Final examination Energy Analysis, 28 January 2010, 9.00 –12.00

- This exam has 4 questions, each having equal weight
- You can use the book, the index to the book, a dictionary and Key World Energy Statistics.
- The answers of the exercises may **not** be used.
- You can use a calculator.
- The answers can be provided either in English or Dutch.
- Provide your name and student number on each separate sheet of paper.

1. Energy efficiency cars

A conventional car has the following characteristics:
C_D=0.25, C_R=0.01, frontal area = 2 m^2, mass = 1100 kg, energy use of accessories: 0.5 kW, transmission efficiency 0.90, engine efficiency = 0.38, mechanical efficiency = 0.50. Assume the car is only driven at a speed of 90 km/h. The car use is 25000 km/year
A new (more efficient) version of the car is heavier (mass = 1250 kg) but the mechanical efficiency has increased to 0.65. The extra weight is 50 weight-% cold rolled steel and 50 weight-% Styrene butadiene rubber (SBR). The lifetime of the car is 10 years. Other characteristics remain the same. The fuel used is gasoline (price € 1.40 / litre)

a. Calculate the energy use of the conventional and the efficient car, in litre per 100 km
b. Calculate the primary energy savings in GJ/year when using the car (use a second order approach.
c. Calculate the energy pay-back period of the efficient car compared with the conventional car.
d. If the efficient car is € 2500 more expensive, and a subsidy of € 400 and a tax benefit of €160/year can be obtained for the efficient car, what is the payback period of the efficient car compared with the conventional car.

2. Solar water heater

A solar water heater converts radiation energy from the sun into heat. In the solar collector, water is heated from 15 °C to 85 °C. Of the incoming solar radiation 50% is converted into heat. The solar water heater produces 6 GJ of heat per year. The (environmental) reference temperature is 10 ^oC.

a. What is the exergetic efficiency of the solar water heater? Take for the incoming solar radiation a ratio exergy/energy of 0.99.

The solar water heater replaces heat that otherwise would have been produced in a high efficiency natural gas fired boiler with an efficiency of 102% (lower heating value, LHV based).
The natural gas in this case consists of 90 volume-% methane (CH_4, LHV = 35.8 MJ/m^3) and 10 volume-% nitrogen (N_2, LHV= 0.0 MJ/m^3). Molar masses are:
C : 12 kg/kmol
H : 1 kg/kmol
O : 16 kg/kmol
N : 14 kg/kmol
Molar volume for any gas: 22.4 m^3/kmol

b. Calculate the energy saved (LHV based) in GJ/year and in m^3/year through the application of the solar water heater

c. Calculate the avoided CO_2 emission in kg CO_2 per year.

3. Decomposition

The production and energy use data of (part of) the Margarine, oil and fat industry in The Netherlands is given in the following table:

	1990		1998		2000	
Product	production	Energy	production	energy	production	energy
	ktonne	TJ	ktonne	TJ	ktonne	TJ
margarine	390.7	543.1	450.3	718.1	429.6	657.0
sauces	97.2	184.3	134.9	245.9	125.9	234.3
fats	87.1	242.8	90.9	228.4	81.5	228.6

a. Determine the separate effects of volume, structure and efficiency between the years 1990 and 2000 using the second simple method in paragraph 13.2 of the book.
b. compose a decomposition graph similar to the one in figure 13.1 of the book.

4. Biomass production

In this question we are going to calculate the cost price of an energy crop. The production of poplar as an energy crop is a process with harvesting cycles of 4 years;
4 years after the trees are planted, they are harvested. A research project on the production of poplar is carried out. Land is bought, and sold again after the project finishes. Assume that the land can be sold for the same price as the purchase price. The following costs are estimated:

- Land purchase price: €5000/ha (ha = hectare)
- Annual overhead cost: €325/ha/year
- Planting cost: €100/ha
- Harvesting cost: €1388/ha

Furthermore:

- Estimated yield = 77 tonne/harvest/ha
- Discount rate = 6%
- Project lifetime = 4 years
- Moisture content poplar = 52%
- Energy content oven-dry poplar = 16 GJ/tonne LHV

As we calculate the cost price of the poplar, the *total* NPV of the project has to be 0, so that the total costs and benefits are equal ($C_{tot} = B_{tot}$). However, both costs *and* benefits need to be discounted: A yield in four years has a lower value than a yield now.

a. Calculate the present value (PV) of the total costs of the project (Hint: make a table of the costs per year).
b. Give an expression for the present value (PV) of the total benefits of the project.
c. Give an expression for the cost price of the yielded poplar, in €/tonne.
d. Calculate the cost price of the poplar in €/tonne.
e. Calculate the fuel cost of electricity (in €/kWh) when the biomass is combusted in a power plant with an efficiency of 40% (LHV based).

Answers Final Exam Energy Analysis 28-1-2010

1. Energy efficiency cars

a. energy use

From the book p.63-64 the following formula for the total fuel consumption of a car can be derived:

$$P_{total} = \frac{\left(P_a + P_r\right)/\eta_{tr} + E_{accessories}}{\eta_{engine,overall}}$$

where:

$P_a -$ power to overcome air resistance (eq. 3.14 book)

$P_r -$ power to overcome rolling resistance (eq. 3.14 book)

η_{tr} – transmission efficiency (90%)

$E_{accessories} -$ 0.50 kW

$\eta_{\text{engine, overall}} = \eta_{th}\eta_{mech}$

$\eta_{th} -$ 0.38

$\eta_{\text{mech}} -$ 0.50 (conventional), 0.65 (efficient)

Further data: frontal area 2 m^2, car mass 1100 or 1250 kg, velocity 90 km/h (=25 m/s), energy content petrol/gasoline: 33 MJ/liter.

Results:

Car	P_a (kW)	P_r (kW)	P_{total} (kW)	Fuel consumption (liter/100 km)
Conventional	4.69	2.70	45.8	**5.55**
Efficient	4.69	3.06	36.9	**4.47**

b. Energy savings

In l/100 km (see table above): 5.55 – 4.47 = 1.08 liter/100 km

25000 km/year gives an energy saving of 1.08 * 25000 / 100 = 270.2 liter/year

Energy content 33 MJ/liter (book table 2.3, p. 28)

Annual saving: 270.2 liter/yr * 33 MJ/liter / 1000 GJ/MJ = 8.92 GJ/yr

Second order approach: use ERE = 1.15 (table 8.1, p. 133, gasoline is a light oil product)

Primary energy saving = 8.92 GJ gasoline / yr * 1.15 GJ_{prim} / $GJ_{gasoline}$ = <u>10.25 GJ_{prim}/year</u>

c. energy payback period

Energy payback period = Primary Energy Investment / annual primary energy savings

Primary Energy Investment = $CED_{\text{extra weight}}$

Extra weight 1250 – 1100 = 150 kg

Use table 9.2 (CED values)

50% cold rolled steel : 75 kg cold rolled steel * 25.2 MJ/kg = 1.89 GJ

50% ABS: 75 kg ABS * 77.5 MJ/kg = 5.81 GJ

Total invested primary energy: 1.89 + 5.81 = 7.70 GJ

Annual primary energy savings: 10.24 GJ (answer question b)

=> energy payback period = 7.70 / 10.24 = <u>0.752 yr (275 days).</u>

d. (economic) Payback period

PBP = I / annual savings

I = investment minus subsidy = € 2500 – €400 = €2100

Annual energy savings: 270.2 liter gasoline / year * € 1.40 / liter = €378.28 / year

Tax benefit €160/year
Total annual savings: €378.28 + €160 = €538.28/year
PBP = € 2100 / €538.28 = 3.90 year

2. Solar water heater
a. Exergetic efficiency
Energy efficiency = output/input = 50/100 = 50%

Exergetic efficiency = output/input. Exergy/energy ratio solar radiation is 0.99. Say 100 units of solar radiation are emitted: input = 100 * 0.99 = 99 units.
For output we need the exergy/energy ratio of the heated water, according to formula [1.9]:

$$B/Q = \left[1 - \frac{T_{ref}}{T_h - T_l} \cdot \ln\left(\frac{T_h}{T_l}\right)\right] = \left[1 - \frac{283}{358-288} \cdot \ln\left(\frac{358}{288}\right)\right] = 0.120$$

50% of the solar radiation is converted into heat, so the output = 0.120*50 = 6.00 units.
Thus, the exergetic efficiency becomes output/input = 6.00/99 * 100% = 6.1%.

b. Energy savings
LHV basis: Annual natural gas savings: 6 GJ / 1.02 = 5.88 GJ / yr

LHV = 10% * 0.0 + 90% * 35.8 MJ/m^3 = 32.22 MJ/m^3
Annual gas savings = 5.88 10^3 MJ/yr / 32.22 MJ/m^3 = 182.5 m^3/yr

c. CO_2 avoided
emission factor natural gas: only the methane (CH_4) contains carbon which will combust to CO_2.
1 m^3 natural gas contains 0.9 m^3 CH_4
0.9 m^3 CH_4 equals 0.9 m^4 / 22.4 m^3/kmol = 0.0402 kmol CH_4/m^3 natural gas
Combustion: $CH_4 + 2O_2 \rightarrow CH_4 + 2H_2O$, so each kmol CH_4 gives a kmol CO_2
→ CO_2 : 0.0402 kmol/m^3 natural gas
Molar mass CO_2 = 1 C * 12 kg/kmol + 2 O * 16 kg/kmol = 44 kg/kmol
CO_2 production: 0.0402 kmol/m^3 natural gas * 44 kg/kmol = 1.77 kg CO_2/m^3 natural gas
LHV natural gas: 32.22 MJ/m^3 (question b)
Emission factor: 1.77 kg CO_2/m^3 / 32.22 MJ/m^3 = 0.0549 kg CO_2/MJ = 54.9 kg/GJ

CO_2 avoided = 5.88 GJ/yr * 54.9 kg CO_2/GJ = 323 kg CO_2/year

3. Decomposition
Table from question, with totals:

	1990		1998		2000	
Product	production	Energy	production	energy	production	energy
	ktonne	TJ	ktonne	TJ	ktonne	TJ
margarine	390.7	543.1	450.3	718.1	429.6	657
sauces	97.2	184.3	134.9	245.9	125.9	234.3
fats	87.1	242.8	90.9	228.4	81.5	228.6
total	**575**	**970.2**	**676.1**	**1192.4**	**637**	**1119.9**

The data for 1998 is redundant (not needed for answering the questions).

(average) specific energy use in 1990:

$$SEC_{1990} = \frac{E_{1990}}{P_{1990}} = \frac{970.2 \text{ TJ}}{575 \text{ ktonne}} = 1.69 \text{ TJ/ktonne}$$

In 2000 total production is 637 ktonnes, so the volume effect is:

$$E_{Vol,2000} = SEC_{1990} * P_{2000} = 1.69 * 637 = 1074.8 \text{ TJ} \qquad (104.6 \text{ TJ or } 10.8\% \text{ increase})$$

The volume+structure effect is determined by using the SEC's of 1990 and the production data of 2000. The SEC's are determined by dividing Energy use by production for each product:

	SEC-1990
	TJ/ktonne
margarine	1.390069
sauces	1.896091
fats	2.7876

$$\begin{aligned} E_{vol+struc,2000} &= P_{marg,2000} * SEC_{marg,1990} + P_{sauces,2000} * SEC_{sauces,1990} + P_{fats,2000} * SEC_{fats,1990} \\ &= 429.6 * 1.390 + 125.9 * 1.896 + 81.5 * 2.788 \\ &= 1063.1 \text{ TJ} \end{aligned}$$

The structure effect is therefore: $\Delta E_{struc,2000} = E_{vol+struc,2000} - E_{vol,2000} = 1063.1 - 1074.8 = -11.7 \text{ TJ}$

(production shifted towards less energy intensive products)

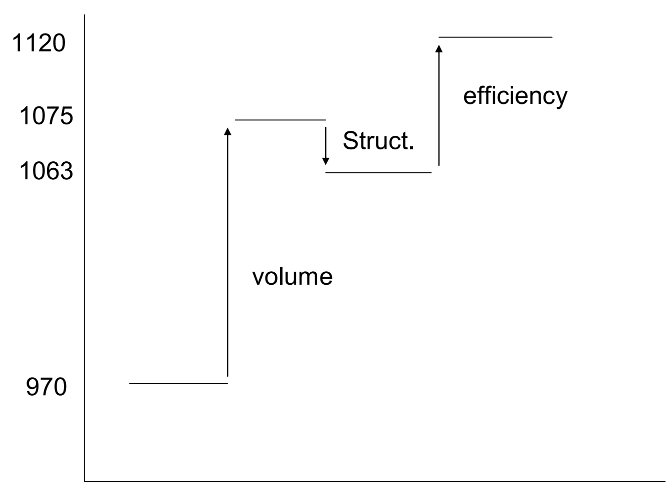
The total effect of volume, structure and efficiency is the energy use in the year 2000:

$$E_{vol+struc+eff,2000} = E_{2000} = 1119.9 \text{ TJ}$$

The efficiency effect is determined by subtracting the volume+structure energy use from the 2000 energy use:

$$\Delta E_{eff,2000} = E_{vol+struc+eff,2000} - E_{vol+struc,2000} = 1119.9 - 1063.1 = 56.8 \text{ TJ} \quad (5.9\ \% \text{ increase})$$

This industry has become less energy efficient!!



4. Biomass production

Use formula 11.1 from the textbook (note that equations 11.2 and 11.3 cannot be used since costs and benefits are not the same each year). We have to calculate the NPV of the costs and benefits per year since costs and benefits are not constant. Since we calculate the cost price of the poplar, the total NPV of the project has to be 0:

NPV = 0 $\rightarrow$ $\sum_{i=0}^{i=4} \frac{C_i}{(1+r)^i} = \sum_{i=0}^{i=4} \frac{B_i}{(1+r)^i}$

a. First we calculate the (N)PV of the net costs. It is important to start in year=0, since there is no discount effect for the initial investment. Overhead costs are applied for 4 years, so not in year 0! The discount rate r = 6%. The following table gives the NPV of the whole project:

	Costs per hectare						
year i	**Ground**	**Overhead**	**Planting**	**Harvesting**	**Total cost**	**$(1+r)^i$**	**NPV Costs**
0	€ 5,000.00		€ 100.00		€ 5,100.00	1	€ 5,100.00
1		€ 325.00			€ 325.00	1.06	€ 306.60
2		€ 325.00			€ 325.00	1.124	€ 289.25
3		€ 325.00			€ 325.00	1.191	€ 272.88
4	€ 5,000.00-	€ 325.00		€ 1,388.00	€ 3,287.00-	1.262	€ 2,603.61-
TOTAL					€ 2,788.00		**€ 3,365.12**

Note the negative sign when the land is sold after year 4. It is ok if you include selling of the land in the benefits, determined in subquestion b.

$\underline{NPV_{COSTS} = €3365.12/ha}$

b. $NPV_{BENEFITS} = \frac{p \cdot Y}{(1+r)^L}$

In which:

p = the cost price of the poplar (€/tonne)

Y = the yield per hectare (tonne/ha)

L = lifetime of the project (harvest cycle: 4 years)

c. $NPV_{COSTS} = NPV_{BENEFITS}$ => $NPV_{COSTS} = \frac{p \cdot Y}{(1+r)^L} \Rightarrow p = \frac{NPV_{COSTS}}{\left(\frac{Y}{(1+r)^L}\right)}$

d. $p = \frac{NPV_{COSTS}}{\left(\frac{Y}{(1+r)^L}\right)} = \frac{3365.12}{\left(\frac{77}{(1.06)^4}\right)} = \underline{55.17\ Euro/tonne}$

e. Moisture content poplar = 52%

Energy content oven-dry poplar = 16 GJ/tonne LHV

Efficiency power plant = 40%

Energy content yield = (1-52%) * 16 GJ = 7.68 GJ_{LHV} /tonne

Electricity generated = 7.68 * 40% =3.07 GJ_e/tonne = 852.78 kWh/tonne

Cost of electricity (coe) = €55.17/852.78 = $\underline{0.065\ €/kWh}$