1.1 Candy bars

a. Candy bars for the course

Assume 200 hours (=720 000 seconds) spent on the course.

$$Candy\ bars\ needed = \frac{power\ consumption\ studying * amount\ of\ seconds\ studying}{energy\ content\ candy\ bar}$$

Fill in:

$$Candy\ bars\ needed = \frac{100\,\frac{\text{J}}{\text{s}} * 720000\ \text{s}}{1000\ 000\ \text{J/bar}} = \text{ 72 bars}$$

b. Check

Needed energy use per year = average energy use (J/s) * seconds in year
Average energy use = 100 W = 100 J/s
Seconds / year = 365 days/yr * 24 hr/day * 60 min/hr * 60 sec/min = 31 536 000 sec/yr
Needed energy use per year = 100 J/s * 31 536 000 s/yr = 3 153 600 000 J/yr (=3.15 GJ/yr)
This is compatible with the 2-3 GJ/year per person mentioned in the introduction of paragraph 1.1.

c. Number of slaves

From figure 1.1 energy per capita for modern society is about 175 GJ/yr/capita. Energy use for work, leisure, sleeping etc is about 3 GJ/yr/capita. Number of fossil (renewable, nuclear) slaves working for you would then be 175/3 = 58 slaves.

1.2 Energy intensity of GDP

a. *Energy intensities*

$$Energy\ intensity\ country = \sum typical\ energy\ intensity_{sector} * fraction\ sector\ contribution\ to\ GDP$$

$$Energy\ intensity_{country\ A}: (0.10 * 5\ \mathrm{MJ/\$}) + (0.35 * 10\ \mathrm{MJ/\$}) + (0.55 * 1\ \mathrm{MJ/\$}) = 4.55\ \mathrm{MJ/\$}$$

$$Energy\ intensity_{country\ B}: (0.02 * 5\ \mathrm{MJ/\$}) + (0.25 * 10\ \mathrm{MJ/\$}) + (0.73 * 1\ \mathrm{MJ/\$}) = 3.33\ \mathrm{MJ/\$}$$

$\underline{Answer: country\ A = 4.55\ \mathrm{MJ/\$}, country\ B = 3.33\ \mathrm{MJ/\$}}$

b. *Energy intensity development USA*

Energy intensity is calculated as (1000 MJ/GJ)*(GJ per head)/(US$/head). Results are:

Year	MJ/$
1945	13.7
1975	13.3
2008	7.5

Energy intensity started to decrease in the seventies, most likely as a consequence of increased oil prices since the beginning of the seventies. Another reason is a shift of activity from primary/secondary sectors to the tertiary sector having a lower energy intensity.

c. *Energy intensity USA, UK and China*

Similar calculations. Result

Country	MJ/$
USA	7.45
UK	3.85
China	12.8

High value for China most likely caused by high share of (growing) energy intensive industry. Differences between USA and UK: 2 explanations given in section 1.2: steel companies use more energy per tonne of steel and cars use more gasoline per km driven.

d. *Comparison a and b*

Energy intensities in *b* are higher. The most important reason for the higher energy intensities found in *b* (and also *c*) compared to *a* is that in *a* only the productive side of the economy is counted. In addition to the energy use in agriculture, industry and services, also energy is consumed in households: heating, electric appliances, private cars. Adding this to the energy use will lead to higher energy intensities.

In addition, he USA has significantly higher energy intensities than countries like the UK and Japan (see question *c*) and therefore the intensities given in question a are not typical for the USA.

1.3 Scaling up global energy use

a. Global energy use all people US level

$\text{Global energy use} = \text{global population} * \text{energy use per capita}$

$\text{Global population in 2014: 7.3 billion} = 7.3 \times 10^9 \text{ inhabitants}$

$\text{Energy use per capita USA: about 324 GJ/capita}$ (table 1.3)

$\underline{\text{Global energy use US level: } 7.3 \times 10^9 \text{ inhabitants} * 324 \text{ GJ/capita} = 2.37 * 10^{12} \text{ GJ}}$

$\underline{= 2370 \text{ EJ}}$

b. Global energy use all countries US or UK energy intensity level

2008 US prim. Energy use / capita: 324 GJ/cap (table 1.3)

2008 US GDP / capita = 43 500 US$ /cap (table 1.3)

So energy intensity US: 324 GJ/43 500 US$ = 0.007448 GJ/US$

Global energy use US level: Energy intensity US * Global GDP

Global GDP = 78 10^{12} US$

Global energy use: 0.007448 GJ/US$ * 78 10^{12} US$ = <u>581 EJ</u>

2008 UK prim. Energy use / capita: 152 GJ/cap (table 1.3)

2008 UK GDP / capita = 39500 US$ /cap (table 1.3)

So energy intensity UK 2008: 152 GJ/39500 US$ = 0.003848 GJ/US$

Global energy use UK level: Energy intensity UK * Global GDP

Global GDP = 78 10^{12} US$

Global energy use: 0.003848 GJ/US$ * 78 10^{12} US$ = <u>300 EJ</u>

1.4 Radiation balance of the Earth

a. Total solar energy

Total solar energy = fraction incoming radiation absorbed by the Earth * solar radiation density * projected area earth
Incoming radiation absorbed by the Earth: 70%
Solar radiation density: 1360 W/m^2
Radius Earth: 6371 km
Surface earth projected: $\pi * r^2 = \pi * 6371^2$ = 127 516 118 km^2 = 1.2752 10^{14} m^2
Total solar energy: 0.70 * 1360 * 1.2752 10^{14} m^2 = 1.2140*10^{17} W
Answer: Q_{abs} = 121.40 ≈ 121 PW

b. Earth temperature with no atmosphere

Absorbed radiation equals outgoing radiation. Using the Stefan-Boltzmann law:

$$Q_{abs} = Q_{out} = \varepsilon \cdot \sigma \cdot T^4 \cdot Area \rightarrow T = \left(\frac{Q_{abs}}{\varepsilon \cdot \sigma \cdot Area} \right)^{1/4}$$

Q_{abs}=1.2140*10^{17} W (question a)
ε=1 (black body assumed)
σ=5.67*10^{-8} W·m^{-2}·K^{-4} (Stefan-Boltzmann constant)
Earth area $Area$=4πr^2 = 4*3.1416*(6371 10^3)^2 =5.101 10^{14} m^2
Filling in gives T=254.5 K (=−18.5 ^{o}C)

c. Why is Earth temperature higher?

The temperature on Earth is higher because much of the radiation emitted by the earth is absorbed in the atmosphere by greenhouse gasses such as water vapour and carbon dioxide (greenhouse effect).

1.5 Solar energy per capita

a. Solar energy per capita

Solar energy per capita = total solar energy absorbed / global population
Total solar energy absorbed: $1.214*10^{17}$ W
Global population early 2016: 7.4 10^{9}
Solar energy per capita = $1.214*10^{17}$ / 7.4 10^{9} = 16.405 10^{6} W/capita
The world average energy use of 80 GJ/capita/year. (section 1.2)
Solar energy per capita per year: 16.405 10^{6} J/s/capita * 365 d * 24 h * 60 m * 60 s = 517300 GJ/capita/year
<u>Answer: $0.517*10^{6}$ GJ/capita/year, which is a lot compared to the average energy use.</u>

b. Average absorbed irradiation per square meter on the Earth's surface

The surface area of a sphere is $4\pi r^2$ and the area of a circle is πr^2, so there are 4 square meters of surface area for every 1 square meter of projected area. The absorbed irradiation on the surface of the earth is: 1360 W/m^2 * 0.70 / 4 = <u>238.0 W/m^2</u>
<u>Other answer</u>:
Absorbed power (q. 1.3a) / Earth surface =$1.2140*10^{17}$ W / 5.101 10^{14} m^2 =<u>238 W/m^2</u>.

c. Area needed per capita

Average energy use per inhabitant: 80 GJ/capita/year (section 1.2)
Useful energy per square meter per year = conversion efficiency of solar irradiation to useful energy * average absorbed irradiation per square meter per year
Conversion efficiency of solar irradiation to useful energy: 20%
Average absorbed irradiation per square meter: 238 W/m^2 (answer question b)
Square meter of solar systems = average energy use per inhabitant / useful energy per square meter per year
Average absorbed irradiation per square meter per year: 238 J/s/m^2 * 365 d * 24 h * 60 m * 60 s * 10^{9} GJ/J = 7.51 GJ/m^2/year
Useful energy per square meter per year = 0.20 * 7.51 GJ/m^2/year = 1.50 GJ/m^2/year
Square meter of solar systems = 80 / 1.50 = 53.3 m^2
<u>Answer: 53 m^2</u>

1.6 Fuel use and emissions

NOTE: erratum in subquestion b: "… Assume that the coal composition by mass is 81% carbon, 7% hydrogen, 2% sulphur and 10% ash. What are the emissions of CO_2 and SO_2 ~~per year~~ per GJ?"

a. *number of wheelbarrows*

Coal required:

(30 + 60 GJ) * (10^3 MJ/GJ) / (27 MJ/kg coal) = 3333 kg of coal.

number of wheel barrows:

(3333 kg of coal) / (60 kg/wheelbarrow) = 56 wheelbarrows

b. *Emissions*

Molar masses: C: 12 kg/kmol; H: 1 kg/kmol; O: 16 kg/kmol; S: 32 kg/kmol
Molar mass CO_2 = 12 + 2*16 = 44 kg/kmol
Molar mass SO_2 = 32 + 2*16 = 64 kg/kmol

CO_2 emission (1 kmol C produces 1 kmol CO_2 upon combustion):

(0.81 kg C/kg coal) / (12 kg C/kmol C) *(1 kmol CO_2/kmol C) * (44 kg CO_2/kmol CO_2)
= 2.97 kg CO_2 /kg coal

(2.97 kg CO_2/kg coal) / (27 MJ/kg coal) * (1000 MJ/GJ) = 110 kg CO_2/GJ

SO_2 emission (1 kmol S produces 1 kmol SO_2 upon combustion):

(0.02 kg S/kg coal) / (32 kg S/kmol S) *(1 kmol SO_2/kmol S) * (64 kg SO_2/kmol SO_2)
= 0.0400 kg SO_2 /kg coal

(0.0400 kg SO_2/kg coal) / (27 MJ/kg coal) * (1000 MJ/GJ) = 1.48 kg SO_2/GJ

CO_2 emission household = (90 GJ/year) * (110 kg CO_2/GJ) = 9900 kg CO_2/year
SO_2 emission household = (90 GJ/year) * (1.48 kg SO_2/GJ) = 133 kg SO_2/year

c. *CO_2 emissions methane*

Molar mass methane (CH_4): 12 + 4*1 = 16 kg/kmol
CO_2 emission methane combustion (1 kmol CH_4 produces 1 kmol CO_2 upon combustion):
(44 kg CO_2/kmol CO_2) / (16 kg CH_4/kmol CH_4)* (1 kmol CO_2/kmol CH_4)
= 2.75 kg CO_2/kg CH_4

(2.75 kg CO_2/kg CH_4) / (50.1 MJ/kg CH_4) * (1000 MJ/GJ) =54.9 kg CO_2/GJ

Natural gas (CH_4) is the better option because it has about half the CO_2 emissions per GJ when compared to coal which has an emission of 110 kg CO_2/GJ.

1.6 Climate change and sustainable development

Section 1.5: The Paris Agreement is that average global temperature increase should stay well below 2 ^oC and pursue efforts to limit the increase to 1.5 ^oC. The agreement will help to making serious steps towards reaching the other aspirational goals set out in Table 1.1.

The agreement directly addresses the first aspirational goal: Stabilising global climate change to 2 °C above pre-industrial levels to be achieved in the 21st century.

Second aspirational goal: "Enhanced energy security by diversification and resilience of energy supply (particularly the dependence on imported oil)". Here further additional steps may be needed to enhance energy security. Energy efficiency will generally lead to a lower dependence. But a transition to renewable energy could also lead to new dependencies, e.g. from imported electricity or bio-energy.

Third aspirational goal: "Eliminating household and ambient air pollution". Increased energy efficiency can very well be combined with decrease in other emissions.

Fourth aspirational goal: "Universal access to modern energy services by 2030". Additional effort in providing access to energy services to people in developing countries would be needed.