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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 2019.pdf
   In 2018: 4'482 Mt oil (p. 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 4'482 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 (7'813 Mt coal · 0.5 = 3'907 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: **14.32 Gt CO_2**
   Total annual emissions from fossil fuels is 12.55 + 7.58 + 14.32 = 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 = **4.56 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) 13'972 Mtoe total primary energy consumption per year = 585 EJ/yr = **18.6 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.

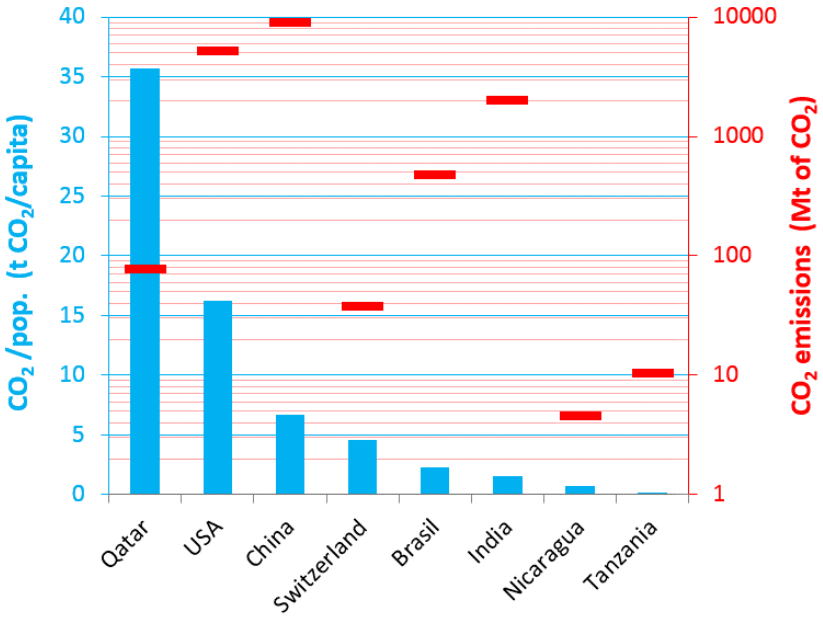

Figure 1: CO_2 emission per capita and CO_2 emissions for different countries

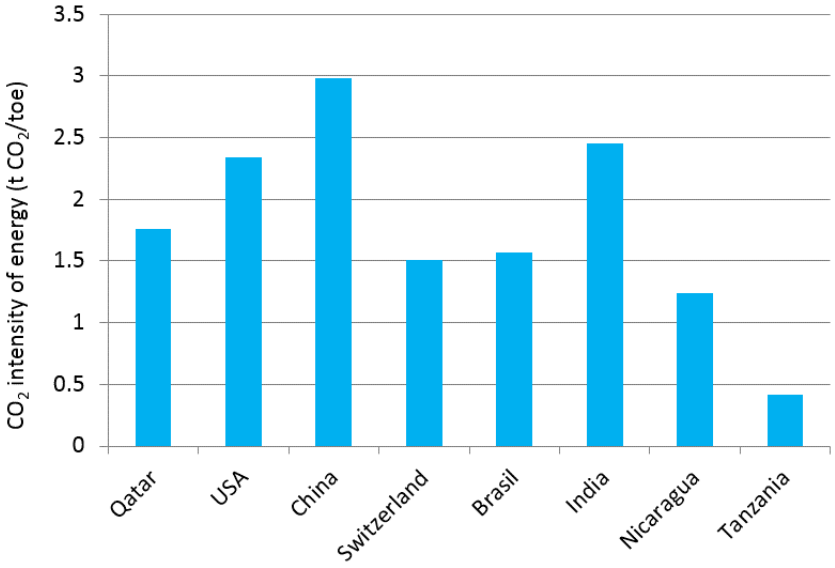

Figure 2: CO_2 emission intensity of countries i) to viii)

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2. Replacement - Biomass

(a) 7'813 Mt coal $\cdot$ 20 MJ/kg = 156.2 EJ. We need $2 \cdot 156.2$ 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%) = 313 EJ and therefore $18.4 \cdot 10^{12}$ kg of wood.
If we can grow 2 kg per m^2 sustainably, the total amount of $18.4 \cdot 10^{12}$ kg grows in $9.2 \cdot 10^{12}$ m^2 = $9.2 \cdot 10^8$ **ha forest to replace coal**.

For replacement of oil: We need 4'482 Mtoe = 188 EJ, 188 EJ / (21 MJ/L) which is $8.94 \cdot 10^{12}$ L. This requires 1 ha / 3'000 L $\cdot$ $8.94 \cdot 10^{12}$ L = $2.98 \cdot 10^9$ **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 $\cdot 10^9 m^3$/2000 (m^3/ha) = $1.97 \cdot 10^9$ **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. 16.4% of earth's forest area would be needed to replace coal by wood for electricity. 195% of the available agricultural area would be needed to replace oil by bioethanol, and 129% to cover the need of gas by biogas.

(c) The total biomass energy needed is given by 7'464 Mtoe for wood (23% of yearly biomass production in forest); 4'482 Mtoe for bioethanol and 3'385 Mtoe for biogas (3'937 $\cdot 10^9 m^3$ 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).

(d) If the increase is entirely covered by forest, it represents 25% of the forest to harvest. If the increase is entirely covered by agriculture area, it represents 219% of the agriculture area to harvest.

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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 · 156.2 EJ energy equivalent in solar = 347.2 EJ. The area to produce this energy by solar is 347.2 EJ / (7.88 · 10^{-9} EJ/m^2) = 44'067 km^2.
The area to replace oil by solar fuels is 4'482 Mtoe = 188 EJ / (7.88 · 10^{-9} EJ/m^2 · 0.18 · 0.75) = 176'725 km^2.
The area to replace gas by solar heat is 141 EJ (3'937 ·10^9m^3 converted to EJ using the heating value) / (7.88 · 10^{-9} EJ/m^2 · 0.65) = 27'528 km^2.
Total area of 248'320 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 6 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 1'894 kWh/m^2 = 6.82 · 10^{-9} EJ/m^2. The area to replace coal-produced electricity is 50'909 km^2. Similarly, the area to replace oil by solar fuels is 204'192 km^2 and gas by solar heat 31'807 km^2. A total PV/absorber area of 286'908 km^2 is required (around 7 times Switzerland).