69 of Keyword World Energy Statistics. These statistics are shown in Figure 1 for different countries.

   (d) 418 EJ primary energy consumption per year = **13.25 TW ⇒ 1.69 kW per person** on the planet on average
   CO_2 intensity of energy: 33.21 Gt CO_2 / 418 EJ ⇒ **79.45 t CO_2/TJ**

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

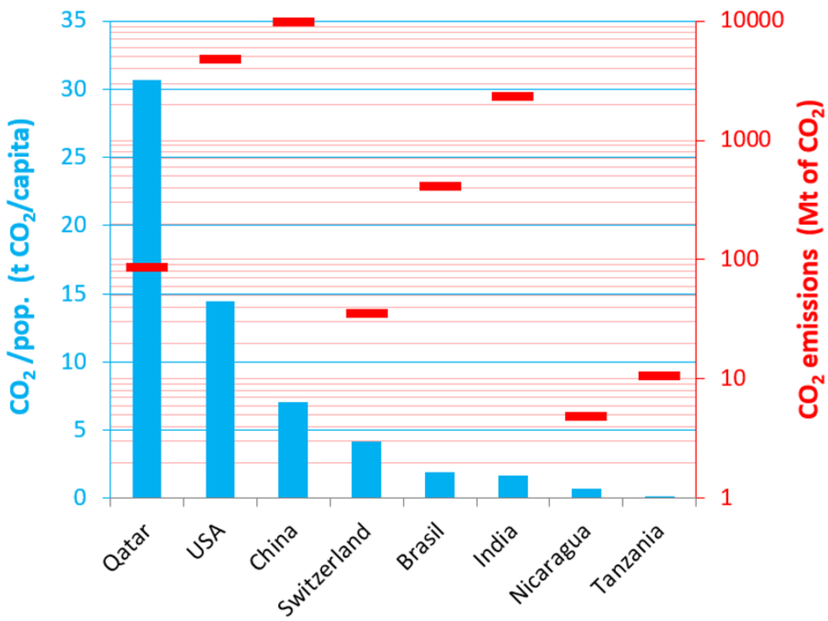

Figure 1: CO_2 emission per capita and CO_2 emissions for different countries

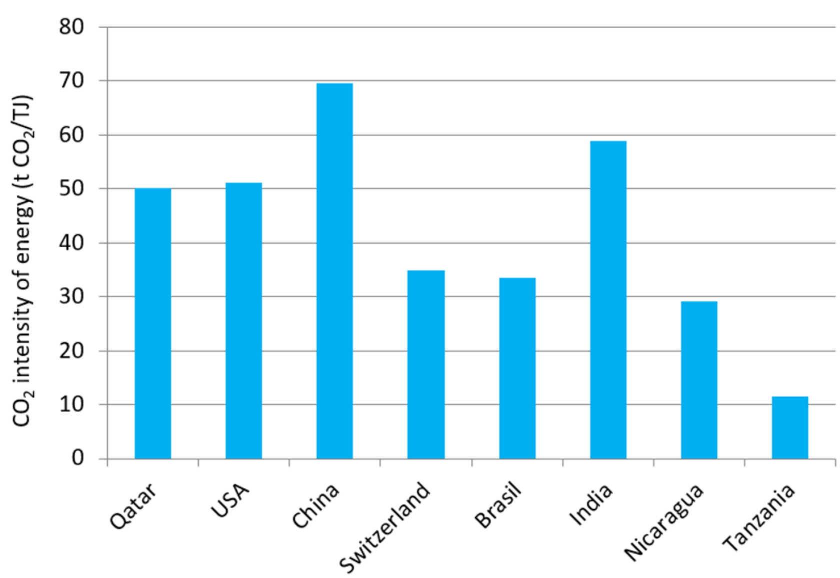

Figure 2: CO_2 emission intensity of countries i) to viii)

2. Replacement - Biomass

   (a) 7'575 Mt coal $\cdot$ 20 MJ/kg = 151.5 EJ. We need $2 \cdot 151.5$ 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%) = 303 EJ and therefore $17.8 \cdot 10^{12}$ kg of wood.
   If we can grow 2 kg per m^2 sustainably, the total amount of $17.8 \cdot 10^{12}$ kg grows in $8.91 \cdot 10^{12}$ m^2 = $8.91 \cdot 10^8$ **ha forest to replace coal**.

   For replacement of oil: We need 4'141 Mtoe $\cdot$ 41.8 MJ/kg (heating value of typical oil) = 173 EJ; 173 EJ / (21 MJ/L) which is $8.26 \cdot 10^{12}$ L. This requires 1 ha / 3'000 L $\cdot$ $8.26 \cdot 10^{12}$ L = $2.75 \cdot 10^9$ **ha crop land to replace oil**.

   We need 4'014 Gm^3 of natural gas per year. By agro-waste digestion we would need 4'014 $\cdot 10^9 m^3/2000$ (m^3/ha) = $5.65 \cdot 10^9$ **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. 15.9% of earth's forest area would be needed to replace coal by wood for electricity. 180% of the available agricultural area would be needed to replace oil by bioethanol, and 131% to cover the need of gas by biogas.

   (c) The total biomass energy needed is given by 303 EJ for wood (23% of yearly biomass production in forest); 173 EJ for bioethanol and 145 EJ for biogas (4'014 $\cdot 10^9 m^3$ converted to EJ using the heating value), a total of 318 EJ Mtoe for bioethanol and biogas (about double of the yearly biomass production in agriculture).

   (d) If the increase is entirely covered by forest, it represents 18.45% of the forest to harvest. If the increase is entirely covered by agriculture area, it represents up to 365% of the agriculture area to harvest.

3. Replacement - Solar

(a) The solar irradiance per year is given by 6 $\text{kWh/m}^2 \cdot 365 = 2'190\ \text{kWh/m}^2 = 7.88 \cdot 10^{-9}\ \text{EJ/m}^2$. To replace coal-produced electricity, we need $0.4/0.18 \cdot 151.5$ EJ energy equivalent in solar = 336.67 EJ. The area to produce this energy by solar is 336.67 EJ / $(7.88 \cdot 10^{-9}\ \text{EJ/m}^2) = 42'724\ \text{km}^2$.
The area to replace oil by solar fuels is 4'141 Mtoe = 173 EJ / $(7.88 \cdot 10^{-9}\ \text{EJ/m}^2 \cdot 0.18 \cdot 0.75) = 162'895\ \text{km}^2$.
The area to replace gas by solar heat is 145 EJ ($4'014 \cdot 10^9 \text{m}^3$ converted to EJ using the heating value) / $(7.88 \cdot 10^{-9}\ \text{EJ/m}^2 \cdot 0.65) = 28'198\ \text{km}^2$.
Total area of 233'796 km^2 is required.

(b) The area of land and ocean on Earth are respectively $1.48 \cdot 10^8\ \text{km}^2$ and $3.62 \cdot 10^8\ \text{km}^2$. The total PV/absorber area needed to replace all fossil fuels by solar energy represents only 0.16% of land or 0.06% of water area. In other words, this PV/absorber area represents around 6 times the area of Switzerland.

(c) Integrating the solar irradiation from the excel file gives yearly global horizontal solar irradiation of $1'863\ \text{kWh/m}^2 = 6.71 \cdot 10^{-9}\ \text{EJ/m}^2$. The area to replace coal-produced electricity is 50'191 km^2. Similarly, the area to replace oil by solar fuels is 191'460 km^2 and gas by solar heat 33'143 km^2. A total PV/absorber area of 274'793 km^2 is required (around 7 times Switzerland).