Universiteit Utrecht

Advanced Energy Analysis GEO4-2508

Final Assignment A – More efficient use of energy in residential areas

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Question 1:

In this assignment is asked to analyse three different energy conversion technologies for residential areas and compare them to the actual situation, the reference scenario (Figure 4), in which each individual house contains a boiler based on CH_4 producing heat.

The first new scenario, Figure 1, represents a central fuel cell cogenerating electricity and heat to individual houses. The fuel cell system uses a reformer to convert CH_4 to syngas and has a fuel cell stack. The process starts when fuel is processed in the reformer and is transformed into syngas, which then reacts with external air producing useful heat and electricity in form of DC power. After this, an inverter transforms DC power into AC power ready to be sent to the electricity grid and used.

Outside the system boundaries there is the national electricity grid, which exchanges electricity and CH_4 with the system.

The only process involving CO_2 emissions is the transformation of CH_4 into heat in the reformer.

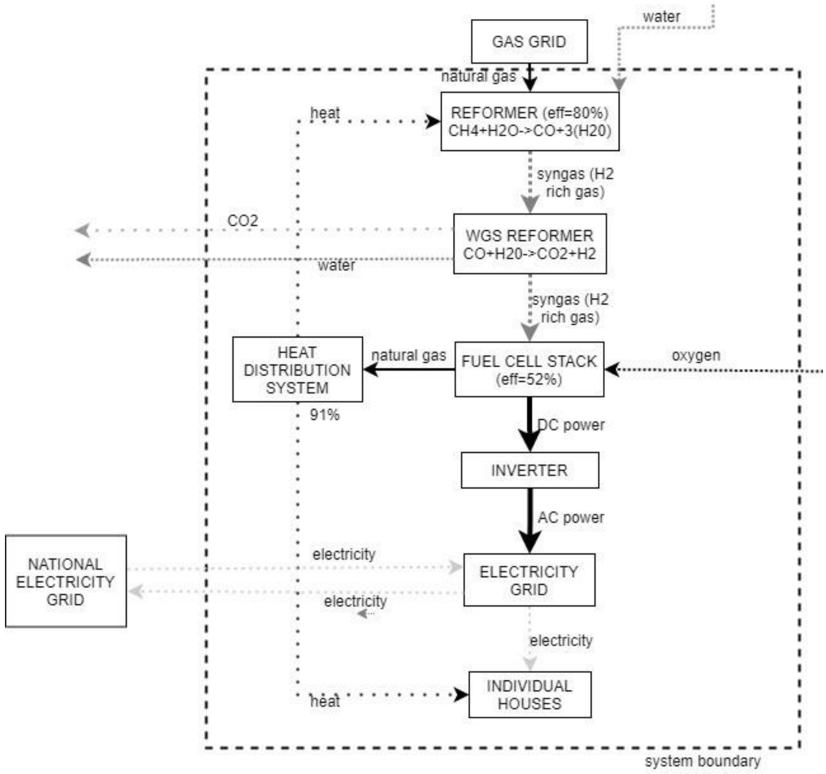

Figure 1: *Flowsheet of scenario 1.*

The second scenario (Figure 2) is similar to the first one, except that CH_4 is delivered directly to individual houses that are provided with a fuel cell, instead of a central one, and the same process happens in the reformer as in Scenario 1.

A big difference is given by the fact that, since each house has a fuel cell, the size of each one of them is smaller compared to Scenario 1 and has lower efficiency. Moreover, each house is connected to the grid so can exchange CH_4 and electricity with it.

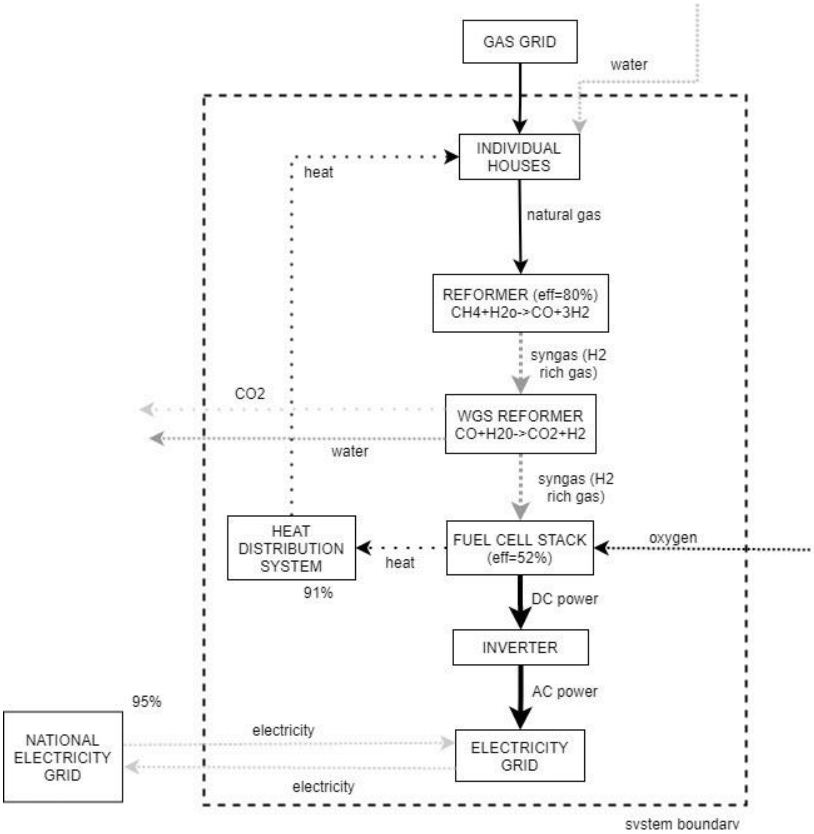

Figure 2: *Flowsheet of scenario 2.*

Lastly, in the third scenario each house, instead of a fuel cell, is equipped with a heat pump that uses electricity to produce heat.

The most important indicator for this scenario is the COP (coefficient of performance), calculated using thermodynamic diagram of a heat pump and thermodynamic tables. It is defined as:

$$COP = \frac{Desired\ output}{Required\ input} = \frac{Q_{useful}}{W_{input}} = \frac{\Delta h_{heat\ output}}{\Delta h_{elec\ input}} \quad [1]$$

Which returns 4.25.

This value has to be corrected by seasonal performance (0.5) becoming $4.25 - 0.5 = 3.75$.

Finally, the Reference Scenario, showed in Figure 4, only has a boiler in each household and does not have the possibility to sell electricity to the grid, just to buy it from.

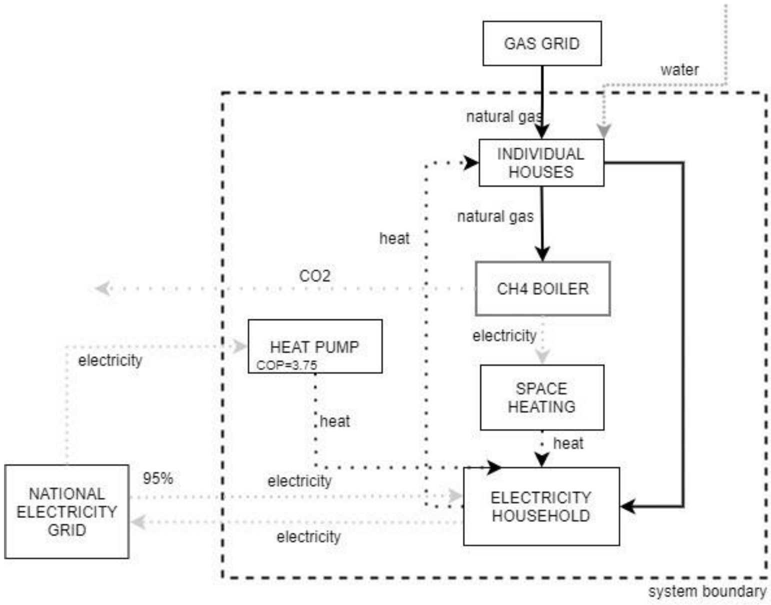

Figure 3: *Flowsheet of scenario 3.*

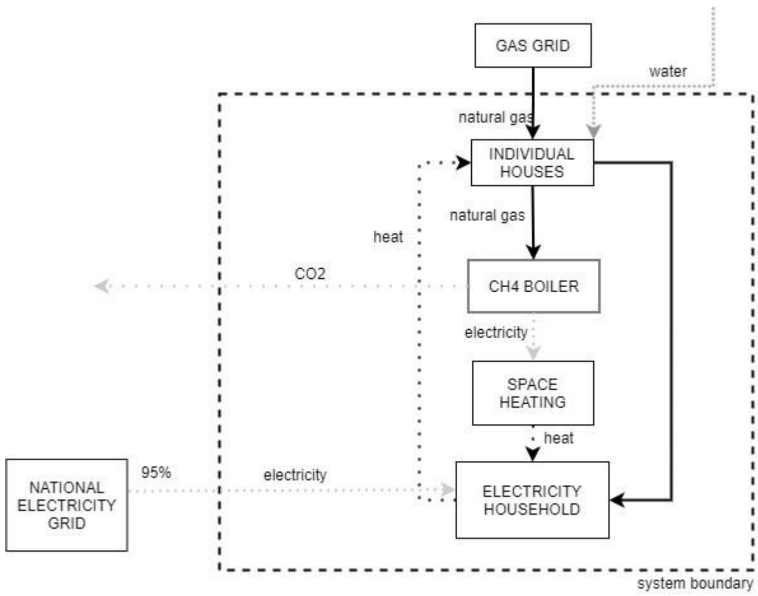

Figure 4: *Flowsheet of the reference scenario.*

Question 2:

Question 2.a:

The average CO_2 emission factor in the Netherlands from electricity produced in the grid is calculated using the following equation:

$$EF_{grid} = \frac{Total\ CO_2\ emitted}{Total\ electricity\ produced} \quad [2]$$

Where:

$$Total\ electricity\ produced = (Total\ electricity\ production - Imported\ electricity) * National\ grid\ distribution \quad [3]$$

And:

$$Total\ CO_2\ emitted = \sum_{fuel\ i} EF_{fuel\ i} * amount\ of\ fuel\ i\ use \quad [4]$$

$EF_{fuel\ i}$ is the emission factor of each fuel type. Fuel types are three in this system: coal, natural gas and other fuels.

After these calculi is showed that the average CO_2 emission factor in the Netherlands is 222.38 $kgCO_2/GJ$, or 0.8006 $kgCO_2/kWh$ if converted.

Question 2.b:

The calculus for the needed amount of natural gas and electricity to cover a household's demand will now be showed divided by scenario, since each one has different characteristics.

Scenario 1:

The amount of natural gas is calculated with the following equation:

$$NG = \frac{Heat\ demand}{\eta_{syngas} * \eta^{th}_{fuel\ cell} * \eta_{heat\ dist\ syst}} \quad [5]$$

The required electricity is calculated considering it is the difference between the household electricity demand and the one produced, in this case by the fuel cell:

$$Electricity = Electricity_{dem} - NG * \eta_{syngas} * \eta^{el}_{fuel\ cell} \quad [6]$$

Where η_{syngas}, $\eta^{th}_{fuel\ cell}$, $\eta_{heat\ dist\ syst}$ and $\eta^{el}_{fuel\ cell}$ are, respectively, the efficiency of the reformer (that produces syngas), the thermal efficiency of the fuel cell, the heat distribution efficiency and the electrical efficiency of the fuel cell. $Heat\ demand$ is 52 GJ, $Electricity_{dem}$ is 18 GJ.

Scenario 2:

For Scenario 2 the calculus for the amount of natural gas is similar to Scenario 1, except that is not divided by the heat distribution efficiency. Thus the equation is:

$$NG = \frac{Heat\ demand}{\eta_{syngas} * \eta^{th}_{fuel\ cell}} \quad [7]$$

The equation for the required electricity is the same as for Scenario 1, Equation 6.

Scenario 3:

In this scenario the amount of natural gas does not depend on the entire heat demand, but only on what is not space heating, since this will be supplied by the heat pump.

The equation here is:

$$NG = \frac{Heat\ demand - Space\ heating}{\eta_{boiler}} \qquad [8]$$

Where η_{boiler} is the boiler efficiency and $Space\ heating$ corresponds to 45 GJ. The COP of the heat pump has already been shown in Equation 1.

Electricity depends strictly on the COP, since its formula is:

$$Electricity = \frac{Electricity_{dem} + \frac{Space\ heating}{COP}}{\eta_{grid}} \qquad [9]$$

Where η_{grid} is the grid efficiency.

Reference scenario:

The reference scenario has only the boiler to supply the households heat demand. The amount of NG is:

$$NG = \frac{Heat\ demand}{\eta_{boiler}} \qquad [10]$$

While electricity is calculated considering the grid efficiency as in Scenario 3:

$$Electricity = \frac{Electricity_{dem}}{\eta_{grid}} \qquad [11]$$

Table 1 contains all the values for amount of natural gas and electricity divided by scenario.

Table 1: *Amount of natural gas and electricity used to cover the heat and electricity demand.*

	Scenario 1	Scenario 2	Scenario 3	Scenario reference
Natural gas (GJ/hh/y)	178.57	185.71	7.37	54.74
Electricity used (GJ/hh/y)	-56.29	-37.90	31.58	18.95

As can be seen in Table 1, Scenario 1 and 2 have a negative value for the electricity used, this is because they produced more electricity than demanded and sell it to the grid. It is assumed that no electricity is lost during exportation to the grid.

Figure 5 shows these figures in a plot.

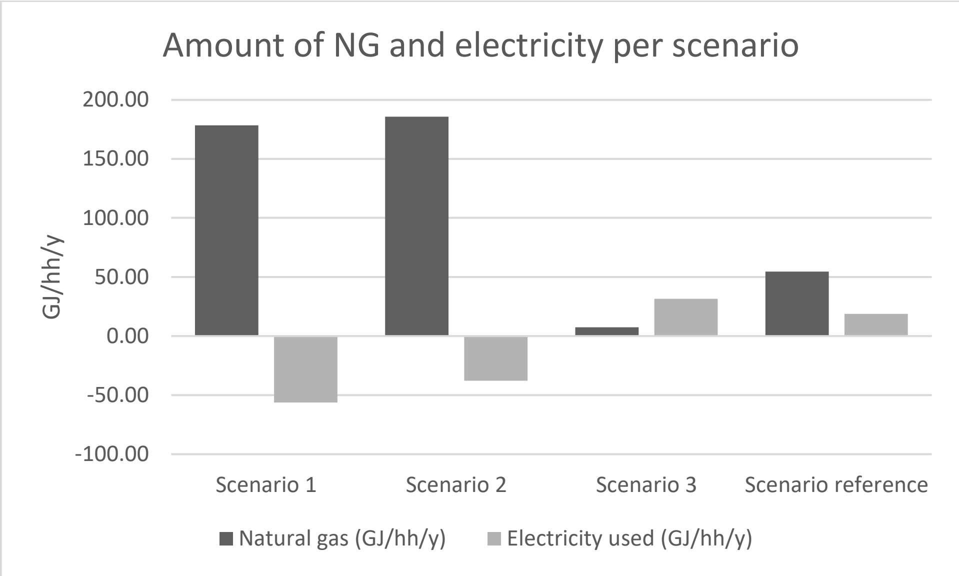

Figure 5: *Amount of Natural Gas and Electricity each scenario needs to cover the energy demand of one household.*

The plot shows clearly that Scenario 3 and the Reference Scenario need much less natural gas, but the natural gas of Scenario 1 and 2 allows to produce more electricity and sell it to the grid.

Question 2.c:

For the calculation of the CO_2 emissions each scenario produces and the difference in respect to the Reference Scenario, there will also be a division between scenarios, in order to better understand what are the differences in their formulas.

One general value is the natural gas emission factor, here considered to be 56 $kgCO_2$/GJ.

Furthermore, the total emissions are, for each scenario:

$$Emissions_{tot} = Emissions_{NG} + Emissions_{elec} \qquad [12]$$

Scenario 1:

The amount of emissions produced by natural gas for this scenario is given by the formula:

$$Emissions_{NG} = NG * EF_{NG} \qquad [13]$$

Where EF_{NG} is 56 $kgCO_2$/GJ, as said above.

Emissions produced by the electricity are calculated with a similar formula, except that electricity has a different emission factor, which is the value calculated in Equation 2.

$$Emissions_{elec} = Electricity * \ EF_{grid} \qquad [14]$$

Scenario 2:

Emissions for this scenario are calculated exactly as for Scenario 1, thus refer to Equation 13 and 14.

Both Scenario 1 and 2 have negative emissions (credits) because electricity is sold to the grid.

Scenario 3:

In this scenario emissions produced by natural gas are calculated again with the same formula of Scenario 1 (Equation 13), but instead emissions from electricity have a different calculus.

$$Emissions_{elec} = Electricity_{dem} + \frac{Space\ heating}{COP} \quad [15]$$

Reference scenario:

Electricity of the Reference Scenario is $Electricity_{dem}$= 18 GJ.

Table 2 contains all the values of total CO_2 emissions and the reduction compared to Reference Scenario. Figure 6 shows these values in a plot.

Table 2: *Amount of CO_2 emissions of each scenario and reduction compared to the reference scenario.*

	Scenario 1	Scenario 2	Scenario 3	Scenario reference
CO2 emissions (GJ/hh/y)	-2516.80	1971.81	7084.02	7068.10
Emission reduction compared to reference (GJ/hh/y)	9584.89	5096.29	-15.92	-

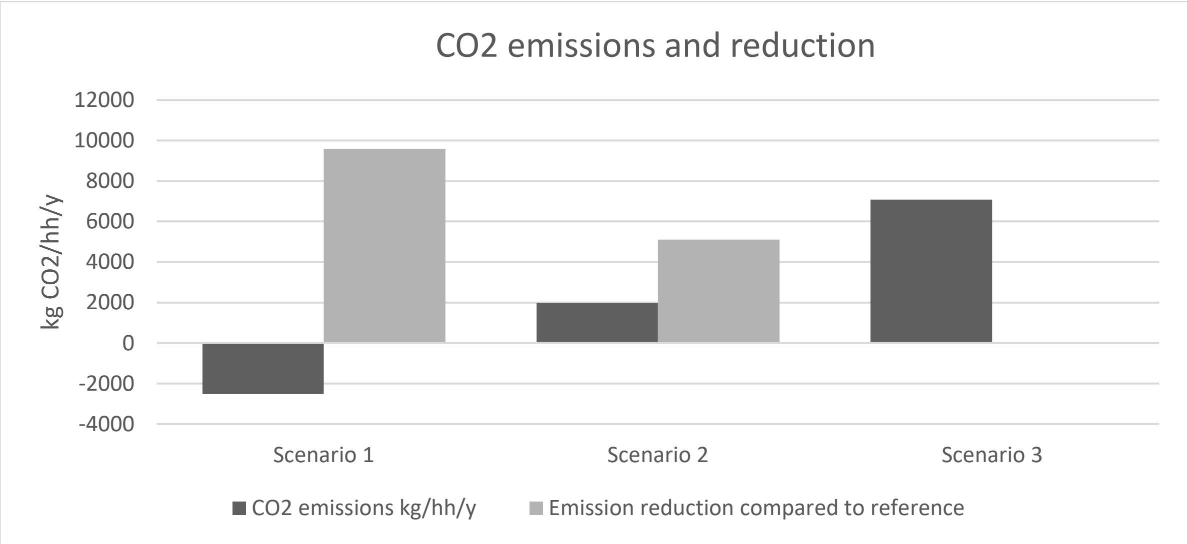

Figure 6: *Bar diagram showing CO_2 emissions of each scenario.*

These data show that only Scenario 1 has negative emissions (credits) despite the fact that Scenario 2 also sells electricity to the grid. This is because the emissions from natural gas overcome the ones from electricity in that scenario.

The negative emissions of Scenario 1 make it have the highest reduction compared to the Reference Scenario, which is quite normal.

Question 3:

Question 3.a:

A What-if analysis will now be performed in order to evaluate the variation in CO_2 emissions for each scenario, modifying the emission factor value. The value range starts at 222.38 kgCO_2/GJ and it is supposed to decrease at 20.9 kgCO_2/GJ, which is the target set for greenhouse gas emissions in the Netherlands by 2030. The greenhouse gas emission decrease has been set by the European Environment Agency.

This decreasing trend is analyzed in Table 3.

Table 3: *Amount of CO_2 emission reduction with Dutch emission factor variation [kgCO_2/hh/y].*

Emission	Scenario 1	Scenario 2	Scenario 3
222.38	9584.89	5096.29	-15.92
200	7922.41	3845.26	252.63
180	6436.69	2727.26	492.63
160	4950.98	1609.26	732.63
140	3465.26	491.26	972.63
120	1979.55	-626.74	1212.63
100	493.83	-1744.74	1452.63
80	-991.88	-2862.74	1692.63
60	-2477.59	-3980.74	1932.63
40	-3963.31	-5098.74	2172.63
20.9	-5385.88	-6169.22	2402.43

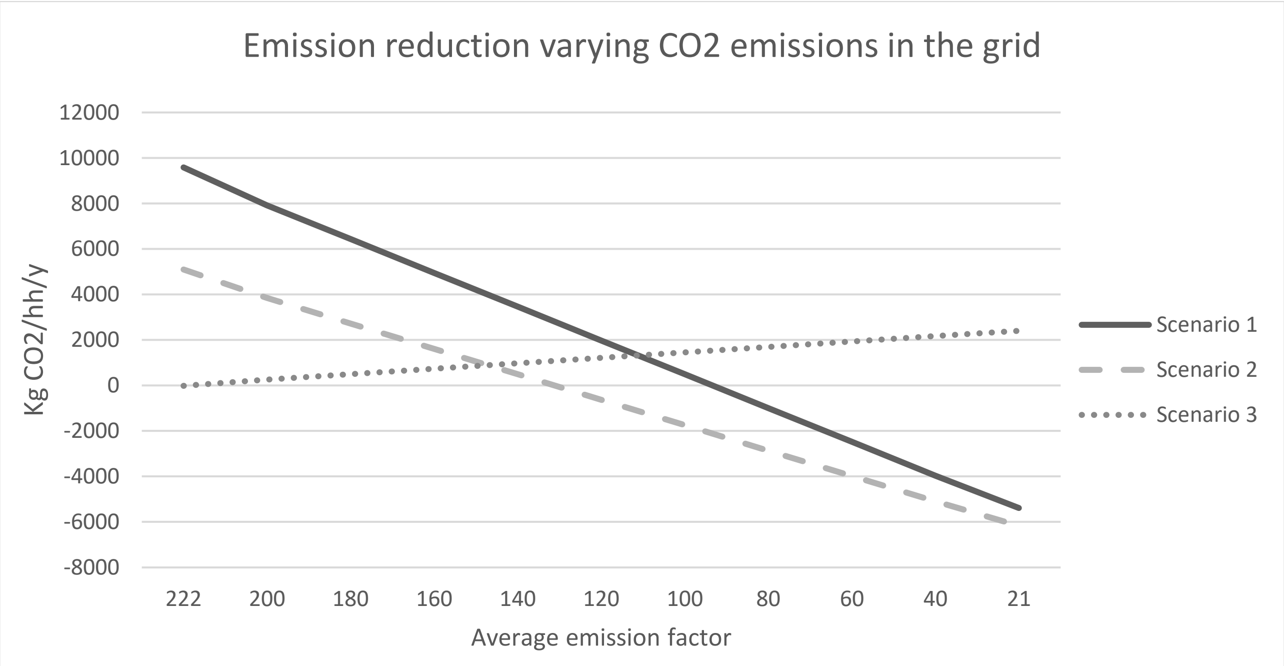

Figure 7: *Emission reduction varying CO_2 emissions in the grid.*

From Figure 7 it is immediately visible that CO_2 emissions in Scenario 1 and 2 have decreased with the reduction of the grid's emissions, while those of Scenario 3 increased.

This difference is given by each scenario's electricity production: Scenario 1 and 2 use a fuel cell, thus if the grid emissions decrease the electricity produced and exported has lower value. Differently, Scenario 3 has a heat pump which would benefit from lower emissions.

Question 3.b:

Another What-if analysis now will show how CO_2 emissions change when the overall efficiency (for the fuel cell) or the COP (for the heat pump) have a different value. Values are shown in Table 4.

Table 4: *Amount of CO_2 emission variation when COP and combined fuel cell or reformer change [$kgCO_2$/hh/y].*

Overall efficiency variation	Scenario 1	Scenario 2	COP	Scenario 3
1.7	13702.54	9378.64	6.375	1082.89
1.6	13334.89	8996.29	6	984.78
1.5	12918.23	8562.95	5.625	873.59
1.4	12442.04	8067.71	5.25	746.52
1.3	11892.59	7496.29	4.875	599.90
1.2	11251.56	6829.62	4.5	428.84
1.1	10493.98	6041.74	4.125	226.67
1	9584.89	5096.29	3.75	-15.92
0.9	8473.78	3940.73	3.375	-312.43
0.8	7084.89	2496.29	3	-683.06

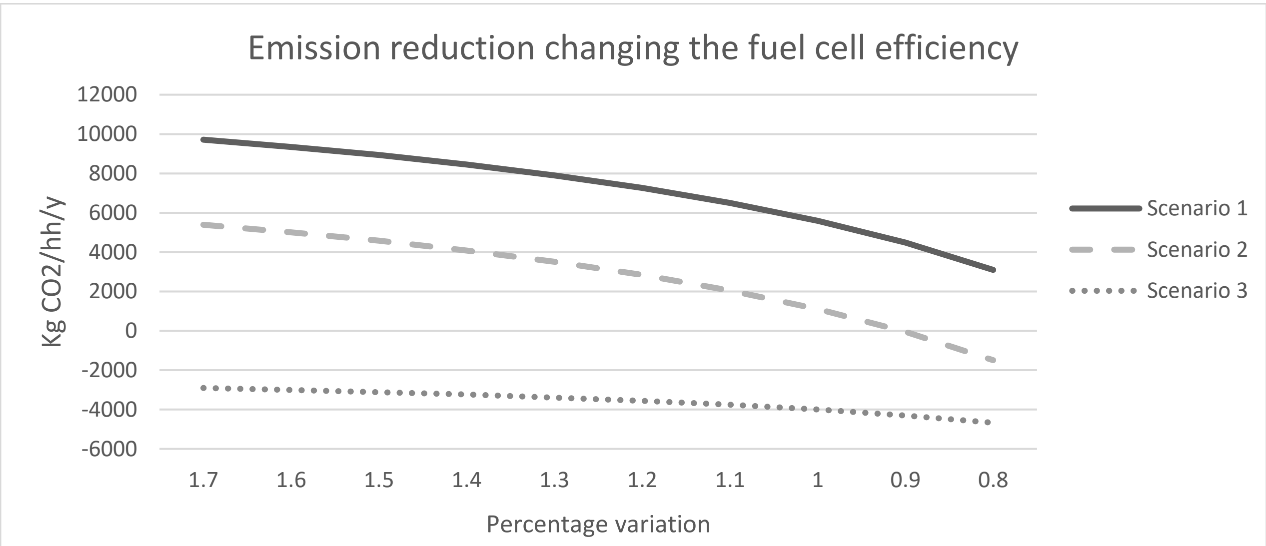

Figure 8: *Emission reduction varying the fuel cell efficiency/ heat pump COP.*

All the scenarios have a decreasing trend, even though Scenario 1 and 2 are steeper than Scenario 3. The trend is not completely linear, even though with a wider range it would probably be slightly more linear.

The decreasing trend depends on the fact that the amount of natural gas depends on $\frac{1}{\eta_{FC}^{th}*\eta_{ref}}$ (Eq.5), while the electricity exported remains constant.

As for Scenario 3, the trend is similar, except that a heat pump needs more energy to produce the same amount of heat, thus the slope is quite smooth.

Question 4:

From now on, the fuel cell or the heat pump will not supply the entire demand of heat, but it is assumed that there is also a boiler.

CF is defined as the fraction of maximum heat production capacity covered by the fuel cell or heat pump respect to the boiler.

Fa is then defined as the heat demand share covered by the fuel cell or heat pump:

$$Fa = 1 - (1 - CF)^2 \qquad [16]$$

And Fb by the boiler:

$$Fb = 1 - Fa \qquad [17]$$

The initial fuel cell capacity was 7 kW, thus $CF = 1$, and the aim here is to perform a sensitivity analysis in which CF varies to see the variation in CO_2 emissions. The analysis has been done varying CF from 0.1 until 0.9, because since it is a fraction its value can be comprised between 0 and 1 and 1 is the same situation analyzed before, while 0 would not give interesting values.

The amount of total CO_2 emissions is given by both natural gas and electricity emissions, as said in Question 3. The amount of CO_2 emissions produced by the reference scenario is always the value calculated in Question 2.c: 7068.1 kg.

Heat covered by the fuel cell or heat pump is given by:

$$Heat_{FC,HP} = Heat\ demand * Fa \qquad [18]$$

And heat covered by the boiler is given by:

$$Heat_{boiler} = Heat\ demand * Fb \qquad [19]$$

Table 5 shows the values for net electricity and the intermediate steps.

Table 5: *Total emissions with different CF.*

			Scenario 1			Scenario 2			Scenario 3	
CF	Fa	Fb	NG used FC	NG used boiler	Net electricity	NG used FC	NG used boiler	Net electricity	NG used boiler	Net electricity
0.1	0.19	0.81	33.93	44.34	3.89	35.29	44.34	7.38	45.74	20.28
0.25	0.44	0.56	78.13	30.79	-14.50	81.25	30.79	-6.46	34.01	23.25
0.375	0.61	0.39	108.82	21.38	-27.27	113.17	21.38	-16.06	25.87	25.31
0.429	0.67	0.33	120.26	17.87	-32.03	125.07	17.87	-19.65	22.84	26.08
0.5	0.75	0.25	133.93	13.68	-37.71	139.29	13.68	-23.93	19.21	27.00
0.675	0.89	0.11	159.71	5.78	-48.44	166.10	5.78	-32.00	12.37	28.73
0.75	0.94	0.06	167.41	3.42	-51.64	174.11	3.42	-34.41	10.33	29.25
0.9	0.99	0.01	176.79	0.55	-55.54	183.86	0.55	-37.34	7.84	29.88

For Scenario 1, the natural gas used by fuel cell is calculated with Equation 5, where instead of Heat demand it's used $Heat_{FC}$. The natural gas used by the boiler is instead calculated using Equation 8.

For Scenario 2, natural gas used by fuel cell is calculated as Equation 7 and the one of boiler is the same of Scenario 1, with Equation 8.

For Scenario 3, only the boiler uses natural gas thus the formula is the same of Equation 8, using Heat as the one in Equation 18.

Table 6 contains the emission reduction of each scenario compared to the Reference. Emissions are calculated exactly like Equations 12-15. Emission reduction is calculated by subtracting emissions to the Reference Scenario of Table 2.

Table 6: *Total emission reduction compared to the reference scenario with different CF.*

	Scenario 1		Scenario 2		Scenario 3	
CF	Emissions produced	Emission reduction	Emissions produced	Emission reduction	Emissions produced	Emission reduction
0.1	5246.97	1821.13	6099.80	968.29	7071.12	-3.03
0.25	2874.71	4193.39	4838.47	2229.62	7075.06	-6.97
0.375	1227.30	5840.79	3962.55	3105.55	7077.80	-9.70
0.429	612.96	6455.13	3635.90	3432.19	7078.82	-10.72
0.5	-120.57	7188.67	3245.88	3822.21	7080.04	-11.94
0.675	-1504.39	8572.49	2510.11	4557.99	7082.34	-14.24
0.75	-1917.74	8985.84	2290.33	4777.77	7083.03	-14.93
0.9	-2420.95	9489.05	2022.77	5045.32	7083.86	-15.76

Here follows in Figure 9 a plot of the emission reduction of each scenario compared to reference.

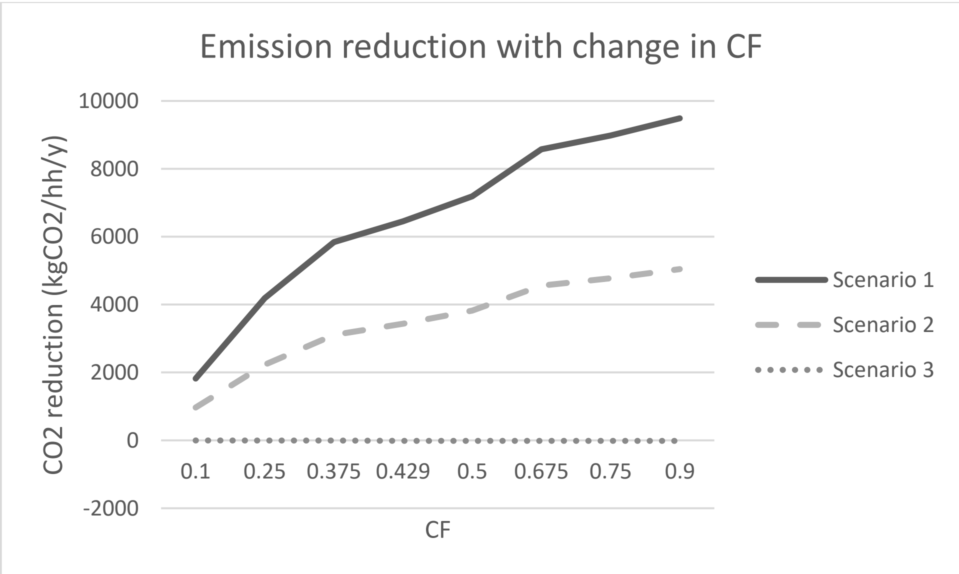

Figure 9: *Emission reduction compared to the reference scenario for each value of CF.*

Since Scenario 1 and 2 export electricity to the grid, emitting credits, the higher is CF, the more their emission reduction increases. The trend of both these scenarios is positive because EF_{grid} is higher than EF_{NG}.

Table 6 and Figure 9 also show that the emissions for Scenario 3 don't change much when CF changes. To better understand the reason of this, let's have a look at the following equation:

$$EF_{HP} = \frac{EF_{grid}}{COP} \quad [20]$$

Which is a constant value, 53.3 kg CO_2/GJ, just a bit higher than EF_{NL}, meaning that even if CF changes and the heat pump produces with a different fraction compared to the boiler, this is not important because their EF is similar so they produce the same amount of emissions.

Question 5:

Now it is supposed that each house also has a boiler and the purpose is to determine the total annual costs. To be able to calculate them, the first thing to do is calculate the actual costs for gas boiler, fuel cell, reformer and heat pump that are set on different scale bases.

The scaling equation is:

$$\frac{Cost\ (size\ 2)}{Cost\ (size\ 1)} = \left(\frac{Size\ 2}{Size\ 1}\right)^R \qquad [21]$$

Where $size\ 1$ is the model system capacity, 7 kW, and $Cost(size\ 1)$ the correspondent cost. $size\ 2$ and its cost are based on the base-scale capacity (in the following equations will be not called size 2 but instead of the '2' the name of the power system, i.e. fuel cell, reformer, heat pump and boiler), which has a different value depending on the scenario. R is the scaling factor.

To calculate the annual cost has been used the formula:

$$Cost_{year} = I * \alpha + O\&M + F \qquad [22]$$

Where F represents the fuel costs (both natural gas and electricity), I is the initial investment and α is calculated as:

$$\alpha = \frac{r}{1-(1+r)^{-L}} \qquad [23]$$

Where r is the discount rate and L the total duration of the plant (20 years). Here r = 0.1, so α = 0.117. Natural gas cost is 10 €/GJ for Scenario 1 and 2, 20 €/GJ for Scenario 3 and the Reference Scenario. Electricity cost is, for each scenario, 60 €/GJ if bought from the grid, 20 €/GJ if sold to the grid.

It is assumed that there are 1000 households and the scaling factor R is 0.9 for fuel cell and boiler while it is 0.75 for reformer and heat pump.

Question 5.a:

Now each scenario will be seen separately.

Scenario 1:

The scenario presents distribution heat losses because the fuel cell is outside, thus its thermal capacity is not 7 kW but is:

$$size_{FC} = \frac{size\ 1 * 1000}{\eta_{heat\ dist\ syst}} \qquad [24]$$

And the reformer size:

$$size_{Ref} = \frac{size_{FC}}{\eta^{th}_{fuel\ cell}} \qquad [25]$$

Table 7 shows the results for both fuel cell and reformer.

Table 7: *Size and scaled cost for fuel cell and reformer in Scenario 1.*

Fuel cell		Reformer	
cost (size 1) (€)	10500	cost (size 1) (€)	450
cost (size 2) (€)	5728646.79	cost (size 2) (€)	8452195.20
size 1 (kW)	7	size 1 (kW)	17500
size 2 (kW)	7692.31	size 2 (kW)	19230.77
R	0.9	R	0.75

Scenario 2:

In this scenario there are no distribution losses since the fuel cell is inside the household instead of outside, thus its heat capacity is exactly 7 kW. The reformer size uses the same formula of scenario 1, Equation 25.

Table 8 shows the results for both.

Table 8: *Size and scaled cost for fuel cell and reformer in Scenario 2.*

Fuel cell		Reformer	
cost (size 1) (€)	10500	cost (size 1) (€)	7875000
cost (size 2) (€)	10500	cost (size 2) (€)	44284.38
size 1 (kW)	7	size 1 (kW)	17500
size 2 (kW)	7	size 2 (kW)	17.5
R	0.9	R	0.75

Scenario 3:

In this scenario there is only a heat pump, and its required power has to take the COP into account. The heat pump size is calculated as:

$$size_{heat\ pump} = \frac{size\ 1}{COP} \qquad [26]$$

Table 9 shows the results.

Table 9: *Size and scaled cost for heat pump in Scenario 3.*

Heat pump	
cost (size 1) (€)	11500
cost (size 2) (€)	7500.88
size 1 (kW)	3.3
size 2 (kW)	1.87
R	0.75

Reference Scenario:

Being the initial scenario, there are no investment costs and no heat distribution losses, thus the boiler size is 7 kW.

Table 10: *Size and scaled cost for boiler in Reference Scenario.*

Gas boiler	
cost (size 1) (€)	1015
cost (size 2) (€)	1015
size 1 (kW)	7
size 2 (kW)	7
R	0.9

The breakdown and total costs of each scenario are now presented in Table 11 and the correspondent plot in Figure 10.

Table 11: *Breakdown and total cost of each scenario.*

	Scenario 1	Scenario 2	Scenario 3	Scenario ref
Fuel cell	672.88	1233.33	0	0
Heat pump	0	0	881.05	0
Boiler	0	0	0	0
Reformer	992.79	5201.63	0	0
Heat dist system	234.92	0	0	0
Low T heat distribution	0	0	587.30	0
O&M Fuel cell	458.29	840.00	0	0
O&M Heat pump	0	0	125.01	0
O&M Boiler	0	0	40.60	0
O&M Other	418.09	1771.38	0	40.60
CH4 cost	1785.71	1857.14	147.37	1094.74
Electricity cost	-1125.71	-758.00	1800.00	1080.00
Average annual total cost [€]	**3436.98**	**10145.47**	**3581.33**	**2215.34**

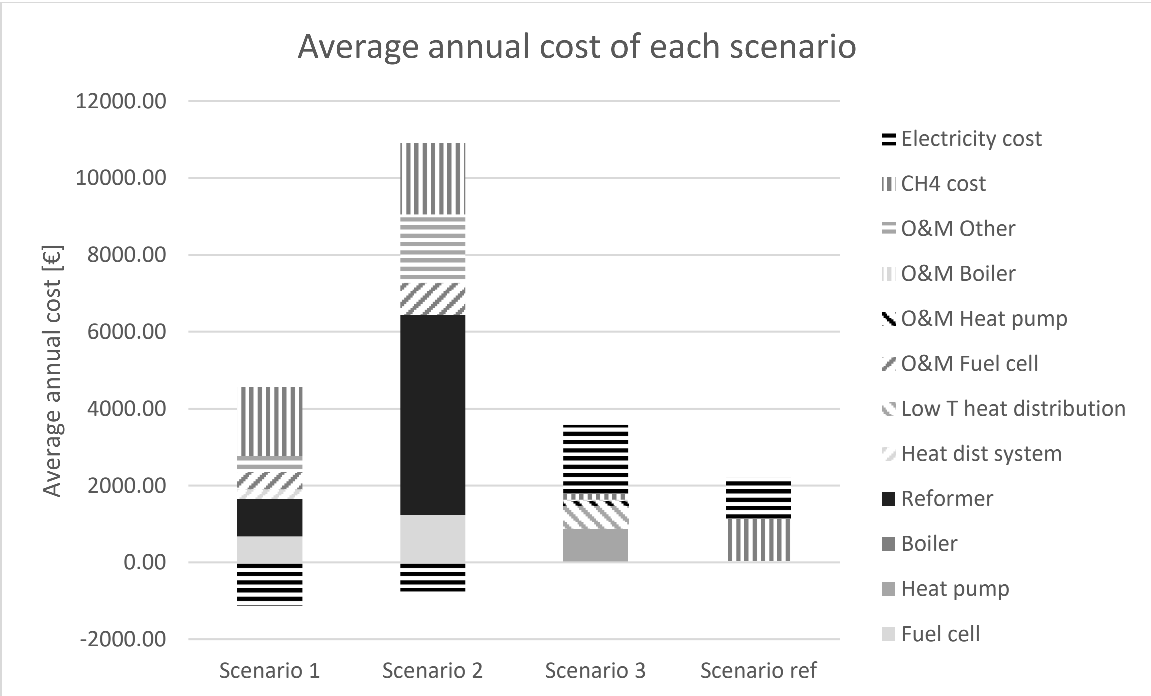

Figure 10: *Breakdown costs of each scenario.*

From Table 11 can be seen that in Scenario 1 the main cost is given by natural gas, followed by the reformer, while the gain from electricity sold is quite high thus contributes to a total cost decrease.

As for Scenario 2, the reformer costs account for more than 50% in the total cost because its down-scaling into single households is not cost efficient, leading to a high O&M Other cost (because it is a percentage of the reformer cost); same as scenario 1, the cost of natural gas is quite high, slightly more than before, and the fuel cell is also high. Again, the electricity cost brings benefits to the total cost because sold to the grid.

Electricity cost in the highest cost for Scenario 3, because it is not sold to the grid like the first two scenarios.

Reference scenario only has two important costs: natural gas and electricity, while O&M Other, that relates to the boiler cost, are minimal.

So, in general, the Reference scenario has the lowest annual cost, followed by Scenario 1, which is helped in having low costs because it can sell electricity to the grid.

Question 5.b:

There will now be a comparison between different scenarios regarding the amount of CO_2 avoided compared to the Reference Scenario and the correspondent cost.

In order to calculate the cost of avoided emissions, the formula has to take into account the costs of each scenario calculated in the previous question and the amount of CO_2 reduced calculated in Question 2c. the formula is:

$$cost_{\text{av.CO2}} = \frac{cost_{sc} - cost_{ref\ sc}}{Emission\ red} \qquad [27]$$

Where $cost_{sc}$ is the cost of the considered scenario, $cost_{ref\ sc}$ the cost of the Reference Scenario and $Emission\ red$ the amount of CO_2 reduction (Question 2c).

Doing the calculus for each scenario, each cost of CO_2 avoided is shown in Table 12.

Table 12: *Cost of CO2 avoided of each scenario.*

	Scenario 1	Scenario 2	Scenario 3
CO2 avoided (€/kg CO2)	0.13	1.56	-85.78
CO2 avoided (€/ton CO2)	127.45	1556.06	-85780.89

The costs have been showed also in €/ton CO_2 for the sake of understandability. Scenario 3 has negative costs because it emits more emissions compared to the Reference, while Scenario 1 has the lowest avoided emissions cost.

Fuel cell and heat pump variation in capacity can lead to a variation in scenario costs and avoided CO_2 costs, as seen in Table 13. The costs for each scenario have been calculated as:

$$Cost\ scenario = Average\ annual\ total\ cost * \frac{New\ installed\ capacity}{Old\ installed\ capacity} \qquad [28]$$

Where the new installed capacity is the capacity variation and the old one is always 7 kW as in Question 5a.

Delta cost is the difference between the new scenario cost and the cost of Reference Scenario calculated before, emission reduction is given by the same values obtained in Question 4 and the cost of CO_2 avoided is given by:

$$Cost\ CO_2\ avoided = \frac{Delta\ cost}{Emission\ reduction} \qquad [29]$$

Table 13: *Cost of CO2 avoided of each scenario with variation in fuel cell and heat pump capacity.*

		Scenario 1			
CF	Installed FC capacity	Cost Scenario 1	Delta cost	Emission reduction	Cost CO2 avoided
0.1	0.7	343.70	-1871.64	1821.13	-1.03
0.25	1.75	859.24	-1356.09	4193.39	-0.32
0.375	2.63	1288.87	-926.47	5840.79	-0.16
0.429	3	1472.99	-742.35	6455.13	-0.12
0.5	3.5	1718.49	-496.85	7188.67	-0.07
0.675	4.73	2319.96	104.62	8572.49	0.01
0.75	5.25	2577.73	362.39	8985.84	0.04
0.9	6.3	3093.28	877.94	9489.05	0.09
		Scenario 2			
CF	Installed FC capacity	Cost Scenario 2	Delta cost	Emission reduction	Cost CO2 avoided
0.1	0.7	1014.55	-1200.79	968.29	-1.24
0.25	1.75	2536.37	321.03	2229.62	0.14
0.375	2.63	3804.55	1589.21	3105.55	0.51
0.429	3	4348.06	2132.72	3432.19	0.62
0.5	3.5	5072.74	2857.40	3822.21	0.75
0.675	4.73	6848.19	4632.86	4557.99	1.02
0.75	5.25	7609.10	5393.77	4777.77	1.13
0.9	6.3	9130.92	6915.59	5045.32	1.37
		Scenario 3			
CF	Installed HP capacity	Cost Scenario 3	Delta cost	Emission reduction	Cost CO2 avoided
0.1	0.7	358.13	-1857.20	-3.03	613.83
0.25	1.75	895.33	-1320.01	-6.97	189.47
0.375	2.63	1343.00	-872.34	-9.70	89.90
0.429	3	1534.85	-680.48	-10.72	63.45
0.5	3.5	1790.66	-424.67	-11.94	35.56
0.675	4.73	2417.40	202.06	-14.24	-14.19
0.75	5.25	2685.99	470.66	-14.93	-31.53
0.9	6.3	3223.19	1007.86	-15.76	-63.93

Question 6:

Question 6.a:

Analyzing two different papers a suitable progress ratio has been chosen for the fuel cell system: Staffel and Green, 2009 and Riverga-Tinoco, Schoots and Zwaam, 2012. The analysis was done in order to determine how the technological learning influences the fuel cell cost and the amount of CO_2 emissions avoided for each scenario.

The first paper deals with the characteristic of experience curves for polymer electrolyte fuel cell CHP systems (PEMFC), with learning rates around 19.1-21.4%.

The second one focuses on learning curves for solid oxide fuel cell systems (SOFC), obtaining a learning ratio of 35% thanks to the combination of different manufacturing processes.

This second learning rate is the value that most suits this assignment, because the paper makes a focus on different deployment phases (R%D, commercial and pilot) and also the SOFC has a higher performance when integrated into a CHP system, compared to one based on PEMFC.

Question 6.b:

The delivered capacity of the fuel cell has now become lower, 3 kW_{th}. Most calculi will be the same as Exercise 4 and 5, with some exceptions.

Since the installed capacity increased by a factor of 10, the formula will now be:

$$\frac{Cost\ (cum)}{Cost\ (in)} = \left(\frac{Cap\ cum}{Cap\ in}\right)^b \qquad [30]$$

Where $Cost(in)$ is the previous cost of question 5 (because there is no additional cost reduction), $\frac{Cap\ cum}{Cap\ in}$ is 10, the increase in capacity and b is given by:

$$b = \log_2(1 - LR) \qquad [31]$$

And LR is the learning rate, here used as 0.35, resulting in b = -0.6215.

The new base-scale costs for the fuel cell and reformer of Scenario 1 and 2, and for the heat pump of Scenario3 are shown in Table 14, 15 and 16.

Table 14: *New base-scale costs for fuel cell and reformer of Scenario 1.*

Fuel cell	
cost (size 1) (€)	1500
cost (size 2) (€)	1369505.15
size 1 (kW)	7
size 2 (kW)	7692.31
R	0.9

Reformer	
cost (size 1) (€)	1500
cost (size 2) (€)	2020603.69
size 1 (kW)	17500
size 2 (kW)	19230.77
R	0.75

Table 15: *New base-scale costs for fuel cell and reformer of Scenario 2.*

Fuel cell	
cost (size 1) (€)	1015
cost (size 2) (€)	1170.91
size 1 (kW)	7
size 2 (kW)	3
R	0.9

Reformer	
cost (size 1) (€)	1500
cost (size 2) (€)	5607.63
size 1 (kW)	17500
size 2 (kW)	7.5
R	0.75

Table 16: *New base-scale costs for heat pump of Scenario 3.*

Heat pump	
cost (size 1) (€)	450
cost (size 2) (€)	3060.60
size 1 (kW)	3
size 2 (kW)	0.80
R	0.75

Question 6.c:

The average annual cost for each scenario have now to consider the capacity delivered for fuel cell and heat pump of 3 kW. One important thing to say it that, since scenario 1 has not a fuel cell for each household, its fuel cell and reformer costs have to be divided by the number of households (1000), while in Scenario 2 and 3 fuel cell and heat pump are per household thus this is not necessary.

Table 17 contains all scenarios cost breakdown and total and the breakdown is showed in Figure 11.

Table 17: *Cost breakdown for each scenario and total cost.*

	Scenario 1	Scenario 2	Scenario 3
Fuel cell	160.86	137.53	0
Heat pump	0	0	359.50
Boiler	0	0	0
Reformer	237.34	658.67	0
Heat dist system	187.94	0	0
Low T heat distribution	0	0	587.30
O&M Fuel cell	109.56	93.67	0
O&M Heat pump	0	0	80.61
O&M Boiler	0	0	40.60
O&M Other	144.82	224.31	0
CH4 cost	1381.36	1429.46	456.71
Electricity cost	-640.58	-392.94	1564.90
Average annual total cost [€]	1581.29	2150.70	3089.61

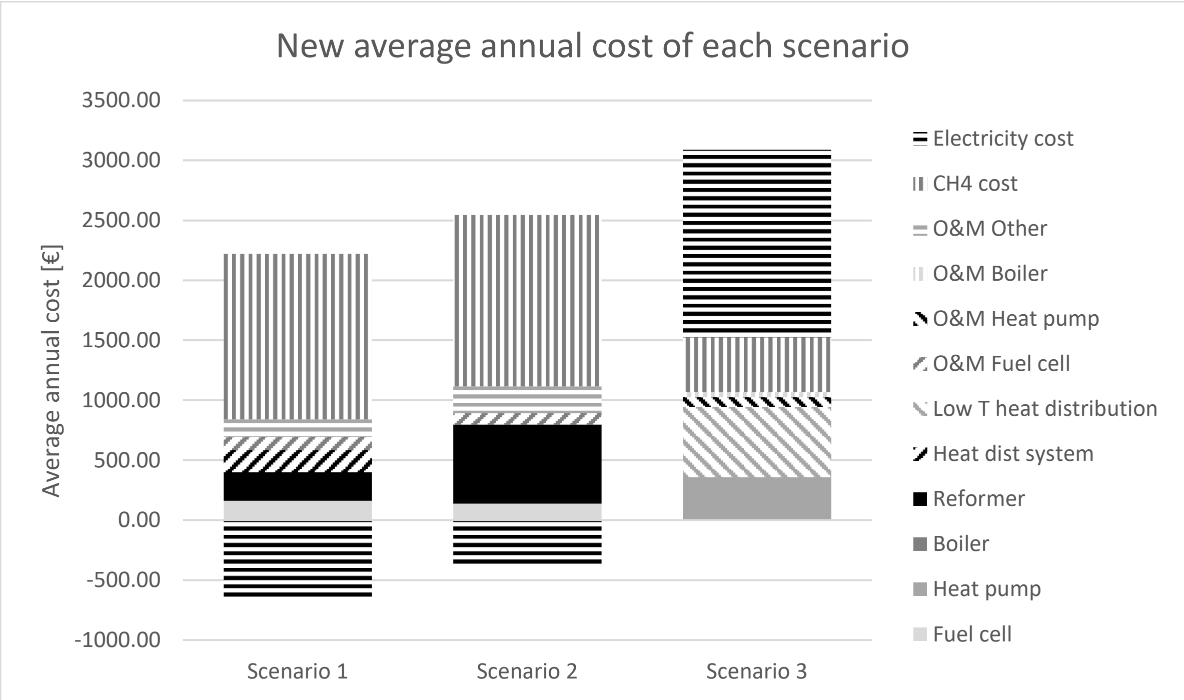

Figure 11: *Breakdown costs of each scenario.*

As can be seen in Table 17, Scenario 1 still has the lowest cost. All the scenarios have a lower cost, but the one of Scenario 2 has decreased the most. Scenario 1 still has that natural gas is the highest cost and it has not decreased much, while the fuel cell cost has become 1/3 of before because of the improvements technological learning has brought.

Scenario 2 has lowered very much the cost of the reformer (from 5201.63 to 658.67) and the fuel cell has also decreased, for the same reason of scenario 1. The highest cost is now the one of natural gas.

Scenario 3 has decreased less compared to the other two and the cost of electricity is still the highest.

Overall, it can be seen that the costs have decreased, meaning that the technological learning has brought a big advantage.

As for the CO_2 avoidance costs the are calculated as in Exercise 5 and are presented in Table 18.

Table 18: *Cost of CO2 avoided for each scenario.*

	Scenario 1	Scenario 2	Scenario 3
Emission reduction [€/kg CO2]	6455.13	3432.19	-10.72
CO2 avoided cost [€/kg CO2]	-0.29	-2.33	45.85
CO2 avoided cost [€/ton CO2]	-287.47	-2329.35	45849.81

Again, for the sake of understanding, the avoidance costs are showed also in €/ton CO2. Scenario 1 has negative avoidance costs because its costs are lower than the Reference Scenario.

Question 7:

Question 7.a:

The heat capacity delivered is still 3 kW and the purpose is to calculate the Annual cumulative energy consumption for 1000 households. For all values has been used the data from Question 4 and 5 with $CF = \frac{3}{7}$ because of the new capacity delivered.

First, using the input/output table given, has been calculated Energy intensity and Labour intensity. All the intermediate matrices are shown below.

$$A = \begin{bmatrix} 0.0796 & 0.0042 & 0.0088 & 0.0038 \\ 0.0074 & 0.2350 & 0.0016 & 0.0114 \\ 0.0024 & 0.0083 & 0.2232 & 0.0152 \\ 0.2379 & 0.2840 & 0.2265 & 0.2721 \end{bmatrix}$$

$$I = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$I - A = \begin{bmatrix} 0.9204 & -0.0042 & -0.0088 & -0.0038 \\ -0.0074 & 0.7650 & -0.0016 & -0.0114 \\ -0.0024 & -0.0083 & 0.7768 & -0.0152 \\ -0.2379 & -0.284 & -0.2265 & 0.7279 \end{bmatrix}$$

$$P = (I - A)^{-1} = \begin{bmatrix} 1.0881 & 0.0084 & 0.0141 & 0.0061 \\ 0.0160 & 1.3151 & 0.0089 & 0.0209 \\ 0.0107 & 0.0243 & 1.2955 & 0.0274 \\ 0.3652 & 0.5234 & 0.4113 & 1.3925 \end{bmatrix}$$

A is the matrix given by the input/output tale, I is the identity matrix and P the Leontief matrix.

So Energy intensity is defined as:

$$E_{nr} = \frac{Energy\ input_i}{Total\ delivery_i} \qquad [32]$$

And Labour intensity as:

$$Labour\ intensity = \frac{Employment_i}{Total\ delivery_i} \qquad [33]$$

So the cumulative energy intensity will be:

$$E_{cum} = E_{nr} * P \qquad [34]$$

And the cumulative labour intensity:

$$L_{cum} = Labour\ intensity * P \tag{35}$$

Values for each scenario of cumulative energy and labour intensity are shown below.

$$E_{nr} = [0.0007 \quad 0.0242 \quad 0.0001 \quad 0.0020]$$

$$Labour\ intensity = [6.02 \quad 1.83 \quad 7.22 \quad 9.58]$$

$$E_{cum} = [0.0018 \quad 0.0329 \quad 0.0012 \quad 0.0033]$$

$$L_{cum} = [10.16 \quad 7.65 \quad 13.4 \quad 13.62]$$

Next, the values for ERE obtained from Blok [1] are extracted: $ERE_{coal} = 1.09$, $ERE_{natural\ gas} = 1.15$, $ERE_{other} = 1.03$ so the total is $ERE_{tot} = 1.1$.

The ERE_{other} is the result of the value for different energy types and ERE_{tot} is calculated as:

$$ERE_{tot} = \sum_f ERE_f * share_f \tag{36}$$

Where f stands for the fuel type.

Now, in order to calculate the Annual cumulative energy consumption, the deliveries have to be calculated. The vector of deliveries (ΔF) is given by the values of the Annual costs calculated as in Question 5, with 3 kW.

ΔF is divided into 4 sections:

- Manufacture of machinery and equipment, i.e. the cost for investments (fuel cell, reformer, heat pump)
- Electricity, gas and water supply, i.e. the cost for natural gas and electricity
- Construction, i.e. the eventual cost for distribution
- Other sectors, i.e. other costs

These values for each scenario are presented in Table 19.

Table 19: *ΔF for each scenario.*

	1. Manufacture of machinery and equipment	2. Electricity, gas and water supply	3. Construction	4. Other sectors
Scenario 1	0.84	0.74	0.19	0.27
Scenario 2	3.33	1.04	0.00	1.33
Scenario 3	1.54	2.02	0.59	0.17
Scenario ref	0.00	2.17	0.00	0.04

Now, the direct and indirect energy use will be calculated, with the formulas:

$$Energy\ use_{ind} = E_{cum} * \Delta F \tag{37}$$

$$Energy\ use_{dir} = Electricity\ used * Primary\ energy\ intensity + Natural\ gas \tag{38}$$

And primary energy intensity is:

$$Primary\ energy\ intensity = \frac{Total\ primary\ energy\ use}{Total\ electricity\ produced} \quad [39]$$

The total cumulative energy use is a combination of different variables:

$$Energy\ use_{tot} = Natural\ gas\ use * ERE_{natural\ gas} + Electricity\ used * ERE_{electricity} * Primary\ energy\ intensity + Energy\ cons_{total} \quad [40]$$

Now all is calculated, so Table 20 shows every value.

Table 20: *Cumulative employment effect vector.*

	Scenario 1	Scenario 2	Scenario 3	Scenario ref
Total cumulative direct energy [PJ]	8.73E-07	0.101	0.126	0.136
Total cumulative indirect energy [PJ]	0.027	0.045	0.071	0.072
Total cumulative energy use [PJ]	0.043	0.101	0.126	0.136
Share indirect energy [PJ]	0.626	0.442	0.561	0.527

Question 7.b:

To calculate the effect of each scenario on employment the formula is a combinaton of ΔF and the cumulative labour:

$$Effect_{employment} = L_{cum} * \Delta F \quad [41]$$

Where L_{cum} is exactly the cumulative labour intensity defined in Equation 33 and ΔF again the deliveries vector.

Table 21 shows the values for each scenario and each section of the input/output table.

Table 21: *Cumulative employment effect vector.*

	1. Manufacture of machinery and equipment	2. Electricity, gas and water supply	3. Construction	4. Other sectors	Total (years)
Scenario 1	8.54	5.67	2.52	3.69	20.41
Scenario 2	33.86	7.93	0.00	18.12	59.91
Scenario 3	15.66	15.48	7.87	2.34	41.35
Scenario ref	0.00	16.65	0.00	0.55	17.20

The effect, as can be seen, is measured in years and means that the higher is the total value, the more positive is the effect on employment. The highest effect is given by Scenario 2 and the lowest by the reference Scenario.

Question 8:

This assignment could be a work made by a consultancy agency for a client, whose aim is to understand the best way to reduce CO_2 emissions. The client could be a local government that wants to build a residential area in a free rural space.

The most important criteria the agency considers are CO_2 emission reduction, average annual cost, employment effect, indirect cumulative energy consumption and Payback Time.

The most important factor is CO_2 emission reduction, thus it will have the highest weight. Referring to the situation where the delivered heat capacity is 3 kW (Exercise 6), Scenario 2 has certainly the lowest cost of CO_2 avoided, having a negative cost.

Scenario 1 has the lowest average annual cost, mainly because since it has only one fuel cell and reformer, all the correspondent costs are scaled and distributed over households. This scenario has also the highest value of electricity sold to the grid that lowers the total cost, in addition of being sure that there is always electricity since the excess is sold.

As seen just above, the employment effect is highest in Scenario 2.

Indirect cumulative energy consumption is lowest in scenario 1. This criteria is important to understand where there could be some emissions not taken into account directly in the emissions part.

Finally, the Payback Time is one very important economic factor. It allows to understand when will the investment be paid back, i.e. how many years will pass before the year in which the investment has been made and the breakeven point (when the total revenues will equal the investment).

Each factor has been given an arbitrary weight based on its importance:

Table 22: *Arbitrary weights for each factor.*

Criteria	Weight
CO2 emission reduction	40
Average annual cost	30
Employment effect	15
Indirect cumulative energy consumption	10
Payback Time	5

Question 9:

This assignment is based on residential areas built more than 20 years ago. The same analysis done in more recent years would need to consider that new houses have a better insulation. This translates in the capacity to have lower values for CF because less heat is needed. Considered this fact, the choice based on calculated data would still make Scenario 1 preferable; in fact, even though from Question 6 can be seen that with a lower CF the investment costs for Scenario 3 are lower than Scenario 1, from Question 4 is clear that the emission reduction of Scenario 1 is still way lower than Scenario 3, and this makes it preferable considering that the most important criterion for the client is CO_2 emission reduction.

References:

[1] K. Blok and E. Nieuwlaar, 2017. Introduction to Energy Analysis 2nd Edition.