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Report on evaluation of overall plant performance

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LIFE+ PROJECT NAME or Acronym

ENERGY WASTE

Data Project

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Project:

Energy exploitation of non-recyclable urban waste in a sustainable waste –to –energy market “ENERGY WASTE”

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Report title:

Deliverable 5.3 Report on evaluation of overall plant performance

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Summary:

Based on the experiment run during Action 5.2 “Establishment of Testing programme and Gasification Test”, the performance of the gasification plant is evaluated in Action 5.3 “Evaluation of the gasification system performance”.

Based on the tests output, the parameters for evaluation of the gasification plant are listed below:

- Detailed mass and energy balances
- Gross and net electrical and thermal efficiency
- Compliance with WID (Waste Incineration Directive 76/2000/EC)
- Operational costs (€/kWhe), broken down to fixed and variable costs
- Environmental performance (in terms of liquid effluents, inert solids and gaseous pollutants)

The validation of the measured and calculated data from the experimental campaign will take place. Moreover a simulation model of the gasifier has been constructed in the commercial code of ASPEN Plus^{TM} v7.1 (company: Aspentech) and used in Deliverable 4.1: “Report on RDF/SRF gasification properties”.

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1 Introduction

1.1 *Scope*

The scope of this deliverable is to assess the performance of the designed gasifier in terms of energy conversion performance and in terms of environmental performance. In order to evaluate the performance the test results from the experiments that were gathered in Action 5.2 "Establishment of testing programme and gasification tests" were used. A mass and energy balance was created for the gasification process, the costs were analysed and an analysis for the environmental performance was done.

2 Mass and energy balance

Utilizing the average values from the experimental results of the gasifier, a detailed mass and energy balance was elaborated for the gasification process.

2.1 *Mass balance*

The first step for the calculation of a detailed mass balance, is the determination of the streams that enter the process and the streams that leave the process is required. In Figure 1, all the streams of the process that react are depicted as inflows, and all the streams that are produced from the gasification process are depicted as outflows.

It was considered that after the experiment, the gasifier contained only ash (named bottom ash) and not any unconverted carbon (char). Part of the ash is carried through the syngas and is held in the second cyclone (named fly ash). Part of the fly ash is char which is acquired in the second cyclone. Tars are produced through gasification and in standard operational conditions they are deposited throughout the gas conditioning system where the temperature of the syngas drops below their condensation temperature.

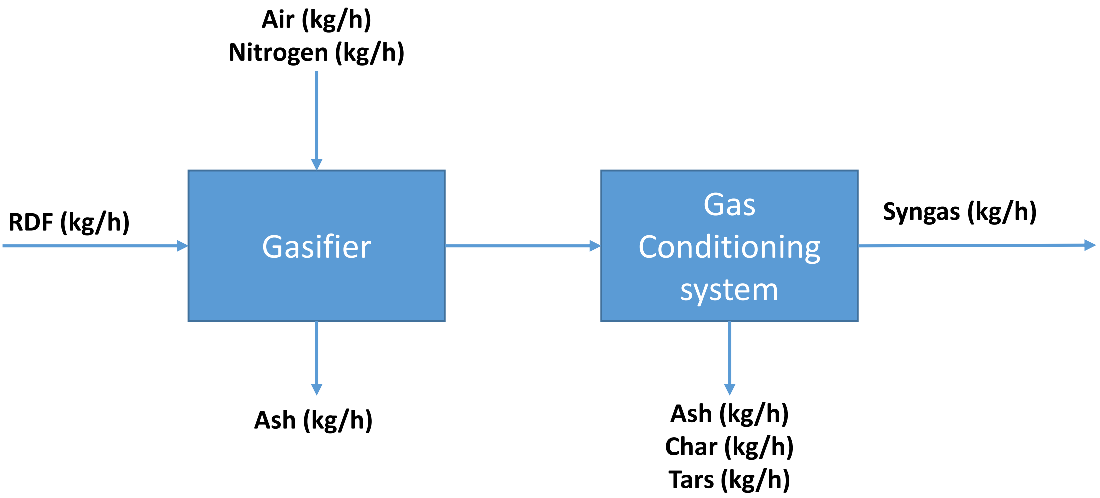

Figure 1: Flow chart for mass balance

In order to create the mass balance, the following parameters were taken into consideration:

- Input fuel quality and analyses (proximate, ultimate). Fuel analyses provide information on the input stream for calculating the mass balance on molar basis, comparing with the results from the measured gases and calculating necessary parameters for the performance of the plant.
- Air mass. Input air, plays an important role as it provides the necessary oxygen for the gasification reactions to take place and it provides the necessary information for calculating the total syngas volume

The mass balance was created for the average quality of RDF used, and the following analyses (Table 1) were taken into consideration:

Table 1: Analyses of the RDF taken into consideration for the mass and energy balance

	As received	Dry basis
Proximate analysis		
Moisture (% wt.)	26.63	-
Ash (% wt.)	8.81	12.01
Volatiles (% wt.)	59.69	81.39
Fixed Carbon (% wt.)	4.87	6.60
Ultimate analysis		
C (% wt.)	36.63	49.94
H (% wt.)	5.22	7.10
N (% wt.)	0.74	1.03
O (% wt.)	21.38	29.10
S (% wt.)	0.23	0.31
Cl (% wt.)	0.37	0.50
Calorific Value		
Low Heating value (kJ/kg)	12942.35	18557.67
Higher Heating value (kJ/kg)		20107.40

Assumptions:

- Air to fuel ratio (λ): 0.3
- Temperature of air density and volume/mol: 0°C
- Air density (0°C and 1atm): 1.288 kg/m^3
- Air volumetric ratio
  - N_2: 78.9%
  - O_2: 21%
  - H_2O: 0.1%
- Nitrogen calculated at the end is a mix from the Nitrogen that is inserted from the L-valve, the air and the fuel
- Fuel feed rate: 5.5 kg/h
- Syngas components taken into consideration:
  - H_2O
  - CO_2
  - CO
  - H_2
  - N_2
  - CH_4
- Tars production ~ 0.004 kgtar/Nm$^3_{syngas}$ (as a mean value of the tars measured)
- Char production rate depending on carbon conversion efficiency

For the creation of the mass balance the following streams were taken into consideration:

- Fuel in
- Air
- Syngas
- Ash (bed ash, fly ash)
- Tars (created during gasification and calculated from literature)
- Char (measured as Loss on Ignition)

From the analyzed percentages of the gas, the only that does not react is N_2. Based on that fact, the total volume of the produced syngas is calculated and the final mole concentrations are computed. The results are given in the following table (Table 2).

Table 2: Composition of produced syngas

Composition	% wet	% dry	% wet (kg/h)
H_2O	14.93	0	1.114586881
CO_2	11.62	13.58	2.193986218
CO	16.56	19.36	1.989726822
H_2	21.82	25.5	0.187266387
N_2	32.5	37.99	0.000000000*
CH_4	2.57	3.00	0.176452655

* Nitrogen free.

Converting from the data presented in the table above, the mass balance can be outlined as input and output (Table 3), as molar percentage in wet and dry which is then converted in kg/h. Comparing the sums of input and output streams, a small percentage of losses is found. This is mostly attributed to the assumptions on tars and char conversion, and to the compounds that could be measured during the experiments that were run. However, the deviation from the mass input is less than 5% and it can be considered as very small.

Table 3: Mass balance input and output

	INPUT	
	Mass (kg/h)	Percentage (%)
RDF	5.50	76.87
Oxygen	1.65	23.13
	OUTPUT	
Syngas	6.34	88.69
Bed ash	0.26	3.63
Fly ash	0.06	0.91
Tars	0.11	1.50
Char	0.36	5.06
TOTAL	7.13	99.79
Losses	0.01	0.21

In the following figure (Figure 2) the results from the mass balance are presented in a Sankey diagram in order to be more easily apprehended in terms of quantities in inflow and outflow.

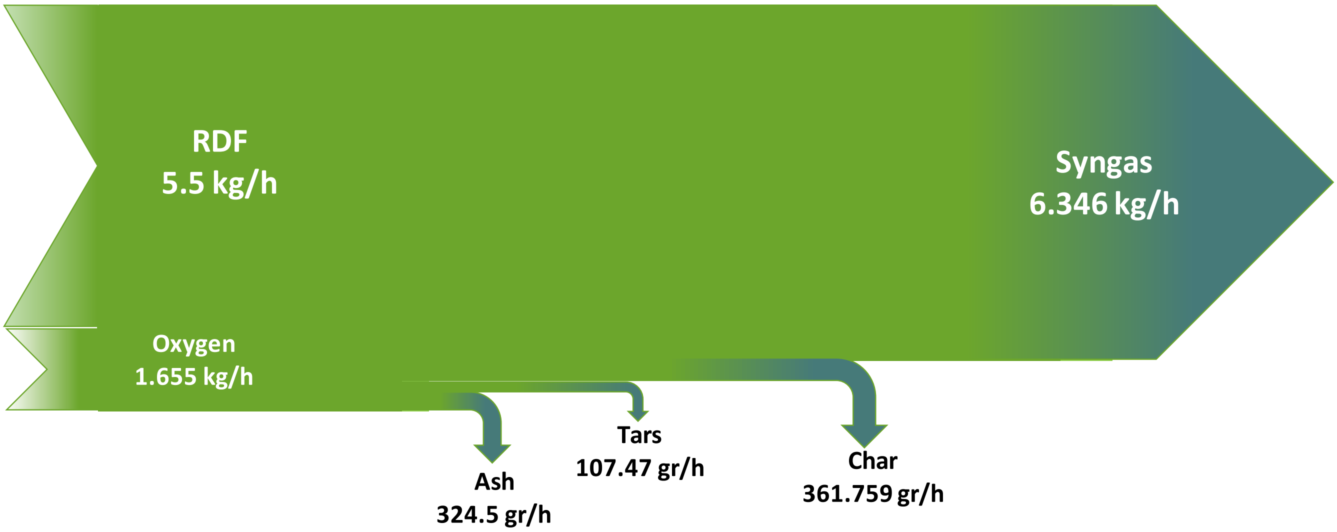

Figure 2: Sankey diagram of mass balance

2.2 *Energy Balance*

For the calculation of the energy balance the parameters that were taken into consideration are the following:

- Fuel chemical energy that is emitted during the combustion of a portion of the inserted fuel (RDF or sample mix of paper/plastic)
- External resistances represent the amount of thermal energy that is given through electrical resistances in order to bring the system in a steady state for the fuel feeding to start, and to complement in very small amounts the heat needed for the gasification process to proceed
- Inert material represents the amount of heat that is stored in the respective inert material (olivine or quartz sand) according to the specific heat of each material
- Air from cooling represents the heat that is absorbed from the free or forced flow of air in the U-shape heat exchanger
- Char represents the energy that is not given to the system by not converting carbon to syngas
- Tars represent the energy that is not acquired by the system through the formation of tars that are not carried in the syngas, and therefore they are not thermally utilized through the syngas.
- Syngas is the potential chemical and thermal energy stream that can be utilized. The chemical energy of syngas is contained in the compounds that can be burned (CH_4, H_2, CO, etc.) while the thermal energy derives from the heat absorbed and contained in the gas due to its increased temperature. The final low heating value of the syngas is found to be **6053.13 kJ/kg**

The following figure (Figure 3) shows the flow chart (inflows and outflows) for the energy balance, as described above.

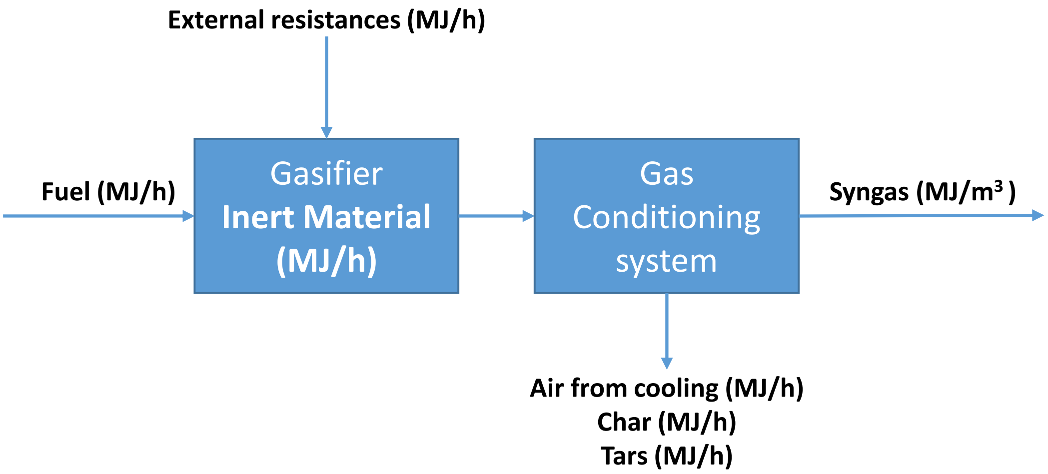

Figure 3: Flow chart for energy balance

Assumptions

The assumptions used for the elaboration of the energy balance are the following:

- RDF quality is the same as presented in mass balance (Table 1)
- Syngas quality and composition is the same as presented in mass balance (Table 2)
- Gas fuel compounds heating values were taken from literature. Namely CH_4, H_2 and CO
- Air to fuel ratio (λ): 0.3
- Temperature of air density and volume/mol: 0°C
- Air density (0°C and 1atm): 1.288 kg/m^3
- Air volumetric ratio
  - N_2: 78.9%
  - O_2: 21%
  - H_2O: 0.1%
- Nitrogen calculated at the end is a mix from the Nitrogen that is inserted from the L-valve, the air and the fuel
- Fuel feed rate: 5.5 kg/h
- LHV of CH_4: 35807.1 kJ/Nm^3
- LHV of H_2: 10784.4 kJ/Nm^3
- LHV of CO: 12627.63 kJ/Nm^3
- LHV of syngas: 6053.13 kJ/kg

- Tar heating value: 40235 kJ/kg$_{tar}$
- Tar concentration: 0.005 kg$_{tar}$/Nm^3
- Char heating value: 32808 kJ/kg$_{char}$
- Specific heat taken into consideration for the calculation of the specific heat of the syngas:
    - CO: 31.528 kJ/kmol·K
    - CO_2: 50.512 kJ/kmol·K
    - CH_4: 60.256 kJ/kmol·K
    - H_2: 29.3 kJ/kmol·K
    - N_2: 31.08 kJ/kmol·K
    - H_2O: 38.034 kJ/kmol·K

The methodology for calculating the parameters for the abovementioned energy balance are described below:

- RDF chemical energy given to the system is based on the Low Heating Value of the fuel as this was found through the analyses that were presented in Deliverables 3.3 and 3.4.
- The thermal input from the external resistances was calculated from the log of the experiment as a function of the percentage of the working load of the different zones of the resistances, the operation time and the maximum power of each zone
- The thermal outflow from the air in the gas conditioning system is calculated via thermodynamic calculations, up to the Temperature of the air that is given from the thermocouples installed.
- Char thermal content is calculated from the Heating value that would otherwise be gained from the conversion of char to methane, carbon monoxide or carbon dioxide.
- Tars thermal content is calculated through the assumption of Tar concentration in Syngas multiplied by an average of tar calorific value.
- Syngas thermal content is affected from two parameters:
    - Chemical energy which is contained in possible fuel compounds such as:
        - CO
        - CH_4
        - H_2
    - Thermal energy calculated through thermodynamics as a potential energy created due to high Temperature

The results from the calculation of all of the parameters necessary for the energy balance are given in Table 4, and an overview Sankey diagram is presented in Figure 4.

Table 4: Results from the energy balance elaborated on the CFB gasifier

INPUT			
	MJ/h	**kW**	**%**
RDF	74.89	20.80	55.31
Electrical Resistances	60.51	16.81	44.69
TOTAL	135.40	37.61	100
OUTPUT			
	MJ/h	**kW**	**%**
Syngas	90.49	25.14	66.83
Olivine	22.08	6.13	16.30
Char	15.23	4.23	11.25
Tars	1.54	0.43	1.14
TOTAL	129.34	35.93	95.52
Losses	6.06	1.68	

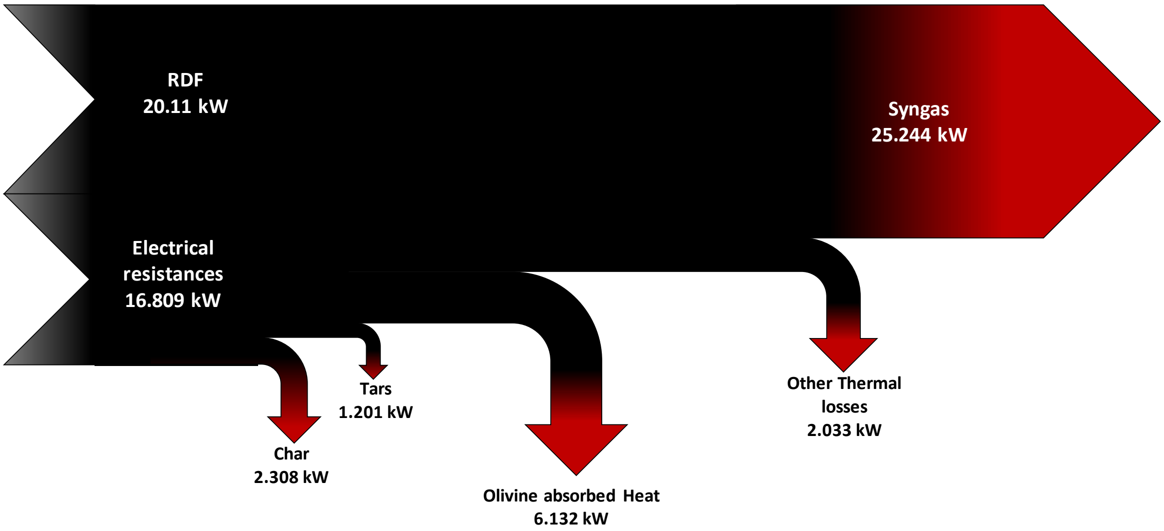

Figure 4: Sankey diagram of energy balance

From the results presented in the table above, it is observed that the energy acquired from the utilization of RDF is almost half the energy that is required for the gasification process to proceed and maintain a steady temperature at the range of 750-800ºC.

This is mainly due to the losses from the cool air that is inserted to the system and the losses from the outer wall of the thermal insulation. The air needs to be heated up to the final temperature of the produced syngas. Moreover there are two facts that contribute in this phenomenon. First of all the electrical resistances power was calculated from the percentage of load given to the electrical resistances multiplied by the power of the electrical resistances. This includes the indirect fault that the percentage given is much bigger than the one needed to stabilize the temperature (i.e. we provide 50% power instead of 5% in order to have a quicker response to external heating, leading to some cases to a thermal deviation of 20-30ºC from the point set). The second factor that contributes to high electrical resistances operation is that the unit is at pilot scale and the stabilization of temperatures is more difficult that a large scale plant due to the process progress in the riser.

The thermal losses taken into consideration are presented in Figure 5.

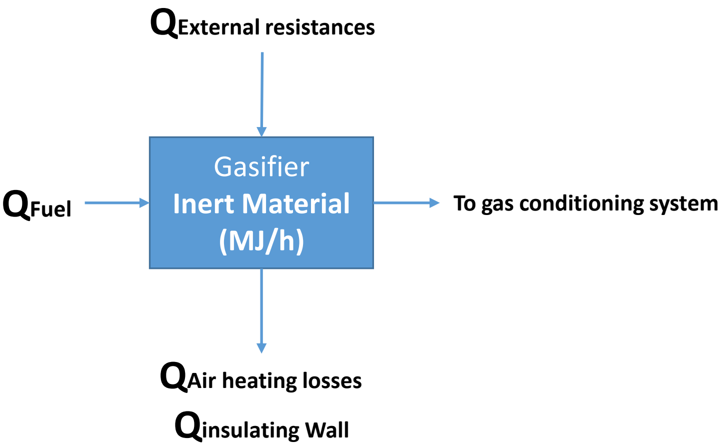

Figure 5: Diagram of losses from the gasifier reactor

3 Efficiency calculation

The efficiency of the gasification process and at an extent of the gasification unit is calculated from two factors:

- The Cold Gas Efficiency (CGE %). Cold Gas Efficiency represents the chemical energy contained from the syngas produced, to the total chemical energy contained to the fuel fed to the gasifier. Practically it is the ratio of the calorific value of the syngas to the calorific value of the feedstock.
- Carbon Conversion Efficiency (CCE %). Carbon conversion is an indicator of the carbon left unreacted during gasification. It is the ratio of the sum of mass of carbon compound in the syngas (CO, CO_2, CH_4) to the total carbon mass inserted to the gasifier.

Cold Gas Efficiency (CGE%)

Cold gas efficiency is calculated as the ratio of thermal input from the fuel, to the thermal output of the syngas.

The thermal input of the fuel is calculated by the following equation:

$$P_{fuel} = \dot{m}_{fuel}(kg/sec) \cdot LHV_{fuel}$$

Where:

P_{fuel} *is the power potential of the input fuel*

$\dot{m}_{fuel}$ *is the feed rate of the fuel in kg/sec*

LHV_{fuel} *is the low heating value of the fuel*

The thermal output of the fuel is calculated the same as in the energy balance by the following equation:

$$P_{syngas} = \dot{m}_{syngas}(kg/sec) \cdot LHV_{syngas}$$

Where:

P_{syngas} *is the power potential of the output fuel*

$\dot{m}_{syngas}$ *is the flow rate of the syngas in kg/sec*

LHV_{syngas} *is the low heating value of the syngas*

Finally the Cold gas efficiency is calculated as:

$$CGE\% = \frac{P_{syngas}}{P_{fuel}}$$

Carbon Conversion Efficiency (CCE %)

As mentioned above, carbon conversion is a ratio of the produced masses of carbon compounds in syngas to the carbon inserted. The carbon mass inserted to the system is calculated from the following equation:

$$\dot{C} = \dot{m}_{fuel} \cdot [C\%]_{fuel}$$

Where:

$\dot{C}$ $is\ carbon\ mass\ flow\ in\ the\ system\ from\ the\ fuel$

$\dot{m}_{fuel}$ $is\ the\ rate\ of\ fuel\ mass\ feed$

$[C\%]_{fuel}$ $is\ the\ concentration\ of\ carbon\ in\ the\ fuel$

Likewise the carbon compounds that are in the syngas produced are calculated from the following equation:

$$[\dot{C}_i] = [C_{i,syngas}\%] \cdot \dot{n}_{syngas}$$

Where:

$[\dot{C}_i]$ $is\ the\ concentration\ of\ compound\ i\ in\ the\ syngas$

$[C_{i,syngas}\%]$ $is\ percentage\ of\ compound\ i\ in\ the\ syngas$

$\dot{n}_{syngas}$ $is\ the\ syngas\ production\ rate$

After calculating the concentration of each compound in the syngas, the final Carbon mass is calculated by multiplying with the Carbon molar weight (12).

Finally:

$$CCE\% = \frac{[\dot{C}_i]}{\dot{C}}$$

The results for the gasifier efficiency factors are presented in the following table (Table 5):

Table 5: Results for gasifier efficiency parameters

Cold Gas Efficiency	
Parameter	**Value**
P_{fuel}	20.11 kW
P_{syngas}	15.86
CGE %	78.88%
Carbon Conversion Efficiency	
Parameter	**Value**
Carbon fuel input	2.52 kg/h
C in CO	0.02554 moleC,CO/sec
C in CO_2	0.01791 moleC,CO_2/sec
C in CH_4	0.00396 moleC,CH_4/sec
Carbon mass in syngas	2.048 kg/h
CCE%	81.36%

3.1 Thermal efficiency

The thermal energy introduced into the system from the external resistances is calculated from the percentage of the operation of each thermal zone, multiplied by the power of each zone (kW). Therefore:

$$\dot{Q}_{resistances} = \sum (ResistancesLoad \times ResistancesPower)$$

The thermal energy inserted by the fuel is calculated as described before from the Lower Heating Value.

The energy carried from the air that is inserted to the gasifier is found by the following equation:

$$\dot{Q} = \dot{m} \cdot C_p \cdot \Delta T = \dot{V}_{air} \cdot d_{air(ambient)} \cdot C_{p(air)} \cdot (T_{reaction} - T_{ambient})$$

Where:

$\dot{Q}\ is\ the\ thermal\ energy$

$\dot{m}\ is\ the\ mass\ flow\ of\ air$

$C_p\ is\ the\ specific\ heat\ capacity\ of\ air$

$\Delta T\ is\ the\ difference\ \ of\ temperatures\ of\ input\ and\ output\ from\ the\ gasifier$

The mass flow of air is calculated every time step of the data recorder (2 sec) from the volume flow and air density. As an ambient temperature 10°C are taken into consideration while $T_{reaction}$ occurs from the mean value of the installed thermocouples. In order to calculate the specific heat capacity of air, the following formula [0] is used for every time step of the data recorded and it's used for the thermal energy flow of each time step:

$$Cp_{air} = a + b \times T + c \times T^2 + d \times T^3$$

where:
$T = \frac{T_{in}+T_{15}}{2}$ [°C]
factors $a = 28.11 \ \frac{J}{mol \times K}$, $b = 1.97 \times 10^{-3} \ \frac{J}{mol \times K^2}$, $c = 4.8 \times 10^{-6} \ \frac{J}{mol \times K^3}$ και $d = -1.97 \times 10^{-9} \ \frac{J}{mol \times K^4}$.

Moreover, there are losses from the thermal insulation of the gasification unit, the temperature of which was measured to be around 60°C. The losses from the insulating wall are calculated through thermodynamics and are equal to:

$$\dot{Q} = h \cdot A \cdot \Delta T = 10 \frac{W}{m^2 \cdot K} \cdot 7.45 m^2 \cdot (333.14K - 283.14K) = 3724.7W$$

Where:
$\dot{Q}$ *is the thermal energy*
h *is the convective heat transfer coefficient*
A *is the total surface area of heat exchange*
ΔT *is the difference of temperatures of outer wall and ambient*

The results calculated regarding the gasifier reactor thermal losses are presented in the following table (Table 6):

Table 6: Table of losses calculated from the gasifier reactor

Parameter	Value (kW)
Losses from air heating	7.87
Losses from insulating wall	3.72
Total Losses	11.59

The thermal energy outflows from the gasifier reactor are presented in the following pie chart (Figure 6) as a percentage of the total given energy through the RDF and external resistances.

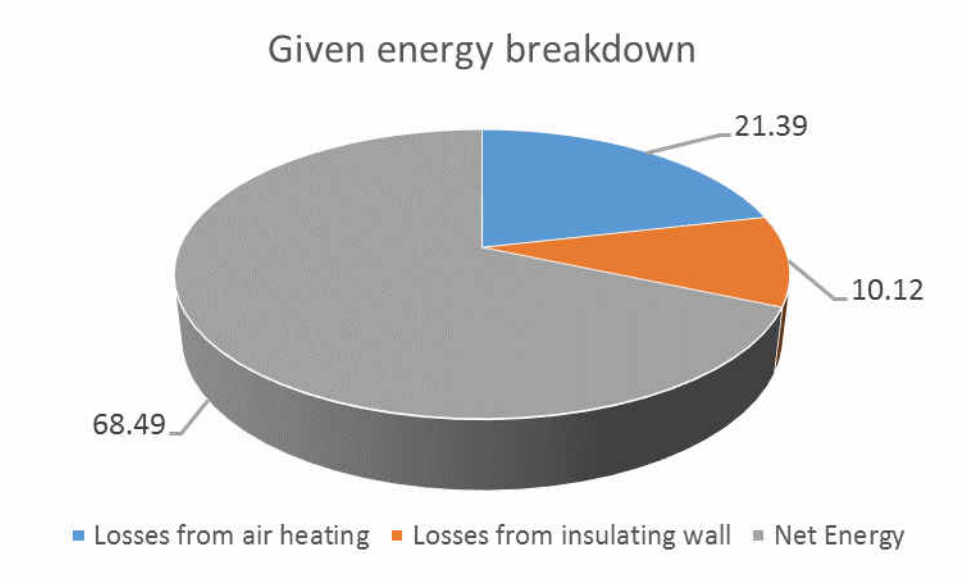

Figure 6: Break down of given energy

3.2 Electrical efficiency

The mass and energy balance presented in paragraphs 2.1 and 2.2 refer to steady state conditions in terms of temperature and air flow, and after the beginning of fuel feeding. It was found interesting to study the start-up of the pilot unit until it reaches the steady state before the feeding of the fuel. It was studied in order to find out the best practice to reach the steady state, targeting to study and minimize the energy loses. This reflects to the efficiency of the electrical resistances used during operation.

Two different scenarios where studied for the start-up in the circulating fluidized bed pilot unit. The first scenario studied a high electrical resistances percentage load in all of the heating zones, with a high air flow. The second scenario studied a low electrical resistances percentage load in all of the heating zones, coupled with a small air flow. In both scenarios, both the riser and downcomer were filled with a total of 27 kg of inert material (17kg in riser, 10 kg in downcomer).

3.2.1 Scenario 1

In this scenario, large amounts of air flow are given from the beginning of the test. Particularly, during the beginning of the trial, about 290 Nl/min of air are inserted in the gasifier and by the end of the trial the air flow reached 760 Nl/min. All of the heating zones operate in their maximum load. In order to specify the energy consumption for electrical resistances heating, the mean recorded value from the system is calculated. From the recording of all the test data, there is a full image of the temperature variation in all of the parts of the main gasification unit.

It is considered that the absorbed heat from the ear is calculated through the thermocouples installed in the bottom (T_{in}) and in the upper part ($T_{out} = T_{15}$ in 5.118m) of the gasification unit. It can be safely assumed that the temperature measured in the upper part represents only the temperature of air since the voidage in that section is 99.29% as calculated through the equation:

$$\frac{\Delta P}{L} = \left(d_s - d_f\right) \times (1 - \varepsilon) \times g$$

Where:

ΔP is the pressure drop (422.76)

L is the length of between the two pressure transducers (1,9m)

d_s is the solid density (~3200 kg/m3)

d_f is the fluid density (~1.23 kg/m3)

ε is the voidage

g is the gravitational acceleration (9.8 m/sec^2)

This indicates that more than 99% in that region is air, therefore the assumption that the indicated temperature is the fluid temperature is correct. In order to find the energy absorbed the following equation was used:

$$Q_{air} = m_{air} \times Cp_{air} \times (T_{out} - T_{in})$$

Where:

Q_{air} is the thermal energy absorbed by the air

m_{air} is the air mass converted from the known volume through the density as described in the previous paragraph 2.2

Cp_{air} is the specific heat capacity, calculated as described in paragraph 2.2

T_{out} is the indicated temperature in T_{15}

T_{in} is the ambient temperature

Except for the air that passes through the riser, significant amounts of energy given are absorbed by the olivine and the metallic walls of the riser. The walls are insulated with 10 cm of ceramic wool and 5 cm of stone wool, a fact that allows a very small heat flow to the environment. All of the aforementioned are calculated through the following formulas.

$$Q_{olivine} = \frac{m_{olivine} \times Cp_{olivine} \times \Delta T}{\Delta t_{start\ up}}$$

Where:

$m_{olivine}$ is the olivine mass in the riser

$Cp_{olivine}$ is the specific heat capacity of olivine

$\Delta T = T15 - T_{in}$

$\Delta t_{start\ up}$ is the duration of the start-up test

Likewise for the 310 stainless steel:

$$Q_{steel} = \frac{m_{steel} \times Cp_{steel} \times \Delta T}{\Delta t_{start\ up}}$$

And the insulation:

$$Q_{blanket} = h \times A_{blanket} \times \Delta T$$

Where:

h is the heat transfer coefficient ($\frac{W}{m^2 °C}$),

$A_{blanket}$ is the total surface area of the insulations (m^2)

ΔT is the temperature difference between the outer thermal insulation surface and the environment (°C).

In the following table (Table 7), all the necessary information regarding the test parameters are provided.

Table 7: Given and absorbed energy amounts during scenario 1

Duration of test $\Delta t_{start\ up}$	1h 25 min
Ambient temperature T_{in}	9 °C
Maximum testing temperature T_{gasif}	550 – 600 °C
Mass flow m_{air}	290 – 760 Nl/min
Heat transfer coefficient h	5 – 10 W/m^2°C
Temperature of insulation surface T_{out}	60 °C
Power given from thermal resistances Q_{resist}	**36.794 kW**
Power absorbed from air Q_{air}	**7.869 kW**
Power absorbed from olivine $Q_{olivine}$	**3.44 kW**

Power absorbed from walls Q_{steel}	**3.78 kW**
Power losses from insulation surface $Q_{blanket}$	**1.425 – 2.849 kW**

Comparing the power given through the electrical resistances and the total losses the following table (Table 8) occurs.

Table 8: Net power and losses during start-up

Input		**Losses**	
Q_{resist}	100 %	Q_{air}	21.39 %
		$Q_{blanket}$	3.87 % – 7.74 %
Net useful power		**70.87 % - 74.74 %**	

The high amount of given energy have as a result a relatively small duration for start-up and for entering the steady state and start of fuel feeding. From the calculations above, it is observed that the total energy utilized is 70-75% which can be considered as satisfactory.

3.2.2 Scenario 2

In this scenario, smaller amounts of air have been introduced to the unit and the electrical resistances have operated in smaller load percentages. This was done in order to create an opposite case scenario than the previous one and study the parameters that affect the heating procedure. More specifically the air flow was steady all the time, and equal to 120 Nl/min. The power load of the external resistances was initially at maximum and after an hour it was dropped to 10% of the total power potential.

Following the same procedure and data analysis as the first scenario, the results are given in the following table (Table 9).

Table 9: Given and absorbed energy amounts during scenario 2

Duration of test $\Delta t_{start\ up}$	2h 3 min
Ambient temperature T_{in}	9 ˚C
Maximum testing temperature T_{gasif}	550 – 600 ˚C
Mass flow m_{air}	120 Nl/min
Heat transfer coefficient h	5 – 10 W/m^{2}°C
Temperature of insulation surface T_{out}	60 ˚C
Power given from thermal resistances Q_{resist}	**10.701 kW**

Power absorbed from air Q_{air}	**2.253 kW**
Power absorbed from olivine $Q_{olivine}$	**2.382 kW**
Power absorbed from walls Q_{steel}	**2.617 kW**
Power losses from insulation surface $Q_{blanket}$	**1.425 – 2.849 kW**

At first, the given power from the electrical resistances is fairly lower, a fact that is attributed to the low operation load percentages. Significantly lower than the first scenario is the amount of energy absorbed from the air, since its flow is in much lower levels. The insulation losses are calculated as the first scenario and therefore they are the same. In the following table (Table 10) the percentages of net useful power are given.

Table 10: Net power and losses during start-up

Input		**Losses**	
Q_{resist}	100 %	Q_{air}	21.06 %
		$Q_{blanket}$	13.31 % – 26.63 %
Net useful power		**52.32 % - 65.29 %**	

While the percentages of power loss are the same in the two scenarios due to the heat transferred from the air flow, the absolute values are lower. As observed comparing the two scenarios, the air flow does not seem to greatly influence the power losses since the percentages are almost the same. On the contrary the lower operational percentage set of the resistances greatly increases the duration until steady state and significantly lowers the net useful power given to the system.

3.3 Environmental Performance

The environmental performance of the gasifier was studied in terms of:

- Liquid Effluents
- Inert Solids
- Gaseous pollutants

3.3.1 Liquid Effluents

In normal operating conditions, the designed gasifier has no liquid effluents that are produced from the gasification process or the circulating fluidized bed technology.

The only liquid compounds used in the experiments are the following:

- Water for cooling the water jacket of the bottom screw feeder. The water used was slightly heated and collected in a plastic container of Volume ~ 3 m^3 and it was recirculated in the water jacket
- Isopropanol for the scrubber that was used in the sampling line. The amount of isopropanol solvent used is approximately 4 litres/experiment

From the aforementioned liquid compounds, only the needs for water should be met in an industrial scale, since there is only a need for screw feeder cooling. On the contrary, the need for isopropanol is not met since there is not any need for constant gas quality measurement and gas cleaning.

3.3.2 Inert Solids

The solids that can be considered as outflows from the gasification process utilizing circulating fluidized bed technology, are the following:

- Inert material used for the fluidization
- Ash produced from the Refuse Derived Fuel utilized
- Char produced during the gasification process

The analysis of potential environmental hazard is described below.

Vassilev and Braekman-Danheux [2], studied the occurrence of trace elements in Municipal Solid Waste. In Table 11 . Taking into consideration the source of each major and minor element contained in the solids derived from the gasification, the produced RDF can be refined by choice.

Table 11: Sources of major and minor elements analyzed by standards of CEN/TC 343

Major Elements	
Al	Building materials, papers, ceramics, films, devices, tins, fireproofs, alloys, steels, conductors, plastics, fatty acids, lubricating oils
Ca	Building materials, organics, fillers, papers, glasses, steels, alloys, textiles, leathers, plastics, medicines, fertilizers, pesticides, plant materials
Fe	Steels, alloys, building materials, devices, magnets, electronics, batteries, pigments, conductors, papers, vegetable oils, fatty acids, lubricating oils
K	Building materials, organics, papers, glasses, foods, textiles, leathers, batteries, soaps, inks, alloys, galvanizing, medicines, photography, fertilizers
Mg	Building materials, organics, papers, alloys, steels, fireproofs, galvanizing, textiles, medicines, pyrotechnics, fertilizers
Na	Building materials, organics, papers, glasses, foods, rubbers, leathers, inks, galvanizing, alloys, medicines, textiles, soaps, soap powders, photography, fuels, fertilizers, plant materials

P	Organics, plastics, pyrotechnics, rubbers, varnishes, glues, tooth pastes, soap powders, alloys, pesticides, fertilizers, steels, semiconductors, solders, textiles, medicines, pigments, lubricating oils
Si	Glasses, building materials, fillers, optics, electronics, semiconductors, fireproofs, abrasives, steels, rubbers, solar batteries, alloys, organometallics
Ti	Building materials, papers, alloys, devices, fillers, paints, pigments, organometallics, plastics (PVC)
Minor Elements	
As	Clay materials, organometallics, paints, medicines, pesticides, electronics, semiconductors, cosmetics, glasses, alloys, solar batteries, lamps, leathers, orchard leaves, sulphuric acid
Ba	Building materials, papers, organometallics, glasses, textiles, ceramics, leathers, paints, plastics PVC , steels, alloys, pigments, electronics, lamps, pyrotechnics, medicines, optics, lubricating oils
Be	Alloys, Fireproofs
Cd	Plastic stabilizers, papers, organometallics, paints, pigments, solar panels, batteries, printing inks, galvanizing, alloys, solders, surface metal coatings, textiles, semiconductors, glazed ceramics
Co	Alloys, steels, organometallics, inks, magnets, fuels, pigments, ceramics, glasses, fertilizers
Cr	Cardboards, papers, glasses, paints, pigments, leathers, alloys, steels, electronics, surface metal coatings, galvanizing, fireproofs, plastics
Cu	Alloys, steels, electronics, organometallics, conductors, papers, printing materials, paints, plastics, galvanizing, building materials, fungicides, plant materials, chicken plasma
Hg	Batteries, thermometers, pyrotechnics, plastics PVC , fungicides, medicines, lamps, herbicides, alloys, galvanizing, pigments, paints, electronics, fluorescent tubes, fish remains
Mo	Alloys, steels, devices, solar batteries, electronics, lamps, papers
Mn	Steels, alloys, batteries, glasses, resins, pigments, galvanizing, devices, fuels, textiles, pesticides, fungicides, fertilizers, laying meals, fatty acids
Ni	Alloys, steels, batteries, plastics, pigments, glasses, coins, electronics, devices, surface metal coatings, magnets, vegetable oils
Pb	Organometallics, plastics, pipes, paints, pigments, alloys, papers, cardboards, rubbers, batteries, printing inks, glazed ceramics, amalgam, electronics, cables, solders, surface metal coatings, galvanizing, glasses, fuels, food remains, blood
Sb	Plastics, alloys, electronics, semiconductors, batteries, rubbers, pigments, textiles, cables, surface metal coatings, glasses, pyrotechnics, medicines
Se	Electronics, semiconductors, cables, glasses, rubbers, steels, pigments, ceramics, lubricating oils, pesticides, pharmaceutics, photography, medicines, soaps
Tl	Building materials, lamps, fireproofs, alloys
V	Steels, alloys, electronics, superconductors, textiles, varnishes, rubbers, ceramics, glasses, medicines
Zn	Organometallics, alloys, printing inks, papers, vulcanization, rubbers, plastics, batteries, surface metal coatings, galvanizing, pigments, semiconductors, pesticides, medicines, food remains, chicken plasma

As observed from the table above, the ten waste streams that contain the most major and minor elements are the following:

1) Alloys with 25 elements
2) Steels with 15 elements
3) Glasses with 14 elements
4) Papers with 14 elements
5) Pigments with 14 elements
6) Electronics with 13 elements
7) Medicine with 12 elements
8) Building materials with 11 elements
9) Plastics with 9 elements
10) Batteries with 9 elements
- Organometallics with 9 elements

Moreover, the elements that are met in the most waste sources are:

1) Lead (Pb) in 22 sources
2) Phosphorus (P) in 18 sources
3) Sodium (Na) in 18 sources
4) Barium (Ba) in 18 sources
5) Zinc (Zn) in 16 sources
6) Potassium (K) in 15 sources
7) Arsenic (As) in 15 sources
8) Cadmium (Cd) in 15 sources
9) Mercury (Hg) in 15 sources
10) Manganese (Mn) in 15 sources

The fact that 7 out of 10 elements that are met in the most waste sources are heavy metals combined with their importance in environmental impact, depict the necessity in good waste separation in Materials Recovery Facilities before the production of RDF. This will reduce the sources of heavy metals that end up in RDF and therefore will increase the possibilities that the produced ash and char during RDF gasification will include less contaminants making them appropriate for landfilling according to European Norms.

Inert material

In the studied gasification process, the inert solid used is olivine. Olivine is an inert solid mineral that is a magnesium iron silicate with the formula $(Mg^{2+}, Fe^{2+})_2SiO_4$.

The quantity of the inert solid that is discarded in every experiment is about 20kg. The analyses of the inert material (as presented in deliverable 5.2) show that the used olivine can be treated as any other inert solid (such as fly ash/ bottom ash) that derives from power plants and there is no need to be treated as a hazardous material.

Ash from RDF

Rocca et al. [3] have studied the environmental properties of ash produced from RDF incineration (operating temperature 1200–1400 ºC) and gasification plant (operating temperature 850–1000 ºC), in terms of total composition, mineralogy, buffering capacity and leaching behaviour. The results that occurred from the experiments showed that the two types of ash appeared similar content of major components and it was found that the content was related to the RDF feedstock characteristics. Taking into consideration the compliance leaching test results, the ash derived from RDF gasification meets the limits of the Italian National legislation for reuse and the European acceptance criteria for inert waste landfilling. Moreover, ash produced from RDF incineration would meet the European acceptance criteria for non hazardous waste landfilling.

Gori et al. [4] investigated the properties (physical properties, chemical composition and leaching behaviour) of ash samples from RDF gasification plants. It was shown from XRD analyses that the produced ash contained large amounts of vitrified inorganic materials. After the chemical composition analysis it was found that the produced ash contained mainly Fe, Mn, Cu and Cr. The samples were tested for inert waste landfilling capability and reuse through the leaching test EN 12457-2 and it was found that one sample passed the test while the other slightly exceeded the limits for Cu, Cr and Ni.

Char produced

Fuente – Cuesta et al. [5] studies the leachability of minor and major elements from char produced from gasification of plastic and paper. Mixture of plastic and paper ideally simulates the behaviour of Refuse Derived Fuels as the major components (~70%). The char samples studied were by-products (residues) from the gasification procedure and the leachates they were analysed for are mainly heavy metals (Al, Ca, Si, Mg, Ba, Cu, Ni, Pb, Zn, Mo and Hg). The results showed that at alkaline pH values, sorption on the solid surfaces of the char was negligible due to the inorganic complexation of cations in the solution. It is reported that the char showed that the leachable concentration of regulated elements were below the established values for the disposal of inert waste on landfill sites by the European Landfill Directive 2003/33/EC.

As it can be deduced from the studies already elaborated and reported, the ash and char produced from the gasification of RDF can be considered as inert waste and landfilled according to the European Landfill Directive 2003/33/EC.

3.3.3 Gaseous pollutants

The gaseous pollutants that are emitted from a fluidized bed gasifier operating with Refuse Derived Fuels can be distinguished in two main categories:

a) Emissions from inadequate sealing of the joints of the fluidized bed gasifier. These emissions mainly include gases such as CO, CO_2, H_2 and CH_4. Out these four gases, CO is hazardous for human health and can lead to death, while the other two (H_2 and CH_4) are dangerous for causing fire accidents. Therefore tight sealing is probably the most important aspect that needs to be taken into consideration for the gaseous pollutants. However, these emissions cannot be taken into consideration since the normal operation of the gasifier is tight sealed.

b) Emissions from the thermal utilization of the produced syngas. After the production of syngas, it is destroyed in a combustion chamber. The emissions from the thermal utilization of syngas include CO_2, some CO, H_2O, SO_x, NO_x, particulate matter, Polyaromatic Hydrocarbons (PAH), dioxins and furans (PCDD/Fs), and heavy metals.

Regarding the aforementioned pollutants after the utilization of the syngas, in depth research has been made from various research teams, none of which confirm a very high environmental impact.

3.3.3.1 Carbon monoxide

Carbon monoxide (CO) in the flue gas of incineration plants in general is the product of incomplete combustion of carbon based compounds [6]. It was studied from Fryda et al. [7] and Kaynak et al. [8] that the CO concentration in combustion gases generally increases when the proportion of biomass in the waste feed increases. Crucial to minimizing CO in the combustion gases is maintaining an optimum excess air ratio, high enough to provide enough oxygen for complete combustion, but low enough to guarantee sufficient residence time for volatile matter to combust completely.

3.3.3.2 Hydrochloric acid (HCl)

Wastes incinerated in FBCs contain varying amounts of chlorine in the form of chlorinated organic compounds or chlorides. As referred from the Best Available Techniques document of EC, in municipal waste, typically about 50% of the chlorine comes from PVC [6]. It was found from Liu et al. [9] that during combustion, almost all the chlorine is volatilized and emitted mostly as gaseous HCl with limited amounts of volatile metal chlorides. This was also demonstrated using a lab scale FBC, fed with simulated raw flue gas, that the formation of Cl_2 was favoured at temperatures above 600^{o} C, in oxygen rich atmospheres and with relatively high HCl concentrations. Altarawneh et al found that Cl_2 appears the major chlorinating agent in the formation of toxic PCDD/Fs [10].

3.3.3.3 Sulphur oxides (SOx)

Sulphur oxides (SOx) are acid flue gas compounds. Boavida et al [11] found that when wastes with relatively high calcium contents are co-incinerated, the calcium anion (Ca^{2+}) present as CaO in the fly ash can act as SOx absorption agent.

Gulyurtlu et al. [12] have found that one of the drawbacks of increasing the SO_x capture in the combustion gases is an increase in the concentration of soluble sulfates in the fly ashes or flue gas cleaning residue. In this way, the sulfate concentration in the solid residues may exceed the limits for the acceptance as inert or even non-hazardous waste set by the EU Directive 2003/33/EC.

3.3.3.4 NO_x and N_2O

Nitrogen oxides (NO_x) are generally emitted as nitric oxide (NO), accounting for up to 95% of NO_x emissions [13], and contribute to acidification, photochemical ozone creation and eutrophication.

The distribution of the fuel Nitrogen between volatiles and char, as well as the distribution of the volatile Nitrogen species depends mainly on the operating conditions (e.g. temperature, excess air) of the incinerator and on the properties of the solid fuel [14, 15]. During fluidized bed combustion most of the fuel Nitrogen is released during devolatilization as volatile Nitrogen species [16, 17].

3.3.3.5 Particulate matter (PM)

Particulate emissions can be classified into two broad classes: particles from incomplete combustion (soot, condensed organic matter or tar) and carbonaceous residues or char on the one hand, and particles from the mineral compounds in the fuel on the other hand. The coarser particles (1 – 10mm) result from agglomeration of non-volatile elements in burning char particles; the finer particles (<1mm), are mostly produced from nucleation and condensation of compounds based on volatile elements such as K, Na and Cl. [18, 19].

3.3.3.6 Polychlorinated dioxins and furans (PCDD/Fs)

PCDD/Fs constitute a group of 75 PCDD- and 135 PCDF-congeners with chlorine atoms at different positions of the two aromatic rings of the molecules. Because of their resistance to chemical degradation, these toxic pollutants can remain intact for many years and become widely distributed throughout the environment. They accumulate in the fatty tissue of animals and humans and their toxic effects include cancer, allergies and developmental effects.

It was found from Van Caneghem et al., that in full scale Fluidized Bed Combustors the incoming PCDD/Fs from the waste are effectively destroyed during incineration, regardless of their concentration [20, 21]. PCDD/Fs found in the flue gas and the fly ash do not originate directly from the waste, but are the result of a recombination reaction of carbon, oxygen and chlorine on ash particles in the post combustion stage, at temperatures of 250 - 450 °C.

3.3.3.7 Polyaromatic hydrocarbons (PAHs)

As reported from Gulyurtlu et al., PAHs are considered as products of incomplete combustion [22]. When the volatilized or recombined PAHs are entrained with the combustion air without further destruction (by oxidation), they are found in the flue gas and fly ash [22 - 25]. The PAH fingerprints of RDF were dominated by PAHs with at least 3 rings, fluoranthene, fenanthrene and chrysene being the most important. In the flue gas however, 99% of the total PAH concentration was accounted for by naphthalene (two ring PAH), which contributed for only 6% to the total PAH concentration in RDF.

At higher temperatures the rate of destruction by oxidation of newly formed PAHs increases and when it exceeds the rate of formation, the PAH concentration in the raw flue gas drops.

As reported from the BAT document, the techniques used to control the PAH emissions of FBCs incinerating waste are the same as for the control of PCDD/F i.e. good control of the combustion process ensuring complete burnout and injection of adsorption agents such as activated carbon in the flue gases [6].

3.3.3.8 Heavy metals

Heavy metals represent a loosely-defined group of metal elements including As, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, V and Zn. Metals present in the waste can either remain in the bottom ash, be retained in the fly ash or be vaporized and entrained with the raw flue gas. The partitioning not only depends on the physical en chemical properties of the metal, but is also related to the presence of gaseous pollutants such as HCl, SO_2, unburned carbon, and particulate matter in the flue gas, to the design of the installation.

Mercury (Hg) is the most volatile heavy metal with a boiling point of 35.7 °C. It is vaporized as elemental Hg and, while the flue gas cools, while passing through the subsequent heat exchangers and flue gas treatment, oxidation may take place, generating Hg^+ or Hg^{2+} -oxides and -salts, e.g. HgO, $HgCl_2$ or Hg_2Cl_2 and $HgSO_4$ depending on the availability of Hg, oxidants and on temperature.

The fate of other heavy metals in FBCs not only depends on the properties of the metal in question, but also on its speciation, which depends on the chlorine and sulphur concentration in the fluidized bed. Different lab scale experiments show that Co and Cu mostly remain in the bottom ash, while Cd, Pb and Zn are mostly found in the fly ash; Cr, Mn, Ni and V are more or less equally distributed between bottom and fly ash [26, 27, 28].

In the following table (Table 12), there is a comparison of the typical main pollutants from waste thermal utilization in Fluidized Bed Combustors, Grate furnace and the EU Directive limit values. As presented, in all of the pollutants already studied, the measurement is below the limits set.

Table 12: Concentrations of main pollutants reported

Pollutant	**FBC**	**Grate furnace**	**Limit values EU Directive**
CO	14-4	6.0-14	50
HCl	0.1-8	0.9-6.1	10
SO_x as SO_2	1-1.6	1.6-10.3	50
NO_x as NO_2	90 – 150	65-145	200
PM10	0.6 - 1	0.0-0.8	10
TOC	0.9 – 5	0.1-1.8	10
Hg	0.013	<0.0005-0.013	0.05
Cd + Tl	<0.016	0.0001	0.05
Sb + As + Pb + Cr	0.05	0.09	0.5
Co + Cu + Mn + Ni + VC PCDD/Fs	0.008 ngTEQ/m^3	0.001-0.01 ngTEQ/m^3	0.1 ngTEQ/m^3

4 Scale-up potential

4.1 Operational and Maintenance costs

After the detailed mass and energy balance that was created for the pilot scale gasifier, a breakdown into the costs for operation and maintenance of the plant was constructed. In the following tables (Table 13, Table 14, Table 15, Table 16), the distribution of costs was made for a monthly operation of the pilot plant. Finally, the reduction in €/kWh$_{th}$ and €/kWh$_e$ is presented in the final table. All of the monthly costs are calculated for 30 days/month and 10h/day of operation.

Personnel Costs

The personnel costs were calculated by the number of personnel needed for the nominal operation of the pilot plant and the percentage of their allocation to the operation of the CFB. More specifically apart from the workers and operator of the plant that are necessary for the operation of the pilot plant, all of the other personnel are partially occupied. The column cost/month is an indicative salary for each type of personnel.

Table 13: Personnel Costs

	Number of personnel	% allocation to the operation	Cost / month	**Total cost**
Workers and operator	3	100.00%	1,400 €	4,900 €
Operator vehicles (loaders, forklifts)	1	10.00%	1,800 €	210 €
Truck driver (RDF transportation)	1	2.00%	1,700 €	40 €
Mechanics-foremen (maintenance-production)	1	10.00%	2,280 €	266 €
Electricians (maintenance-production)	1	10.00%	2,100 €	245 €
Engineer Operations Manager	1	5.00%	4,000 €	233 €
			Total Cost / month	5,894 €

Maintenance - Consumables - Parts

In the following table, the costs for M&O are presented. The calculation of these costs, is based on the costs that occurred during the operation of the plant. More specifically the following assumptions were used:

- Vehicle fuels cost = Fuel Price (€/lt) x Average litres required (for the transportation of RDF from the operation plant to the warehouse were the plant is located, and for loading the fuel in the bunker)
- Gas (N_2) is calculated from the consumption of 50lt/h of N_2 for the operation of the plant, the concentration of each gas cylinder array (86,4 m^3) and the cost.
- The rest were calculated approximately according to the needs that have occurred during the operation of the pilot plant for the experiments that were conducted

Table 14: Consumables, parts and maintenance costs

	Total Cost
Vehicle fuels for forklifts, loaders, trucks	33 €
Lubricants for equipment and vehicles, filters (grease, oil)	50 €
Gas (N2)	78 €
Small parts (bearings, seals etc.)	50 €
Micro Materials (screws, electrodes etc.)	30 €
Other consumable parts (e.g. inert material, etc.)	50 €
Various external teams work (workshop, solder etc.)	50 €
Electrical parts / consumables	30 €
Parts of mobile equipment (vehicles)	20 €
Contingencies due to extraordinary damage (parts, services)	50 €
Means of personnel protection	250 €
Total Cost / month	691 €

Electricity costs

The whole materials recovery facility of WATT in Koropi is connected to the Public Power Company (PPC) grid, with an industrial tariff of ΒΓ type of invoice. This type of tariff charges the installed power and separately the consumption during weekends and from Monday-Friday. In our case the installed power of the unit calculated is around 85kW, while the energy consumption presented is for the operation of the electrical resistances in the average load per day and the operation of all other secondary equipment (air compressor, burner, screw feeders, rotary valves etc.)

Table 15: Electricity costs for unit operation

		Cost	**Total Cost**
Installed power	85 kW	0.071 €/kW	6.04 €
Operation during week	204 kWh	0.06428 €/kWh	288.49 €
Operation during weekend	204 kWh	0.05062 €/kWh	82.61 €
		Total	377.14 €

Management costs

The category of management costs includes the other/general costs as well as the administrative costs. The costs are calculated approximately according to the yearly cost for the operation of the plant.

Table 16: Other costs

	Total Cost
insurance	166.67 €
Insurance works vehicles (@ 10%)	25.00 €
Security (@25%)	1,000.00 €
Gas for vehicles (reimbursement external work)	50.00 €
Office supplies	40.00 €
Detergents (detergents, etc.) (@20%)	35.00 €
Water	100.00 €
Medical (examinations / vaccines)	10.00 €
Technical Safety / Work Doctor	100.00 €
Rodent control	50.00 €
Other contingencies	100.00 €
Total	1,676.67 €

Technical parameters

For the calculation of some necessary parameters for the operational costs, the assumptions that are described in Table 17 are taken into consideration. The amount of syngas produced and its Net Calorific Value are taken from the energy balance constructed in previous paragraphs of this deliverable, but a nominal operation of 30kg/h. The electric production and the combined heat and power production are calculated assuming the utilization of an internal combustion engine (ICE) that will provide the capacity for the respective production.

Table 17: Produced power

Parameter	Value
Fuel feed	30.00 kg/h
Hours of operation per month	300.00 h/month
Total of fuel utilized	9,000.00 kg
Net Calorific Value of RDF input	14,000.00 kJ/kg
Total energy input	116.67 kWh_{th}
Syngas produced	15,430.91 kg/month
Net Calorific Value	6,053.00 kJ/kg
Total Energy produced	93,403,292.73 kJ
Total Energy produced	25,945.36 kWh_{th}
electric production	10,378.14 kWh_{e}
combined heat and power	19,459.02 kWh

From the aforementioned cost breakdown, the following indexes are calculated for the operation of the plant.

- Opex for syngas production based on the syngas thermal power
- Opex for electricity production in an Internal Combustion Engine with efficiency of 40%
- Opex for combined heat and power production from ICE with a total efficiency of 75%.

Index	Cost
€/kWh_{th}	0.33
€/kWh_{e}	0.83
€/kWh_{CHP}	0.44

Regarding the final costs occurred, it is noted that the following parameters are the ones that influence the most the costs that occur:

- **Personnel costs:** The high personnel costs can be regulated through the automation of the pilot plant, in order to reduce the operating personnel to only one person per shift.
- **Security costs:** Security costs for the guarding the pilot unit during the hours that it does not operate are the highest of other costs, but are considered necessary for safeguarding the circulating fluidized bed gasifier

- **Fuel feed:** Managing a potential increase of the fuel feeding rate, a consequent increase in the power produced will occur. E.g. doubling the fuel feed will reduce the cost (€/kWh) to half, therefore leading to a reduction to the indexes.
- **Net Calorific Value of syngas produced:** A possible upgrade of the produced syngas, in order to increase the produced power from it will reduce even more the calculated indexes.

4.2 Scale-Up

For the scale up of the studied pilot plant, a study was elaborated for a larger semi – Industrial scale that will produce 85kWe.

The technical specifications for the scale up of the circulating fluidized bed gasifier studied in the project ENERGY WASTE, are summarized in the following table (Table 18). In order to calculate the parameters of a plant with 15 times larger fuel feed the following were taken into consideration:

- The fuel feed of 450 kg/h is significantly less than the nominal (~20%) of the total potential for RDF feeding that will be able to cover the whole RDF production of WATTs' facility in Koropi.
- For large scale facilities (such as semi-industrial) it is essential to consider 3 shifts per day (24 hours continuous operation), in order to avoid stalling due to the facility startup.
- An availability of more than 80% was taken into consideration, leading to 300 the operation days/year
- The net calorific value of the produced syngas is considered the same as the pilot scale, even though there might be differences in the scale up of the process

Table 18: Semi industrial scale of pilot plant

Parameter	Value
Fuel feed	450.00 kg/h
Hours of operation per month	600.00 h/month (3 shift for 25days/month)
Total of fuel utilized	270,000.00 kg/month or 270 t/month
Total energy input	1,050,000.00 kWh_{th}
Syngas produced	462,927.27 kg/month
Net Calorific Value	6,053.00 kJ/kg
Total Energy produced	2,802,098,781.82 kJ
Total Energy produced	778,360.77 kWh_{th}
Electric production (40% eff. of ICE)	311,344.31 kWh_e
Combined heat and power (75% eff. of ICE)	583,770.58 kWh

Although the main focus is the purchase cost of the equipment, the cost of a fully installed and operational unit is usually required. The following costs are estimated:

- Engineering of the larger scale facility, including large scale designs and more complex automations.
- Gasifier Island: including the dosing bunker (with weight measuring load cells, the reactor, syngas cooler and a series of cyclones for removing particles from the produced syngas)
- Automatic fuel transport to the RDF bunker. For this purpose a conveyor belt will be utilized for loading the bunker with RDF for continuous operation. At the end of the conveyor belt the flow will be controlled by a rotary valve. The rest of the feeding system will be of the same philosophy including two screw feeders for feeding and two rotary valves for air sealing.
- Syngas burner and piping
- Ash handling system. The ashes separated from the syngas by means of the separation cyclones, will be transported towards a silo with enough capacity to store the ashes for 2 days minimum. All the alkali minerals like Na, K are still present in the ashes. In case of RDF gasification the ashes probably will have to be disposed to land fill, or can be upgraded to be used in civil construction material.
- Steam cycle. For the production of electricity and hot water for use. A typical steam cycle comprises of a boiler, dearator (for removing air), turbine, cooling tower and condenser. In our case a combined heat and power module is taken into consideration
- Flue gas cleaning. This system includes bag filters, DeNOx and additives to the reactor as catalysts.
- Emission measurements and monitoring. This system is required in order to continuously measure the emissions which is enforced through European directives for the efficiency of the semi-industrial plant
- Electrical control and automation. A more advanced system will need to be designed and introduced to a larger scale unit, in order to reduce the needed personnel and more accurately control the operation of secondary systems (e.g. external resistances, valves, burner safety automations etc.)

An example of the upscale of the gasification unit is given in the following figure (Figure 7).

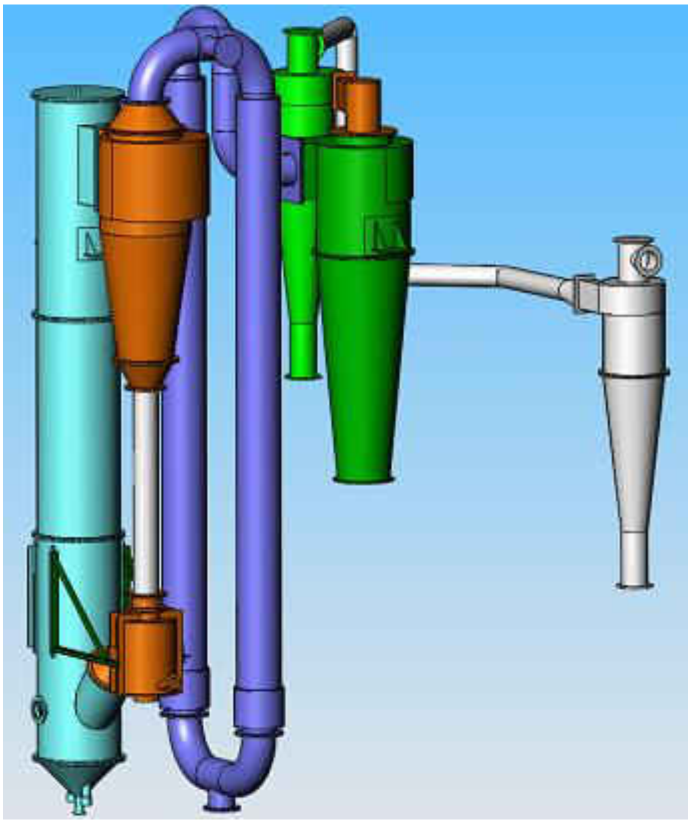

Figure 7: gasifier island: reactor (light blue), sand recycle cyclone (red), syngas coolers (dark blue), ash separation cyclones (green and grey).

Capital Cost Estimation

Overall costs of capital projects are known to be subject to economies of scale.

For the estimation of the capital cost a proportional increase to the budget cost of the pilot scale gasifier with the following equation.

$$C_{new} = C_{old} \times \left(\frac{Q_{new}}{Q_{old}}\right)^{0.6}$$

A crude estimate is that if the capital cost for a given sized piece of equipment is known, changing the size will change the capital cost by the 0.6 power of the capacity ratio (the point six power rule) [29]. The new costs are provided in the following table (Table 19).

Table 19: Cost breakdown for circulating fluidized bed gasifier

Part	Cost
Engineering	120,000.00 €
Gasifier Island (dosing bunker, reactor, syngas coolers, cyclones)	900,000.00 €
Fuel Transport to dosing bunker gasifier	20,000.00 €
Syngas burner and piping	150,000.00 €

Ash handling system gasifier (silo, ash/water mixer)	30,000.00 €
Steam sycle (boiler, dearator, cooling tower, turbine, condensor)	450,000.00 €
Flue gas cleaning (baghouse filter, additive dosing, DeNOx)	450,000.00 €
Emission measurements and monitoring	80,000.00 €
Electrical control and automation (ouside gasifier island)	180,000.00 €
Contingencies (10%)	243,000.00 €
TOTAL	2,623,000.00 €

Major exclusions involve:

- civil works (including noise cover/building for turbine)
- local infrastructure and connections to the local grid
- electrical connections on terminals of the generator
- analysing equipment for syngas, fuel, ashes and so on
- consumables
- performance measurements
- obtaining of permits

After the scale up, the already studied indexes for O&M are presented in the following table, taking into consideration that the costs for operation and maintenance grow with the same patern as the capital costs.

Index	Cost
€/kWh$_{th}$	0.011
€/kWh$_e$	0.028
€/kWh$_{CHP}$	0.015

Taking into consideration the scale up, it is obvious that the costs that occur for larger scale units are significantly smaller per kWh produced.

For this reason two diagrams were created for various feeding rates and the respective production in kW and kWh. The scenarios taken into consideration are depicted in the following table (Table 20). The parameters used for the calculation of the power and energy produced are the following:

- Operation of plant 660 hours per month (330 days/year)
- Syngas NCV: 6053 kJ/kg
- Electrical efficiency (n_{el}): 40%
- Combined heat and power efficiency (n_{tot}): 75%

Table 20: Scale up scenarios for the pilot gasifier erected in ENERGY WASTE

kg/h	kWe	kW$_{CHP}$	kWth,in	kWhe	kWh,$_{CHP}$	kWhth,input
30	35	65	108	22,832	42,810	71,500
150	173	324	542	114,160	214,049	357,500
300	346	649	1,083	228,319	428,098	715,000
450	519	973	1,625	342,479	642,148	1,072,500
600	692	1,297	2,167	456,638	856,197	1,430,000
750	865	1,622	2,708	570,798	1,070,246	1,787,500
900	1,038	1,946	3,250	684,957	1,284,295	2,145,000
1,200	1,384	2,595	4,333	913,277	1,712,394	2,860,000
1,500	1,730	3,243	5,417	1,141,596	2,140,492	3,575,000
1,800	2,076	3,892	6,500	1,369,915	2,568,591	4,290,000
2,200	2,537	4,757	7,944	1,674,341	3,139,388	5,243,333
2,500	2,883	5,405	9,028	1,902,660	3,567,487	5,958,333

For the aforementioned scenarios two different diagrams were plotted. The first included the capital cost (CAPEX) required to design, erect and start the unit (Figure 8). Three curves are presented, all of them representing the reduced cost per kW of the type of production:

- Electricity
- Combined heat and power
- Thermal Input for waste destruction

The second diagram (Figure 9) depicts the operating and maintenance costs (OPEX) reduced per kilowatthour produced.

As observed from both of the diagrams, the designed circulating fluidized bed unit can be comparable and competitive with other state of the art technologies with a capital cost of less than 2,500 €/kWe for an installation of 3MWe. Respectively the operational cost is reduced to just a cent for each kWh$_e$ produced (0,012 €/kWh$_e$).

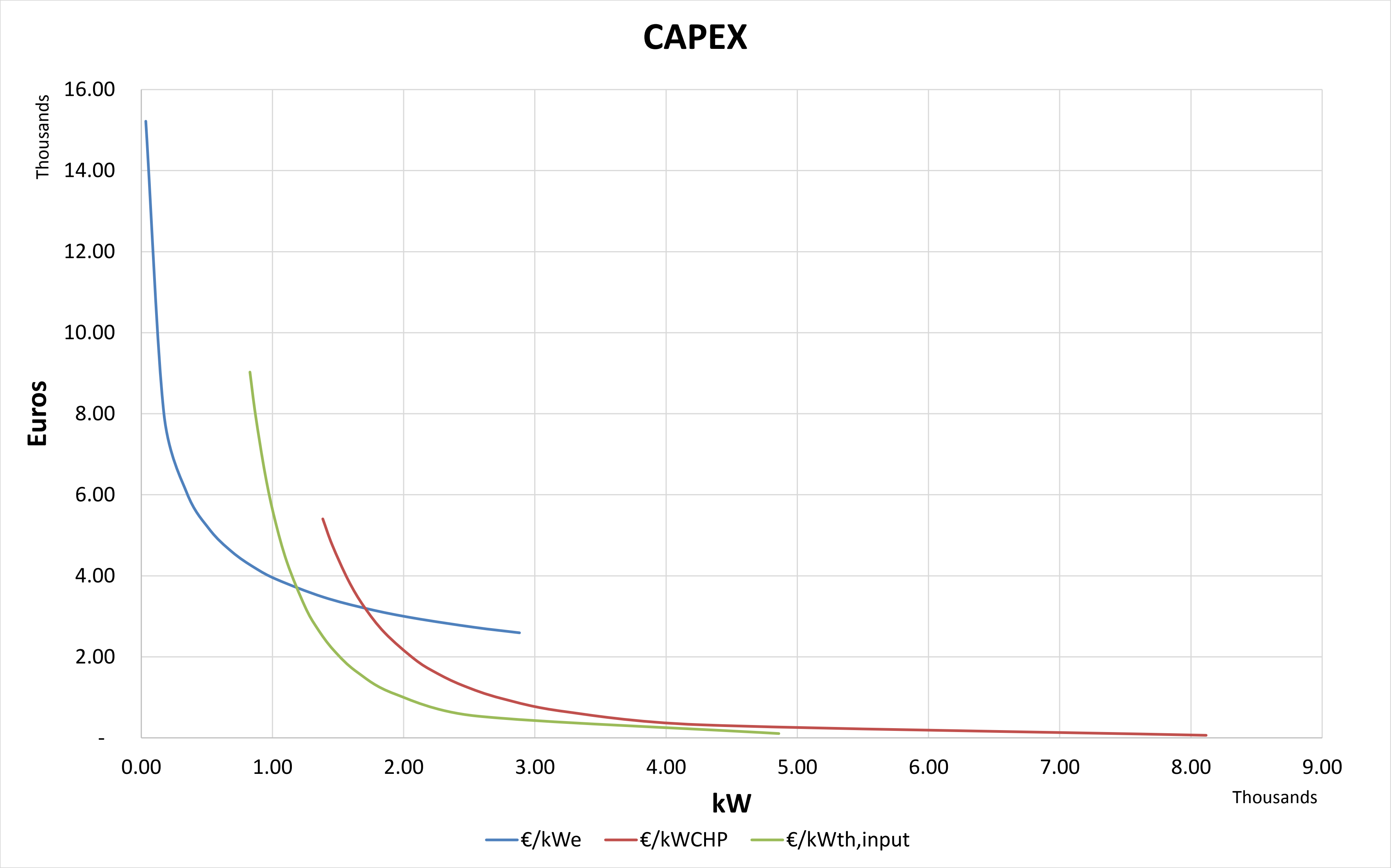

Figure 8: Capital costs

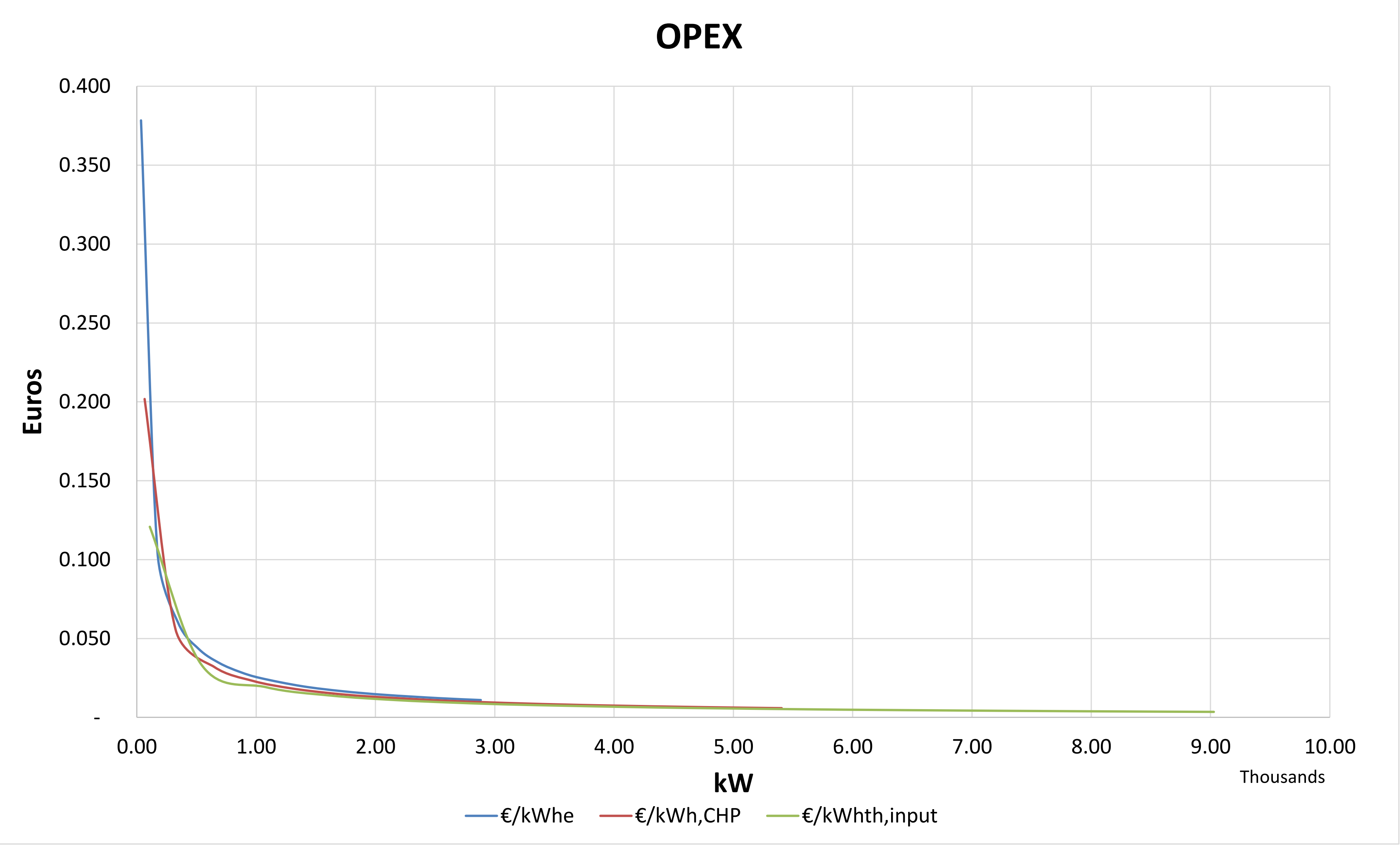

Figure 9: Operation and Maintenance costs

5 Conclusions

In this deliverable the mass and energy balance was constructed for the pilot circulating fluidized bed gasifier that was constructed. All of the data used were collected during the tests run and from the expertise gathered during the construction and experimentation period.

From the constructed mass balance it was concluded that the syngas produced represents about 88,5% of the outflows of the pilot plant. However the rest solid/liquid remains including ash, tars and char are extracted after each experiment. The produced ash and char can be both treated as non-hazardous waste and led to a landfill. In some cases they can be upgraded for utilization in other processes and therefore considered as by-products. The tars compose about 1,5% of the products of the pilot plant, and unfortunately they are concentrated and stick to the walls of the syngas cooler. For that reason a further study will be needed on tar cracking catalysts, in order to reduce this percentage.

Taking into consideration the energy balance, it was observed that the energy acquired from the utilization of RDF is almost half the energy that is required for the gasification process to proceed and maintain a steady temperature at the range of 750-800°C. This is mainly due to the losses from the cool air that is inserted to the system and the losses from the outer wall of the thermal insulation. There are also two facts that contribute in this phenomenon. First of all the electrical resistances power was calculated from the percentage of load given to the electrical resistances multiplied by the power of the electrical resistances. This includes the indirect fault that the percentage given is much bigger than the one needed to stabilize the temperature (i.e. we provide 50% power instead of 5% in order to have a quicker response to external heating, leading to some cases to a thermal deviation of 20-30°C from the point set). The second factor that contributes to high electrical resistances operation is that the unit is at pilot scale and the stabilization of temperatures is more difficult that a large scale plant due to the process progress in the riser. Based on the losses factor, a study was made for an optimal start-up procedure using slow heating and small air flow, and high heating and high air flow. It was found that in both cases the losses occurred from air were about 21% of the given amount of energy while the percentage of useful energy ranged from 55-75%. In the case of useful net energy the fast heating showed a higher useful energy acquisition and therefore is more preferable.

The indicators of the efficiency of the pilot gasifier presented a Cold Gas Efficiency equal to 78.88% and a Carbon Conversion Efficiency equal to 81.36%. Considering the efficiency of the gasifier the environmental efficiency was studied, showing that there are no effluents from the unit that can be considered as hazardous waste, and the designed system for syngas utilization will produce gas emissions that are in the limits that have been set from the European Directive 2010/75/EC. The produced solid effluents can be either landfilled as non-hazardous material or in some cases after being upgraded as input to other processes (e.g. catalysts).

Finally the scale-up potential of such a unit was studied along with operational and capital indexes. It was found that the designed circulating fluidized bed unit can be comparable and competitive with other state of the art technologies with a capital cost of less than 2,500 €/kWe for an installation of 3MWe. Respectively the operational cost is reduced to just a cent for each kWh$_e$ produced (0,012 €/kWh$_e$). In the present case of only 30 kg/h (~35kWe) the costs were significantly higher providing a capital cost of 15,000€/kWe and an operational cost of 0.378€/kWhe. This indicates an imperative need for scaling up the present plant in order to acquire better results.

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