

Final examination Energy Analysis, 25 January 2007, 9.00 –12.00

- This exam has 4 questions, each having equal weight
- You can use 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. Metal production

For a certain country, the amounts of steel, copper and aluminum produced are shown in the table below. Also, the total amount of energy used for the production of these metals is given.

Year	Steel (ton)	Copper (ton)	Aluminium (ton)	Primary energy use (TJ)
1990	5000	300	150	151
1995	6000	350	200	180
2000	7000	350	300	204

In the year 1990, the SEC for the production of steel was 20 GJ/ton, for copper this was 80 GJ/ton and for aluminium this was 180 GJ/ton.

- a. Calculate the PPI for 1995 and 2000 (1990 = 100).
- b. Calculate the EEI for 1995 and 2000 (1990 = 100).
- c. Calculate the average annual SEC reduction from 1990 until 2000.

2. Energy pay-back time photovoltaic power system

A 1 kW_p photovoltaic (PV) power system produces 1275 kWh electricity per year. The system consists of a 1 kW_p module, a 2.3 kg profile made from aluminium and an inverter of 1 kW capacity. The electric power system consists of coal power plants (efficiency 35%) and gas power plants (efficiency 50%). 40% of the electricity production of the power system is produced by coal power stations. The efficiency of electricity transport & distribution is 95%

Primary energy use for module production: 21 000 MJ per kW_p

Energy use for Aluminium production: 17.5 kWh electricity + 40 MJ natural gas per kg Aluminium.

Primary energy use for inverter production: 4000 MJ per kW installed capacity.

Use a second order approach for calculating primary energy requirements.

Question: What is the energy pay-back period (in years) of this PV power system?

3. HRe boiler versus Heat Pump

A HRe boiler is a micro-cogeneration unit suitable for households with an electrical efficiency of 24% and a total efficiency (LHV) of 105%. These boilers will soon be available in the market at a cost which is higher than standard boilers with an efficiency of 95% (LHV) and a price of € 2500,=. A possible competing technology is the electrical heat pump with a CoP of 4.0.

A typical household has a heat demand of 28 GJ/year.

Further data: gas price € 0.50 /m³ (LHV =31.5 MJ/m³), electricity price € 0.18/kWh. Efficiency of national electricity production: 42.5%. Assume no extra operation and maintenance costs. Life time of boilers and heatpumps is 15 years, discount rate is 10%.

- a. Calculate the first order primary energy savings of the HRe boiler and the heat pump per household per year

- b. Prices of HRe and Heat Pump systems are now more than €6000,= per household. What price should the HRe boiler and the heat pump have to become competitive with the standard boiler

4. Free rider and rebound effects of subsidies

In Lumenland energy saving fluorescent lightbulbs are sold for € 7. One 15 W energy saving lamp replaces a standard incandescent lamp of 60 W. Lumenland households have 15 lamps: 5 of them are used 2000 hours per year, 5 are used 1000 hours per year and 5 are used 100 hours per year. The electricity price is €0.20 per kWh.

The government of Lumenland considers giving a subsidy of € 3.00 for each energy saving lamp sold.

Further information:

lamps have a life time of 10000 burning hours.

Efficiency of electric power production in Lumenland: 40%

Lumenland households require (implicitly) that investments in energy efficiency must have a pay back period of no more than 5 years.

Average energy intensity of household expenditures: 2.90 MJ/€ (ignore this for expenditures on lamps)

Ignore extra operation and maintenance costs and the cost of standard incandescent lamps.

- a. How much electricity is saved in kWh per year per Lumenland household without subsidy
- b. When the subsidy plan is implemented: how much subsidy per household will be given and what part of this subsidy is free rider subsidy
- c. After implementation of the subsidy plan, estimate the annual primary energy savings per household accounting also for the rebound effect.
- d. Determine the efficiency of the subsidy plan by calculating how much primary energy is saved per year per € of subsidy after accounting for free rider and rebound effects.

Answers Final Exam Energy Analysis 25-1-2007

1. Metal production

a. Use formula 10.4 of the textbook. Use the reference SEC of 1990 as a weighting factor.

$$PPI_{1990} = 151 \text{ TJ} = \text{index } 100$$

$$PPI_{1995} = 20 \cdot 6000 + 80 \cdot 350 + 180 \cdot 200 = 184 \cdot 10^3 \text{ GJ} = 184 \text{ TJ} \rightarrow \text{index } 184/151 = 122$$

$$PPI_{2000} = 20 \cdot 7000 + 80 \cdot 350 + 180 \cdot 300 = 222 \cdot 10^3 \text{ GJ} = 222 \text{ TJ} \rightarrow \text{index } 222/151 = 147$$

b. Use formula 10.5 in textbook:

$$EEI_{1990} = \text{index } 100$$

$$EEI_{1995} = E_{1995}/PPI_{1995} = 180/184 = 0,978 \rightarrow \text{index} = 97.8$$

$$EEI_{2000} = E_{2000}/PPI_{2000} = 204/222 = 0,919 \rightarrow \text{index} = 91.9$$

c. Calculate the average annual SEC reduction:

PPI_{2000} is the energy use in 200 at constant SEC of the metals. E_{2000} is the actual energy use.

Therefore:

$$E_{2000} = PPI_{2000} \cdot (1-x)^{10} \quad \text{where: } x = \text{average annual SEC reduction}$$

$$204 = 222 \cdot (1-x)^{10}$$

$$1-x = (204/222)^{0,1} = 0,9915$$

$$x = 1 - 0,9915 = 0,0085 = 0,85\%$$

2. Energy Pay Back Period PV

Analysis: we have to calculate the period in which the 'invested' primary energy for producing the 1 kWp PV system is compensated by the primary energy savings caused by not having to produce the electricity in fossil fuel fired electric power plants. For this we have to calculate the 'invested' energy E_i (in MJ/kWp) and the annual primary energy savings E_s (in MJ/year). The energy payback period is then calculated as:

$$EPBP = \frac{E_i [\text{MJ}]}{E_s [\text{MJ/year}]} [\text{year}]$$

Note that second order primary energy calculations have to be performed.

We first calculate the primary energy requirement for electricity (because we will need this value in two places):

$$ERE_{el} = \frac{ERE_c \cdot f_c / \eta_c + ERE_g \cdot f_g / \eta_g}{\eta_{distr}} [\text{MJ}_p / \text{MJ}_e]$$

where ERE is the Energy Requirement for Energy (table 8.1, p. 133), f the fraction of the electricity production, η is the efficiency of electricity production, subscript c stands for coal, g stands for gas. η_{distr} is the efficiency of electricity production. Filling in the values (average values for fuel ERE):

$$ERE_{el} = \frac{1.07 \cdot 0.4 / 0.35 + 1.03 \cdot 0.6 / 0.50}{0.95} = 2.59 [\text{MJ}_p / \text{MJ}_e]$$

The energy investment E_i (in MJ/kWp) is calculated by adding the energy requirements for the three components:

Module: 21 000 MJ/kWp

Aluminium: $2.3 \text{ kg} \cdot (17.5 \text{ kWh/kg} \cdot 3.6 \text{ MJe/kWh} \cdot 2.59 \text{ MJp/MJe} + 1.03 [\text{MJp/MJgas}] \cdot 40 \text{ MJgas}) = 2.3 \text{ kg/kWp} \cdot 204 \text{ MJp/kg} = 470 \text{ MJp/kWp}$

Inverter: $4000 [\text{MJp/kW}] \cdot 1 [\text{kW/kWp}] = 4000 \text{ MJp/kWp}$

Total: 25470 MJp/kWp

The annual primary energy savings E_s (in MJp/year) are calculated by multiplying the annual electricity production by its ERE:

$$E_s = 1275 \text{ [kWh/year]} * 3.6 \text{ [MJe/kWh]} * 2.59 \text{ [MJp/MJe]} = 11880 \text{ MJp/year}$$

The energy payback period: $EPBP = 25470 / 11880 = \underline{2.14 \text{ year}}$

3. HRe versus Heat Pump

a. primary energy savings

HRe system: the primary energy savings are calculated by subtracting the primary energy use of the HRe system from the primary energy use of the conventional system. The HRe system produces electricity which does not have to be generated in the electric power system:

$$\begin{aligned} PES_{HRe} &= G_{conv} - (G_{HRe} - E_{HRe} / \eta_{e, publ}) \\ &= \frac{H}{\eta_{conv}} - \left(\frac{H}{\eta_{th}} - \left(\frac{\eta_e H}{\eta_{th}} \right) / \eta_{e, publ} \right) \\ &= \frac{28}{0.95} - \left(\frac{28}{1.05 - 0.24} - \left(\frac{0.24 * 28}{(1.05 - 0.24)} \right) / 0.425 \right) \\ &= 14.4 \text{ GJ/yr} \end{aligned}$$

Primary Energy Use Conventional boiler: 29.47 GJ/yr

Primary Energy Use HRe = 34.57 - 19.52 = 15.05 GJ/yr

For the heat pump the primary energy savings are calculated by subtracting the primary energy use of the electricity needed from the primary energy use of the conventional system:

$$\begin{aligned} PES_{HP} &= G_{conv} - \frac{E_{HP}}{\eta_{e, publ}} = \frac{H}{\eta_{conv}} - \left(\frac{H / COP}{\eta_{e, publ}} \right) \\ &= \frac{28}{0.95} - \left(\frac{28 / 4}{0.425} \right) = 29.47 - 16.47 = 13.0 \text{ GJ/year} \end{aligned}$$

b. Maximum boiler/heatpump price

To become competitive the extra investment (relative to the conventional boiler) should be lower than the present value of the energy cost benefits. Use eq. 11.2a from the book

$$NPV = -I + \frac{B - C}{\alpha}$$

set NPV to zero. The investment I is the extra investment relative to the conventional boiler, B-C is the annual net cost benefit.

$$I = \frac{B - C}{\alpha}$$

The capital recovery factor, given $r=0.1$, $L=15$ yrs can be calculated with eq. 11.2b or found in table 11.1. $\rightarrow \alpha=0.131$.

For the HRe boiler:

$$\begin{aligned}
I &= \frac{p_G G_{conv} - p_G G_{HRe} + p_{el} E_{HRe}}{\alpha} \\
&= \frac{p_G \frac{H}{\eta_{conv}} - p_G \frac{H}{\eta_{th}} + p_{el} \frac{\eta_e H}{\eta_{th}}}{\alpha} \\
&= \frac{0.5[\text{€}/\text{m}^3]/31.5 \cdot 10^{-3}[\text{GJ}/\text{m}^3] * \frac{28[\text{GJ}/\text{yr}]}{0.95} - 0.5/31.5 \cdot 10^{-3} * \frac{28}{1.05 - 0.24} + 0.18/3.6 \cdot 10^{-3} * \frac{0.24 * 28}{1.05 - 0.24}}{0.131[1/\text{yr}]} \\
&= \text{€}2540
\end{aligned}$$

The highest price is for the HRe boiler is therefore €2500 + €2540 = €5040

For the Heat Pump:

$$\begin{aligned}
I &= \frac{p_G G_{conv} - p_{el} E_{HP}}{\alpha} \\
&= \frac{p_G \frac{H}{\eta_{conv}} - p_{el} \frac{H}{COP}}{\alpha} \\
&= \frac{0.50[\text{€}/\text{m}^3]/31.5 \cdot 10^{-3}[\text{GJ}/\text{m}^3] * \frac{28[\text{GJ}/\text{yr}]}{0.95} - 0.18[\text{€}/\text{kWh}]/3.6 \cdot 10^{-3}[\text{GJ}/\text{kWh}] * \frac{28}{4}}{0.131} \\
&= \text{€}896
\end{aligned}$$

The highest price for the heat pump is therefore €2500 + €896 = €3396

Note: another more or less similar approach is calculating the cost of heat production for a conventional boiler using eq. 11.3 and setting this equal to the cost of heat production for the alternatives (using the same equation), giving one equation with the investment of the alternative as the only unknown.

4. Lumenland

a. Electricity savings without subsidy

Energy saving lamps will be applied when the Pay Back Period is less than 5 years:

Pay Back Period is function of burning hours h :

$$PBP = \frac{I}{B - C} = \frac{I}{B} = \frac{7[\text{€}]}{0.20[\text{€}/\text{kWh}](60 - 15)[\text{W}] * 10^{-3}[\text{kW}/\text{W}] * h[\text{hr}/\text{yr}]}$$

burning time [hr/yr]	2000	1000	100
PBP	0.39	0.78	7.77
Electr. savings [kWh/yr/lamp]	90	45	4.5

Only the lamps burning 2000 or 1000 hr/yr will be installed.

Savings: $5 * (90 + 45) = 675$ kWh/household

b. Subsidy per household.

The lamps now cost € 4 per lamp

burning time [hr/yr]	2000	1000	100
PBP	0.22	0.44	4.44
Electr. savings [kWh/yr/lamp]	90	45	4.5

All lamps will be implemented. Subsidy: 15 lamps * €3 = € 45

Without subsidy the lamps burning 100 hr/yr would not have been installed.

Free rider subsidy (discussed on p. 244 of the book) is therefore 10 lamps * €3 = € 30 (accepted answer).

Better answer: for the lamps burning 100 hours per year only € 2.50 subsidy is needed to fulfil the 5 year PBP requirement therefore free rider becomes €30 + 5 *(€ 3.00 – €2.50) = €32.50/household

c. Rebound (book p. 248-249)

Energy savings after subsidy: all lamps are installed,

Energy savings: 5 *(90 + 45 + 4.5) = 697.5 kWh/hh/yr

Energy cost savings: 0.20 [€/kWh] * 697.5 [kWh/hh/yr] = 139.5 [€/hh/yr]

Rebound: assume households use the savings for average expenditures which require 2.90 MJ/€

=> Rebound = 2.90 [MJp/€] * 139.5 [€/hh/yr] = 405 [MJp/hh/yr]

Primary energy savings: 697.5 [kWh/hh/yr] * 3.6 [MJ/kWh] / 0.4 [MJ€/MJp] = 6277 MJp/hh/yr

Primary energy savings after accounting for rebound: 6277 – 405 = 5872 MJp/hh/yr

d. efficiency of subsidy

Extra savings caused by subsidy is only the savings caused by the lamps burning 100 hr/yr.

Savings: 4.5 * 5 = 22.5 kWh/yr

Energy cost saving by these lamps: 0.20 * 22.5 = 4.5 €/hh/yr

Rebound: 4.5 * 2.9 = 13.05 MJp/hh/yr

Primary energy savings: 22.5 kWh/yr * 3.6 MJ/kWh / 0.4 [MJp/MJ] = 202.50 MJp/hh/yr

Net primary energy savings: 202.50 – 13.05 = 189.45 MJp/hh/yr

Subsidy: 15 lamps/hh * € 3 /lamp = €45 /hh

efficiency: 189.45 / 45 = 4.21 MJp/€/yr

Alternatively: calculate efficiency in MJp/€ taking life time of 10 000 burning hours into

consideration: savings 5 lamps * 45 W * 10⁻³ [kW/W] * 10 000 [h] = 2250 kWh

Energy cost savings: 0.20 * 2250 = €450

Primary energy savings: 2250 * 3.6 /0.4 = 20 250 MJp/hh

Rebound: 450 * 2.9 = 1305 MJp/hh

Net primary energy savings 20250 – 1305 = 18945 MJp/hh

Subsidy 15 * €3 = €45

efficiency: 18945 / 45 = 421 MJp/€