Programme Area: Bioenergy

Project: Energy From Waste

Title: Appendix 3.1: Report on Selected and Validated Models

Abstract:

This deliverable is number 1 of 3 in Work Package 3. It summarises the model testing and validation carried out on waste-to-energy component process models. These component process models were later incorpoated in to a single system level model, details of which are set out in the other Work Package 3 reports.

Context:

The Energy from Waste project was instrumental in identifying the potential near-term value of demonstrating integrated advanced thermal (gasification) systems for energy from waste at the community scale. Coupled with our analysis of the wider energy system, which identified gasification of wastes and biomass as a scenario-resilient technology, the ETI decided to commission the Waste Gasification Demonstration project. Phase 1 of the Waste Gasification project commissioned three companies to produce FEED Studies and business plans for a waste gasification with gas clean up to power plant. The ETI is taking forward one of these designs to the demonstration stage - investing in a 1.5MWe plant near Wednesbury. More information on the project is available on the ETI website. The ETI is publishing the outputs from the Energy from Waste projects as background to the Waste Gasification project. However, these reports were written in 2011 and shouldn't be interpreted as the latest view of the energy from waste sector. Readers are encouraged to review the more recent insight papers published by the ETI, available here: http://www.eti.co.uk/insights

The Centre for Process Innovation Innovation Services

ETI – Energy from Waste Project

Deliverable 3.1 – Report on Selected and Validated Models

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Executive Summary

While Energy From Waste represents the potential generation of clean, renewable, and secure low carbon energy in excess of 100TWh, the technology landscape and the available waste resource is unclear. The Energy Technology Institute (ETI) Energy From Waste project aims to unlock this potential by identifying the most promising technology systems aligned with the available waste resource. In order to achieve this aim, a consortium led by Caterpillar, involving CPI Services Ltd, Shanks Waste Management, EDF Energy, and Cranfield University, will complete a 16 month study with four Work Packages to define the technology system and the UK benefits case. To identify the technology needs, a system model will be generated in Work Package 3 that evaluates each unit operational component model for incorporation into the system.

The Centre for Process Innovation (CPI) is the leader of Work Package 3 and was tasked with the identification and creation of the individual component models. These component models will serve as the basis for investigating the economic and sustainable aspects of the conversion of waste materials to fuels and energy in the system model for deliverable 3.2.

The models for the project were created in an excel format and transferred to matlab software or created directly in matlab. They are based on literature data and operational experience gained within CPI.

The models in Table 1 below were identified based on their inclusion into the technology landscape summarised within Figure 2 and defined based on their use with pre-processing, processing, post-processing or heat and power generation. The identified models were then coded into Matlab:

Technology Nomenclature	**Process Type**	**Brief Descriptor**
Autoclave	Pre-processing	Thermal homogenisation
Milling	Pre-processing	Particle size requirements
Pelletisation	Pre-processing	Particle size requirements
Drying	Pre-processing	Reduction in H2O content
Downdraft Fixed bed gasifier	Process	Small Scale Syngas generation (< 1MW)
Updraft Fixed bed gasifier (Same report as Downdraft Fixed Bed gasifier)	Process	Mid Scale Syngas generation (> 1MW)
Fluidised bed gasifier	Process	Syngas generation
Pyrolysis	Process	Highly tolerant to waste input (low energy use)
Fluidised bed pyrolysis	Process	Highly tolerant to waste input (low energy use)
Mesophilic Anaerobic digester	Process	Wet waste CH4 generation
Thermophilic Anaerobic Digester (Same report as Mesophilic AD)	Process	Wet waste CH4 generation
Plasma gasifier	Process	Highly tolerant to waste input (high energy use)
Plasma Gas Cleaning (Same report as Plasma Gasifer)	Post-processing	Gasification of gas contaminants
Oil scrubber	Post-processing	Removal of contaminants
Molten carbonate fuel cell	Heat and Power	Highest electrical

	Generation	efficiency, but low tolerance to contaminants
Gas Turbine Genset	Heat and Power Generation	Higher High H2 tolerance
Gas Engine Genset	Heat and Power Generation	Higher electrical efficiency

Where models are variations of the same technology, they are discussed in the same report.

Table 1.Technology Component Modelling Summary

Pre-processing technologies, include pre-treatment technologies, such as milling or pelletising, are sometimes required to prepare the material before conversion. This is followed by the processing technoology, or conversion stage, where the feed material is converted in a reactor to either an oil or a synthetic gas.

The raw oil or gas will require cleaning as it will contain particulates and tars that will affect the performance of the heat and power conversion device. The selected techniques are modelled to provide a measure of the overall energy use and the quality of the gas or oil product from the post-processing.

All of the above models were developed by defining the required inputs (including energy to drive the process) and their overall outputs for complete energy and mass balancing. The energy balances are performed to confirm that the process is self sustaining. For all the processing based technologies, available literature data, CPI operational experience and an input of wood was used as the based for development. A standard component model template was compiled for each model that includes the overall approach and assumptions for the modelling effort. The assumptions will be validated and tested within the Work Package 2 technology testing based on the identified test plan in deliverable 2.1. The additional waste input and output information from each test will supplement the information not available from the literature.

The most promising of these technologies are to be identified, while the input-output data from the pilot experiments is to be incorporated into the models to give a more realistic assessment of the benefits of performing these processes.

Introduction

The ETI's Energy from Waste Flexible Research Project (FRP) will:

- Evaluate the energy which could be generated from the UK's wastes
- Quantify the benefit of Energy from Waste to the UK in relation to the ETI criteria
- Identify the potential technology developments to maximise the Energy from Waste opportunity in relation to the UK waste arisings

The Energy from Waste (EfW) project comprises four work packages to establish the waste and technology opportunity and derive the overall benefits case. A schematic of the project is shown in Figure 1. Work Package 1 (WP1) will evaluate waste availability and its energy value. In parallel, WP2 will provide technology operational data based on the literature and rig scale experimentation using real wastes for modelling different end-to-end EfW system configurations in WP3. Technology development opportunities to enable energy cost reductions through greater utilisation of wastes and/or more robust system operation will be identified in WP2 and 3. Finally, the benefits of Energy from Waste, and the identified development opportunities, will be quantified in relation to the ETI criteria will occur in WP4.

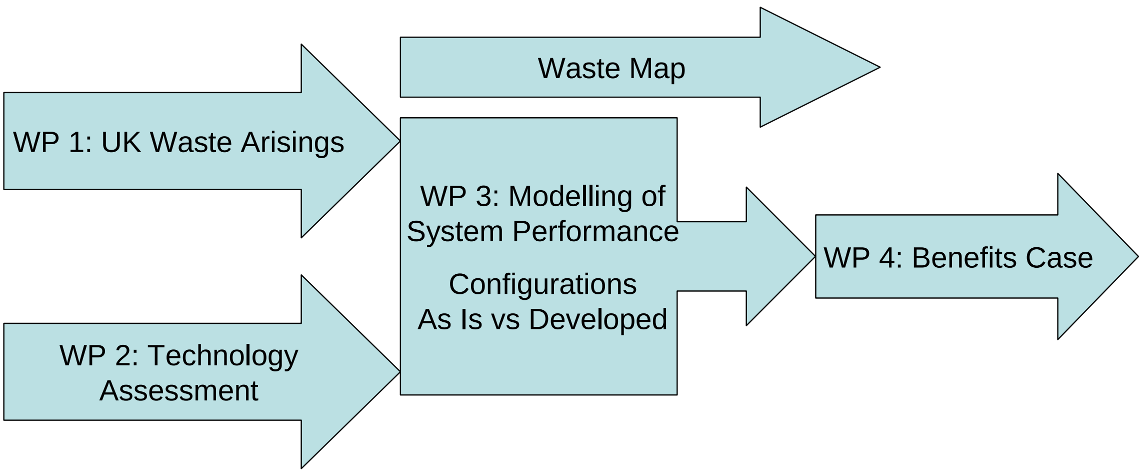

Figure 1 Schematic Representation of ETI EfW FRP Project

This report and the matlab component models forms the first deliverable in WP3.

Technology Assessment

Technology selection

Current energy recovery from waste is largely based on the need for landfill avoidance and hence destruction of wastes through mass-burn incineration with heat energy recovery to steam for conversion to power. As such, material-defined maximum steam cycle pressures limit system efficiency. In practice, the presence of corrosive chemicals in wastes released upon high temperature combustion (such as Hydrogen Chloride (Hydrochloric acid) and Sulphur Dioxide) limit the temperature at which the heat energy can be extracted from the flue gases, and hence the energy recovery potential from wastes. Whilst it is recognised that energy recovery of wastes through incineration and combustion technologies could be further developed from their current states, these inherent cycle efficiency limitations will always be a limiting factor on the total energy recovery efficiency of these systems. However, gasification, pyrolysis and digestion technologies exist (“advanced” processing technologies), which have to date been developed for other energy industries (i.e. coal, biomass etc), and have the theoretical potential to increase the energy recovery efficiency of wastes significantly. Whilst development of these waste processing technologies remains ongoing with specific waste streams, this project seeks to explore the potential to increase the electrical and thermal outputand to enable systems to process a wider range of wastes. The final benefits case to be delivered in WP4 of this project will compare the energy recovery potential of these advanced technologies to the incumbent energy-recovery through combustion technology.

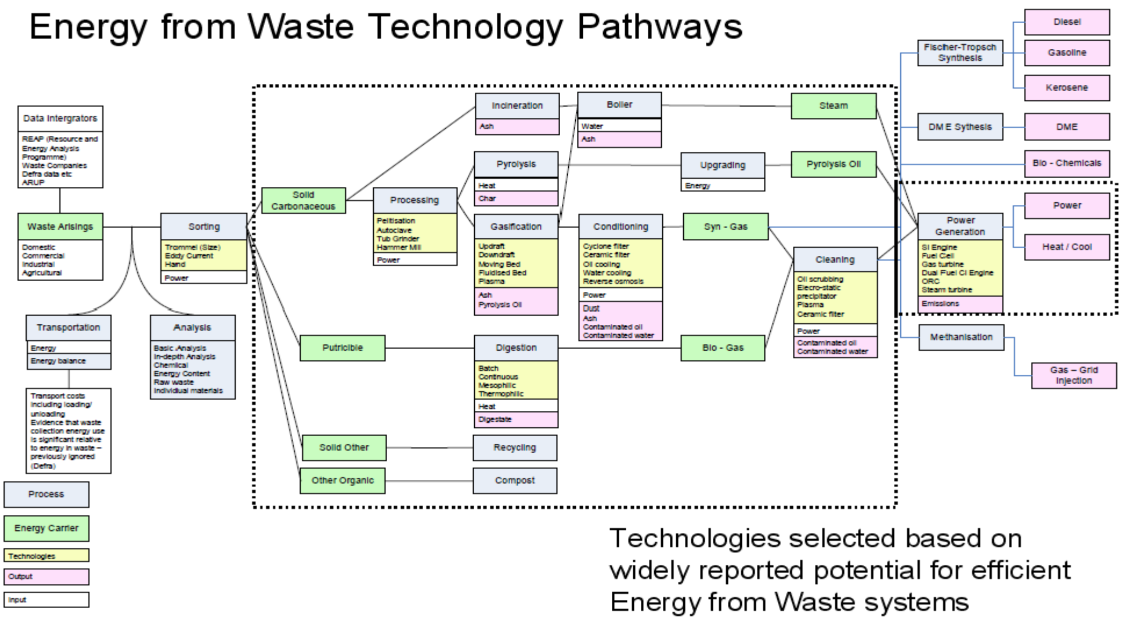

Figure 2: Energy From Waste Technology Landscape

Model Selection

Technology Modelling

Development and validation of component level models of the selected technologies for system performance simulation requires the composition of the outputs to be known in relation to the inputs and the operational parameters at the time of conversion. Such a complete information set has been labelled a “comprehensive” data set and is shown schematically in Figure 3.

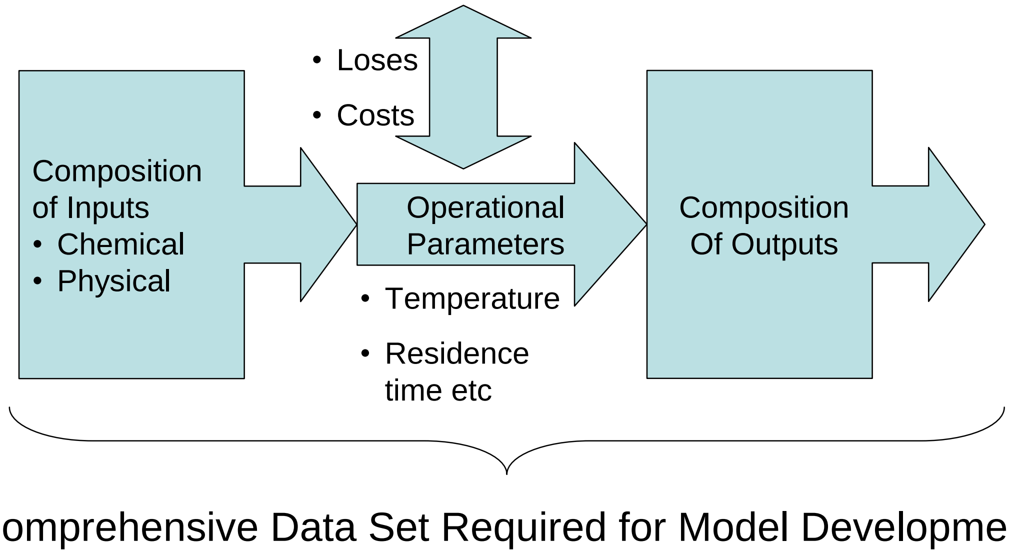

Figure 3 Technology Attributes Required for Modelling

Whilst partial or descriptive data sets may be used to validate sections of a model's performance and indicate directional validity of aspects of a model, only fully comprehensive data sets can be used to develop models, or to validate existing models in relation to different feedstocks and/or operational parameters.

Overview of existing technologies

The technology landscape for Energy From Waste is well represented by Figure 2. While this figure includes the entire Energy From Waste landscape, the focus of this project is to identify the technology systems and technology improvement areas for use within distributed energy. In this project, we will be reviewing technologies in the pre-processing stage (pretreatment and/or preparation of the waste), processing (thermochemical conversion of the waste into a gas or oil), post-processing (cleaning of the subsequent gas or oil for use as a fuel) and heat and power conversion of the post-processed fuel. The following table lists which technologies have been chosen for modelling and indicates whether they are a processing step, or form part of pre, or post processing or the heat and power conversion.

Technology Nomenclature	**Process Type**	**Brief Descriptor**
Autoclave	Pre-processing	Thermal homogenisation
Milling	Pre-processing	Particle size requirements
Pelletisation	Pre-processing	Particle size requirements
Drying	Pre-processing	Reduction in H_2O content
Downdraft Fixed bed gasifier	Process	Small Scale Syngas generation (< 1MW)
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Thermophilic Anaerobic Digester (Same report as Mesophilic AD)	Process	Wet waste CH4 generation
Plasma gasifier	Process	Highly tolerant to waste input (high energy use)
Plasma Gas Cleaning (Same report as Plasma Gasifer)	Post-processing	Gasification of gas contaminants
Oil scrubber	Post-processing	Removal of contaminants
Molten carbonate fuel cell	Heat and Power Generation	Highest electrical efficiency, but low tolerance to contaminants
Gas Turbine Genset	Heat and Power Generation	Higher High H2 tolerance
Gas Engine Genset	Heat and Power Generation	Higher electrical efficiency

Where models are variations of the same technology, they are discussed in the same report.

Table 2. Technology Component Modelling Summary

These models include the thermo-chemical routes of gasification and pyrolisis plus the microbial fermentitative route of anaerobic digestion. The thermo chemical processes have a number of options to perform the conversion, so the models selected were based on relevance to the waste industry but with proven scaled operations in other industries. The technologies chosen, on this basis, were updraft, downdraft, fluidised bed gasifiers and fluidised bed, rotary kiln pyrolisis.

Anaerobic digestion is also a recognised technology which produces a fuel in the form of methane and thus an obvious choice. The route of classical fermentation to produce an alcohol fuel was discounted as there is presently a technology gap in the breakdown of the waste material into a fermentable sugar as well as as transport liquid fuels were previously defined out of scope for this project.

The technologies previously mentioned require that the feed materials are pre-processed to produce a material of consistent size and homogeneity. This is either due to the fact that the thermo chemical processes are fast and a small consistent particle size is necessary or that in the anaerobic digestion process consistency of feed is required to prevent upset to the micro organisms. Again standard proven technologies where chosen here to be modelled. These are generally energy intensive processes and thus will have an impact on the overall economics and sustainability of the selected routes.

Post-processing of the produced fuel, be it gas or liquid, is important as the quality and the constituents of the fuel can have dramatic effects on the lifetime of the energy producing device regardless of whether a turbine, combustion engine or fuel cell is used. The waste processing industry has had to balance the cleanliness of the gas or liquid with significant capital and operating energy and financial costs, so several technologies are being reviewed with varying impacts on both quality and cost. The technologies that look at particulate removal and tar reduction have been modelled, as they will have a major effect on fuel quality.

In order to model the various technologies, a number of assumptions had to be made, especially physical properties, and are listed in each model summary below. Unless otherwise stated all values are standard literature values. These assumptions will be further validated and updated once experimental values of the detailed mass and energy balances become available from Work Package 2.

Out of Scope

Below is a list of agreed items and technologies that are not included within scope of this project:

- Waste testing (sampling) will only cover waste available at Shanks sites
- Hazardous waste, clinical waste, radioactive etc.
- Non energy bearing wastes
- Waste currently in Landfill – all waste will be collected pre-landfill
- Off-site waste preparation – sorting and separation
- Materials flow, energy use in sorting machinery
- Energy from landfill
- Current gas capture from landfill, uncaptured landfill, landfill gas, landfill gas processing technologies, waste already landfilled
- Recycling processes
- Sorting of recyclables, processing of recyclables, energy trade-off with recycling processes, recycling trade-off with raw material production, waste reduction, materials re-use
- Incineration/combustion
- Technologies, energy recovery using steam power generation as primary generator
- Technologies or systems with capacity for power generation <100 kWe, >10 MWe or equivalent materials throughput
- Technologies not on list below including further post-processing of waste derived liquids/gases into transport fuels
- Manure, while an agricultural waste, is only classified as such if it leaves the farm and is not included in this scope

Autoclave Model Report

CPI: Steve Donegan, Gustavo Valente
Caterpillar Inc.: Jalaja Repalle

1. Abstract

A waste autoclave is a form of steam and pressure treatment which processes the waste and sterilises it to produce a high biomass fibre allowing the remaining materials to be readily separated by a series of mechanical processing operations into clean recyclable product fractions.

Temperatures of typically between 140ºC and 160ºC are used to break down the biodegradable organic materials into a sterile, homogenous pulp. In the sterilising process all living organisms throughout the mass are inactivated, making it biologically safe.

After autoclaving, the residual organic pulp is suitable for further processing for energy from waste technologies such as anaerobic digestion. Metals are clean and easily separated using a combination of magnets and eddy current separators. Plastics can be separated and treated according to type, and other objects are steam-cleaned removing labels etc. to provide a higher quality product compared to that of MBT.

2. Description

The feedstock containing organic and inorganic material is fed into the autoclave, where it is steamed under a specified pressure.

The model calculates the energy required by the autoclave process based on the amount of steam necessary to heat the feedstock to be processed and also takes into account the properties of the autoclave such as the mass of steel in the vessel and its heat capacity.

The products of the autoclave will be mainly 2 fractions, one organic and one inorganic. The organic fraction can then be processed in an anaerobic digestion plant.

3. Assumptions for this model

- The waste heat capacity is assumed to be 2 kJ/kg/°C
- Feed temperature is ambient (30°C for the example which can be changed)
- Steam Pressure 6.2 bar
- Organic material, inorganic material and steam condensate as water are products of the autoclave process.

4. Inputs/Outputs

Inputs	**Units**
Waste type	
Moisture content	%
Feedstock mass	kg
Feeestock temperature	ºC
Autoclave temperture	ºC
Outputs	
Organic matter	kg
Non-organic matter	kg
Water	kg
Heat required	kJ
Steam usage	kg

5. Example

```
2: Pig Slurry
Please choose waste type from the above list: 2
*****************************
Feedstock Name: Pig Slurry
Organic matter (% of dry feedstock):    62.0
*****************************
Please enter moisture content in input feedstock (%): 5
Please enter total feedstock mass (Kg):   12546
Please enter feedstock temperature (C):   125
Please enter autoclave temperature (C) (Should be greater than feedstock temp
*****************************************
Feedstock Inputs
*****************************************
Organic Feedstock (Kg): 7389.6
Non-Organic Feedstock (Kg): 4529.1
Feedstock Temperature(C):   125.0
*****************************************
Autoclave Outputs
*****************************************
Autoclave Temperature (C):  126.0
Steam Usage (Kg):   11.9
Organic (Kg):   7389.6
Non-Organic (Kg):   4529.1
Water(Kg):  11.9
Heat Required(KJ):  24837.4
*****************************************
```

6. References

- Fabian Monnet “An introduction to anaerobic digestion of organic wastes” REMADE November 2003
- The National Non food crops centre “A detailed economical assessment of anaerobic digestion technology and its suitability to UK farming and waste systems” Defra funded project NNFCC April 2008

7. Glossary

- **Anaerobic digestion (AD):** The process of biological degradation of organic material in the absence of oxygen.
- **Biodegradable**: Capable of being decomposed by biological action
- **Biomass**: Organic materials, such as wood, agricultural crops or wastes, and municipal wastes, especially when used as a source of fuel or energy. Biomass can be processed into bio fuels.
- **Dry basis:** Material data calculated to a theoretical basis in which no moisture is associated with the sample. This basis is determined by measuring the weight loss of a sample when its inherent moisture is driven off under controlled conditions of low temperature air-drying followed by heating to just above the boiling point of water (104^{o}C to 110^{o}C).
- **Feedstock:** Any material fed into the system which is converted to another form or product.
- **Homogeneous:** Having similar properties, such as density, throughout
- **Inorganic:** Material of mineral origin such as metal or glass
- **MBT:** Mechanical Biological Treatment
- **Organic:** Material which comes from animal or plant sources
- **Sterilization**: The process of destroying all micro organisms in or on a given material, usually done by using heat, radiation, or chemical agents.

Milling Model Report

CPI: Steve Donegan, Gustavo Valente
Caterpillar Inc.: Jalaja Repalle,

1. Abstract

Preparation of the feedstock is important for most of the EFW technologies, for example biomass particle size can have an effect on gasification reaction rates and gas composition. These feedstock preparation operations can be expensive and energy demanding, and there is a trade-off in terms of cost and energy requirements between particle size reduction and yield and characteristics of the product gas.

Some of the highest energy consumption operations are related to milling raw material before drying as well as to wood densification after drying. Therefore the importance of developing this model

2. Description

Each one of the constituents of the feedstock has a different specific energy consumption factor, which will be listed on the inputs of the model; we will have as many factors as constituents in the feedstock by correlating the specific energy consumption factor with the mass flowrate we can calculate the energy demand in this operation, the total feedstock flowrate, feedstock moisture content, product moisture target as well as particle sizes will help to select the right type of mill and mill capacity. A range of feedstocks can be used including agricultural residues such as wheat and rape straw.

3. Assumptions for this model

- Each Specific feed has its own Specific Energy Consumption Factor Depending on the type of mill used. These consumption factors can be obtained from vendors.
- The Bulk density is Approximately of 190 kg/m3
- The particles were reduced to approximately 10 mm
- The model can be modified easy at the stage of optimization of the models.
- Torrefaction, is considered a WTE technology, rather than a pre-treatment process. It is not included in this model. It can be done before gasification, but is not a technology that has been developed to the same degree of economically readiness than the others that we have included

4. Inputs/Outputs

Inputs	Units

Waste type	
Feedstock feed rate	kg/h
Outputs	
Energy required	kWh/kg

5. Example

```
1: Poplar
3: Rape Straw
Please choose waste type from the above list: 1
Please enter feedstock feed rate (Kg/Hr):  1254
*****************************
Energy Required for Milling (KWh/Kg):   32.6
```

6. References

- R. Ramos Casado, L.E. Esteban Pascual " Biomass Feedstock preparation methods for energy production and its economic evaluation" CIEMAT – Centre of Development of Renewable Energies), SPAIN
- Jerzy Świgoń_, Jaroslav Longauer "Energy consumption in wood pellets productions" Department of Engineering Mechanics and Thermal Techniques, The August Cieszkowski Agricultural University of Poznań, Department of Environmental Technology Technical University in Zvolen, Poland 2005

7. Glossary

- **Dry basis:** Material data calculated to a theoretical basis in which no moisture is associated with the sample. This basis is determined by measuring the weight loss of a sample when its inherent moisture is driven off under controlled conditions of low temperature air-drying followed by heating to just above the boiling point of water (104 to 110 degrees Centigrade).
- **Feedstock:** Any material feed into the system which is converted to another form or product.
- **Inorganic:** Material of mineral origin such as metal or glass
- **Milling:** Milling: The grinding or crushing of material with the objective of reduce the particle size of the particles
- **Milling capacity:** The maximum rate at which a mill is capable of treating material in mass unit per time unit.
- **Moisture:** Moisture refers to the amount of water present in the material
- **Organic:** Material which comes from animal or plant sources

Pelletisation Model Report

CPI: Steve Donegan, Gustavo Valente
Caterpillar Inc.: Jalaja Repalle,

1. Abstract

The use of biomass for gasification involves a series of steps that are energy consuming. One of these steps is pelletisation, the objective being to optimise the product gas composition. Since this operation is energy intensive and therefore expensive, there is a trade off between the characteristics of the biomass and the product gas.

2. Description

Similar to the Milling model, each of the constituents of the feedstock has a different specific energy consumption factor. This is listed on the inputs of the model. We will have as many factors as constituents in the feedstock. By correlating the specific energy consumption factor with the mass flowrate, we can calculate the energy demand in this operation, the total feedstock flowrate, and type of feedstock. This will help to select the right type of pelletiser mill and equipment capacity. A range of feedstocks can be used including agricultural residues.

3. Assumptions for this model

- Each specific feed has its own Specific Energy Consumption Factor. These consumption factors can be obtained from vendors.
- The total composition must add up to 100%
- The Bulk density is Approximately 600 kg/m^3 for Rape and 670 Kg/m^3 for Poplar
- Moisture levels can be fixed depending on conditions at which the vendor determined the Energy Consumption Factor. Then, the drying model can be used.

4. Inputs/Outputs

Inputs	**Units**
Waste type	Poplar, Pig slurry, Rape straw
Feedstock feed rate	kg/h
Outputs	
Energy required	kWh/kg

5. Example

```
1: Poplar
2: Pig Slurry
3: Rape Straw
Please choose waste type from the above list: 2
Please enter feedstock feed rate (Kg/Hr):  1256
*****************************
Energy Required for Pelletization (KWh/Kg): 31.4
```

6. References

- R. Ramos Casado, L.E. Esteban Pascual " Biomasa Feedstock preparation methods for energy production and its economic evaluation" CIEMAT – Centre of Development of Renewable Energies), SPAIN
- Jerzy Świgoń_, Jaroslav Longauer "Energy consumption in wood pellets productions" Department of Engineering Mechanics and Thermal Techniques, The August Cieszkowski Agricultural University of Poznań, Department of Environmental Technology Technical University in Zvolen, Poland 2005

7. Glossary

- **Feedstock:** Any material feed into the system which is converted to another form or product.
- **Pellets:** Compressed biomass for example wood and waste wood products, straw, and grasses. The pellets created burn cleanly and efficiently and a small volume of burning pellets can produce a large amount of heat as they are a dense store of energy.
- **Pelletising:** The grinding or crushing of material with the objective of producing a compacted material
- **Pelletising capacity:** The maximum rate at which a pelletiser is capable of treating material in mass unit per time unit.
- **Moisture:** Moisture refers to the amount of water present in the material

Drying Model Report

CPI: Steve Donegan, Gustavo Valente
Caterpillar Inc.: Jalaja Repalle

1. Abstract

It is often emphasized as advantageous to dry raw materials before use, as such preparation results in the increase of the net calorific value for some technologies, and is in itself a preparation step for others. However, it is important to quantify the energy consumed during drying.

2. Description

The drying model calculates the electrical energy necessary to drive off water from a feedstock. The energy is calculated by correlating the latent heat of vaporization of liquid water in relation to the initial and final moisture contents of the processed material.

3. Assumptions for this model

- A value of 2.25 MJ/kg is used as the latent heat of vaporization of liquid water

4. Inputs/Outputs

Inputs	**Units**
Feedstock moisture content	%
Feedstock feed rate	kg/h
Required moisture content	
Outputs	
Evaporated water	kg/h
Energy required	MJ/kg

5. Exmaple

```
Please enter moisture content in input feedstock (%): 45
Please enter feedstock feedrate (Kg/hr): 4565
Please enter required moisture content in output feedstock (%): 5
*****************************************
Evaporated Water (Kg/hr):    1928.7
Energy Required (MJ/Kg):     4339.6
*****************************************
```

6. References

- Jerzy Świgoń_, Jaroslav Longauer "Energy consumption in wood pellets productions" Department of Engineering Mechanics and Thermal Techniques, The August Cieszkowski Agricultural University of Poznań, Department of Environmental Technology Technical University in Zvolen, Poland 2005
- R. Ramos Casado, L.E. Esteban Pascual " Biomasa Feedstock preparation methods for energy production and its economic evaluation" CIEMAT – Centre of Development of Renewable Energies), SPAIN

7. Glossary

- **Dry basis:** Material data calculated to a theoretical basis in which no moisture is associated with the sample. This basis is determined by measuring the weight loss of a sample when its inherent moisture is driven off under controlled conditions of low temperature air-drying followed by heating to just above the boiling point of water (104ºC to 110ºC).
- **Feedstock:** Any material feed into the system which is converted to another form or product.
- **Moisture:** Moisture refers to the amount of water present in the material
- **Organic:** Material which comes from animal or plant sources

Fixed Bed Gasifier Model Report

CPI: Steve Donegan, Gustavo Valente
Caterpillar Inc.: Jalaja Repalle

1. Abstract

Gasification is the process of breaking down any waste that contains carbon and hydrogen into Syngas (gaseous fuel), a mixture of combustible gases that contains mainly carbon monoxide and hydrogen, with small quantities of methane and carbon dioxide.

The temperature of gasification is between 900-1100°C in air and between 1000-1400°C in oxygen. The process is exothermic but heat is required to initialise and sustain the process.

In some cases the Syngas can be cleaned to produce a fuel that can be used in a high efficiency gas engine or in electrochemical technologies such as fuel cells.

2. Description

Fixed Bed Gasifier Up & Down-draft

The approach taken to modelling the fixed bed gasifier partitions the unit into four sections: drying; pyrolysis; reduction; and oxidation. A mass balance is then performed across each section. Each section is seen as a black box and no account has been taken of reaction time or dynamics.

The feed to the gasifier is assumed to be wood at present, with a typical elemental balance.

In the first stage drying, residual free moisture is driven from the feedstock entering the gasisfier. This is a simple split, with the energy demand coming from the exit gas.

The second stage is a pyrolysis step, where oils, gases and some syngas are driven from the feed material. A typical pyrolysis oil and gas product is defined as coming off this section. In Up-draft pyrolysis the product is composed of oil and gas elements, while down-draft produces only gaseous products. This can be varied as long as the totals add up to 100% and an elemental balance is performed to calculate the solid material continuing down the gasifier. If the carbon and hydrogen content start to go too high or too low the model may produce results that are inconsistent. it should be possible to interchange both the feed stock elemental content and the pyrolysis products and still attain a credible result.

The third stage is modelled as a reduction stage where water produced from char combustion or injected, reacts with the carbon in the solid char phase to produce the syngas. The model at present produces an amount of syngas equivalent to the water produced in the final oxidation zone plus any which is injected. There is probably an efficiency factor or limit to the combustion that would reduce the syngas production.

The final zone is the oxidation zone where the residual char is burned to provide the process heat. An air excess is assumed in the feed.

The energy balance is the more difficult part of the model and there are assumptions in the calculations. For a more accurate view on the temperature profile, it would be required to break the zones down into more elements. In the oxidation zone the HHV of char is assume from the following correlation:-

$$HHV = 146.58C + 568.78H - 51.53(O+N) - 6.58A + 29.45S$$

Ref. Large-Scale Pyrolysis Oil Production: A TechnologyAssessment and Economic Analysis Technical Report NREL/TP-510-37779 November 2006
M. Ringer, V. Putsche, and J. Scahill

The verification of this correlation for the processes that the project is investigating will require the feedback from the experimental work performed in the laboratory studies. The heat and mass balance data from these laboratory studies will be matched against the model and a fit made.

By using the Wt% of the elements in the char gives a heat of combustion in BTU/lb. The temperature is then calculated using an estimated specific heat capacity.

In the reduction zone the heat of formation of the water reacted and the carbon monoxide produced results in an endothermic reaction and the temperature drop is again calculated using an estimated heat capacity. A similar approach is performed in the pyrolysis and drying zones, which are both net users of energy.

Finally an assessment of the solids temperature has made by assuming that they match the gas temperatures. A value of average temperature has been made for completeness.

3. Assumptions

- The gas composition in based on wood
- After the other components of the waste are identified they can be added to the model and their heat of formation can be added to the model to give a better gas modelling composition
- Sulphur and chlorine are not being considered in this model, they will be added in the next stage of model development
- The energy balance will also be further developed in the next stage

4. Inputs/Outputs

Up-draft gasifier

Inputs	**Units**
Waste type	Poplar, Pig slurry
Moisture content	%
Feedstock feedrate	kg/h
Outputs	
O_2 mass flowrate	kg/h
N_2 mass flowrate	kg/h
Syngas mass flowrate	kg/h
Oil mass flowrate	kg/h

Down-draft gasifier

Inputs	**Units**
Waste type	Poplar, Pig slurry
Moisture content	%
Feedstock feedrate	kg/h
Outputs	
O_2 mass flowrate	kg/h
N_2 mass flowrate	kg/h
Syngas mass flowrate	kg/h
CH_4 mass flowrate	kg/h
C_2H_4 mass flowrate	kg/h
C_3H_6 mass flowrate	kg/h
CO_2 mass flowrate	kg/h
H_2 mass flowrate	kg/h
NH_3 mass flowrate	kg/h
H_2O mass flowrate	kg/h
NO_2 mass flworate	kg/h

5. Example

Up-draft gasifier

```
1: Poplar
2: Pig Slurry
Please choose waste type from the above list: 2
*****************************
Feedstock Name: Pig Slurry
Units:  Wt %
C:  47.9
H:  7.6
N:  5.9
S:  1.2
O:  37.4
Ash:    0.0
*****************************
Please enter moisture content in input feedstock (%): 5
Please enter feedstock feedrate (Kg/hr): 1256
****************Air Feed (Kg/hr) *************
Total Air:  1006.1
O2 content: 211.3
N2 content: 794.8
****************Syn Gas Outputs (Kg/hr) ***********************Syn Oil Outputs (Kg/hr)

GasMassFlRate1 =

    Units: 'Kg/Hr'
      CH4: 0.4176
     C2H4: 1.6943
     C3H6: 1.8137
      CO2: -189.5009
       CO: 457.7570
       H2: 34.1220
      NH3: 0.1444
      H2O: 128.8656
       N2: 794.8395
       O2: 19.2079
      NO2: 230.9197
    Total: 1.4803e+003

OilMassFlRate =

       Units: 'Kg/Hr'
       Total: 714.7268
      C2H4O2: 70.7568
      C3H6O2: 87.2229
      C7H6O2: 7.2785
     C8H10O3: 45.3416
       CH2O2: 40.6881
    C10H12O3: 195.2075
       C6H6O: 5.4887
        C7H8: 27.0856
      C5H4O2: 226.4694
        C6H6: 9.1876

*****************************
```

Down-draft gasifier

```
1: Poplar
2: Pig Slurry
Please choose waste type from the above list: 1
*****************************
Feedstock Name: Poplar
Units:  Wt %
C:  50.9
H:  6.0
N:  0.2
S:  0.1
O:  41.9
Ash:    0.9
*****************************
Please enter moisture content in input feedstock (%): 5
Please enter feedstock feedrate (Kg/hr): 1254
****************Air Feed (Kg/hr) *************
Total Air:  2961.3
O2 content: 690.0
N2 content: 2271.3
****************Syn Gas Outputs (Kg/hr) *************

GasMassFlRate =

    Units: 'Kg/Hr'
      CH4: 0.4170
     C2H4: 1.6916
     C3H6: 1.8108
      CO2: 886.7599
       CO: 846.4526
       H2: 71.0767
      NH3: 0.1441
      H2O: 125.0034
      NO2: 7.4385
       N2: 2.2713e+003
       O2: 0
    Total: 4.2121e+003

*****************************
```

6. References

- S. Phillips; A. Aden; J. Jechura; D. Dayton; T. Eggeman. “Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass” NREL/TP-510-41168, April 2007
- Andre Faaij; Rene Van Ree; Lars Waldheim; Eva Olsson; Andre Oudhuis; Ad Van Wijk; Cees Daey-Ouwens; Wim Turkenburg, “Gasification of biomasa wastes and residues for electricity production” Utrech Univiersity, The Netherlands, January 1997

7. Glossary

- **Ash**: Impurities consisting of silica, iron, alumina, and other non-combustible matter contained in coal. Ash increases the weight of coal, adds to the cost of handling, and can affect its burning characteristics. Ash content is measured as a percent by weight of coal on an "as received" or a "dry" (moisture-free, usually part of a laboratory analysis) basis.
- **Char:** The remains of solid biomass that has been incompletely combusted, such as charcoal if wood is incompletely burned.
- **Combustion:** The transformation of biomass fuel into heat, chemicals, and gases through chemical combination of hydrogen and carbon in the fuel with oxygen in the air.
- **Feedstock:** Any material feed into the system which is converted to another form or product.
- **Fixed bed gasifier ("Up-draft"):** A bed of carbonaceous fuel through which steam, oxygen and/or air flows. The resultant ash is either removed dry or as a slag. Tar and methane production is significant at typical operating temperatures, so product gas must be extensively cleaned before use. The tar can be recycled to the reactor.
- **Fixed bed gasifier ("Down-draft"):** Similar to the fixed bed gasifier, but the gasification gas flows co-current with the fuel in a downward direction, hence the name "down draft gasifier". Heat needs to be added to the upper part of the bed, either by combusting small amounts of the fuel or from external heat sources
- **Gasification:** A chemical or heat process to convert a solid fuel to a gaseous form.
- **Gasifier:** A device for converting solid fuel into gaseous fuel.
- **Heating value:** The maximum amount of energy that is available from burning a substance.
- **Syngas:** Syngas is a gas mixture containing carbon monoxide, hydrogen and other trace gases. It is generated by gasifying fossil fuels or biomass. Gasification means breaking down hydrocarbons at high temperatures by carefully controlling the amount of oxygen. Syngas from biomass is used as a fuel, for hydrogen production or as a precursor to synthetic diesel.

Fluidised Bed Gasifier Model Report

CPI: Gustavo Valente
Caterpillar Inc.: Jalaja Repalle

1. Abstract

The gasification Model converts a mix of feedstocks and steam to syngas and char. The gasifier is heated indirectly by recirculation of hot sand, which is heated by the combustion of the char further down the process. The steam works as the fluidising medium and takes part in the reactions at higher temperatures.

2. Description

The Dried wood is fed into the gasifier, which operates at low pressure and is indirectly heated. Heat for the endothermic gasification is provided by circulation of hot sand between the gasifier and the char combustor. A small amount of MgO needs to be added to the fresh sand to prevent the bed media becoming a sticky agglomerate which will eventually defluidise.

The fluidization medium is steam. The temperature of the gasifier and the char combustor are dictated from the energy balances around the gasifier and char combustor. The char that is formed in the gasifier is burned in the combustor to reheat the sand. The gasifier and the char combustor tend to reach equilibrium. Particulates can then be removed from the raw syngas using cyclone separators

3. Assumptions

- The mass and molar amounts of the elements are determined from the biomass's chemical analysis.
- The gasifier pressure is 23 psia.
- The char combustor Temperature is 995°C
- The steam-to-feed ratio is 1:2.5 steam to bone dry biomass
- The Sand circulating flow rate is 27 lb of olivine/lb of bone dry wood.
- The char combustor operates with 20% excess air.
- The quantity of syngas and its chemical composition is determined from the gasifier correlations.
- The quantities of carbon in the syngas and tar are determined. And the residual carbon becomes part of the char.
- Correlations were obtained from experiments carried out in the Battele Columbus Laboratory as reported in the NREL in a 9 tonne/day test facility. (Referenced in the reference section of this report). The data is based on different wood types such as Red Oak, Birch, Maple, and Pine chips, sawdust, and other hard and soft wood chips.
- The amount of oxygen in the syngas is calculated.

- A minimum amount of oxygen is required to be included to the char (4% of biomass oxygen).
- A set amount of sulphur is included in the char (8.3%). All remaining sulphur is placed as H_2S in the syngas.
- A set amount of nitrogen is included in the char (6.6%). All remaining nitrogen is placed as NH_3 in the syngas.
- The amount of hydrogen in the syngas (including tar, H_2S, NH_3, and decomposed water) is calculated and all remaining hydrogen is included in the char.
- All ash becomes part of the char.
- The heat of formation of the char is estimated from the resulting chemical analysis.
- The temperature in the gasifier has to be adjusted so the there is no net heat for an adiabatic reaction.

The use of these correlations is to give the models a basis to go forward. Detailed assessment of the results of the laboratory work is required. This data must then be incorporated and back validated to the models.

4. Inputs/Outputs

Inputs	**Units**
Waste type	Poplar, Pig slurry
Moisture content	%
Feedstock feedrate	kg/h
Gasification temperature	ºC
Outputs	
Sand mass flowrate	kg/h
Water mass flowrate	kg/h
Syngas mass flowrate	kg/h
Syngas enthalpy	kJ/h

5. Example

```
1: Poplar
2: Pig Slurry
Please choose waste type from the above list: 2
*****************************
Feedstock Name: Pig Slurry
Units:  Wt %
C:  47.9
H:  7.6
N:  5.9
S:  1.2
O:  37.4
Ash:    0.0
*****************************
Please enter moisture content in input feedstock (%): 5
Please enter feedstock feedrate (Kg/hr): 12546
Please enter gasification operating temperature(815C-1000C): 889
*****************************
Sand Mass Flow Rate (Kg/hr):    326196.0
Water Mass Flow Rate(Kg/hr):    5018.4
*************Syn Gas Mass Flow Rates (Kg/hr)**********************Syn Gas Enthalpies (KJ/hr)*

SynGasMassRate =

    DrySyngasmass_scfmplbmol: 14.1330
         DrySyngasmass_m3pkg: 0.8805
           DrySyngasFlowrate: 1.1047e+004
                          CO: 5.5111e+003
                         CO2: 2.5750e+003
                         CH4: 1.1354e+003
                        C2H4: 547.0128
                        C2H6: 32.7129
                          H2: 235.5548
                        C2H2: 51.5615
                         Tar: 166.1512
                         H2S: 146.6847
                         NH3: 839.5084
                       Water: 5.6457e+003
                        Sand: 326196
                        Char: 1.3054e+003
                           C: 4.6141e+003
                           O: 5.0219e+003
                           H: 775.2238
                       Units: 'kg/hr'
```

```
SynGasEnthalpy =

       CO: 4.7830e+006
      CO2: 2.2348e+006
      CH4: 4.0313e+006
     C2H4: 1.2948e+006
     C2H6: 9.8080e+004
       H2: 2.8157e+006
     C2H2: 6.5091e+004
      Tar: 1.6256e+005
      H2S: 1.1573e+005
      NH3: 1.3247e+006
    Water: 2.3893e+007
     Char: 7.3126e+005
     Sand: 2.4450e+008
```

6. References

- S. Phillips; A. Aden; J. Jechura; D. Dayton; T. Eggeman. “Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass” NREL/TP-510-41168, April 2007

7. Glossary

- **Char:** The remains of solid biomass that has been incompletely combusted, such as charcoal if wood is incompletely burned.

- **Combustion:** The transformation of biomass fuel into heat, chemicals, and gases through chemical combination of hydrogen and carbon in the fuel with oxygen in the air.
- **Feedstock:** Any material feed into the system which is converted to another form or product.
- **Gasification:** A chemical or heat process to convert a solid fuel to a gaseous form.
- **Gasifier:** A device for converting solid fuel into gaseous fuel.
- **Heating value:** The maximum amount of energy that is available from burning a substance.
- **Syngas:** Syngas is a gas mixture containing carbon monoxide, hydrogen and other trace gases. It is generated by gasifying fossil fuels or biomass. Gasification means breaking down hydrocarbons at high temperatures, by carefully controlling the amount of oxygen. Syngas from biomass is used as a fuel, for hydrogen production, or as a precursor to synthetic diesel.

Pyrolysis Model Report

CPI: Steve Donegan, Gustavo Valente
Caterpillar Inc.: Jalaja Repalle

1. Abstract

Pyrolysis is the process of thermal degradation of waste at temperatures between 400°C and 800°C with controlled amounts of oxygen supplied to prevent full gasification or combustion. The products from the Pyrolysis process are synthesis gas (syngas), liquid (oil) and a solid char.

The product of the process is dependent on the method of Pyrolysis and the reaction parameters, such as temperature, pressure and residence time.

The three main methods of Pyrolysis are:

Rotary Kilns

The method involves feeding waste into a cylinder rotating on its axis. Providing mixing and direct contact of the waste with the gases within the kiln as the cylinder rotates. As the waste progresses through the cylinder, it is dried and thermally decomposed into volatiles and char. There are two basic types of rotary kilns: direct fired and indirect fired.

Heated Tube

In this method, the waste is passed through a tube that is externally heated at a set speed to ensure the pyrolysis process is complete. The movement of waste is achieved by screw action.

Surface contact

The waste is pre-treated, reducing the particle size. Consequently there is a better surface contact between the waste and heat. This method enables fast pyrolysis to occur.

2. Description

The pyrolysis model takes a set feed, initially specified as wood. This feed is assumed to breakdown in the process to a bio-oil and a char residue. The composition of the bio oils are taken from a literature study.

Any oil composition can be input. If as a result of laboratory research, a correlation for the bio oil composition can be developed then this can be applied to the output stream. The composition of the char is determined from an elemental balance on the system. As stated, if either the feed or the bio-oil elemental composition changes, the char will adjust.

An estimation of the heat required to drive the process (Pyrolysis is essentially an endothermic process) is also made. The heats of formation of the products are subtracted from those of the feed materials. This heat is then used in the process, in this case, the outside of the kiln. The energy of combustion of the Char is calculated from a NREL correlation

HHV = 146.58C + 568.78H - 51.53(O+N) - 6.58A + 29.45S (NREL report)

By using the Wt% of the elements in the char gives a heat of combustion in BTU/lb. The temperature is then calculated using an estimated specific heat capacity.

This correlation came from a report from the NREL (listed in the references section of this model). The correlation was based on a design throughput of 550 dry tons/day.

The use of these correlations is to give the models a basis to go forward. Detailed assessment of the results of the laboratory work is required. This data must then be incorporated and back validated to the models.

This model will need refining as laboratory data is received. This shows that the whole process can have an excess of energy when the Char is combusted.

3. Assumptions

- Pre-treatment has been carried out
- In general there is a requirement for the pre-treatment of waste to deliver a refined waste fuel (Solid Recovered Fuel SRF), and therefore investment in pre-processing technologies, such as Materials Recycling Facilities (MRF), mechanical biological treatment (MBT) or autoclave. The pre-treatment can include:

  1. Removal of non combustible materials such as metals and glass or very wet materials,
  2. Shredding / milling waste fractions to smaller particle size,
  3. Raw waste is dried to reduce moisture content, as the Pyrolysis process is not designed to process wet waste

4. Inputs/Outputs

Inputs	**Units**
Waste type	Poplar, Pig slurry
Feedstock feedrate	kg/h
Moisture content	%
Outputs	

Syngas mass flowrate	kg/h
Oil mass flowrate	kg/h

5. Example

Rotary kiln pyrolysis

```
1: Poplar
2: Pig Slurry
Please choose waste type from the above list: 1
*****************************
Feedstock Name: Poplar
Units:  Wt %
C:  50.9
H:  6.0
N:  0.2
S:  0.1
O:  41.9
Ash:    0.9
*****************************
Please enter moisture content in input feedstock (%): 5
Please enter feedstock feedrate (Kg/hr): 1256

OilMassFlRate =

       Units: 'Kg/Hr'
       Total: 714.7268
      C2H4O2: 70.7568
      C3H6O2: 87.2229
      C7H6O2: 7.2785
     C8H10O3: 45.3416
       CH2O2: 40.6881
    C10H12O3: 195.2075
       C6H6O: 5.4887
        C7H8: 27.0856
      C5H4O2: 226.4694
        C6H6: 9.1876


GasMassFlRate =

    Units: 'Kg/Hr'
      CH4: 0.4176
     C2H4: 1.6943
     C3H6: 1.8137
      CO2: 64.6714
       CO: 78.2739
       H2: 7.0160
      NH3: 0.1444
      H2O: 191.6656
    Total: 345.6970
```

6. References

- ENVIROS “Assessment of North East England’s wate to energy indrustrial solutions” ONE Northeast, February 2009
- M. Ringer, V. Putsche, and J. Scahill, “Large-Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis“ NREL/TP-510-37779, November 2006

7. Glossary

- **Char:** The remains of solid biomass that has been incompletely combusted, such as charcoal if wood is incompletely burned.
- **Combustion:** The transformation of biomass fuel into heat, chemicals, and gases through chemical combination of hydrogen and carbon in the fuel with oxygen in the air.
- **Feedstock:** Any material feed into the system which is converted to another form or product.
- **Gasification:** A chemical or heat process to convert a solid fuel to a gaseous form.
- **Gasifier:** A device for converting solid fuel into gaseous fuel.
- **Heating value:** The maximum amount of energy that is available from burning a substance.
- **Pyrolysis:** The thermal decomposition of biomass at high temperatures in the absence of air. The end product of pyrolysis is a mixture of solids (char), liquids (oils), and gases (methane, carbon monoxide, and carbon dioxide) with proportions determined by operating temperature, pressure, oxygen content and other conditions.
- **Syngas:** Is a mixture of combustible gases that constitutes carbon monoxide, hydrogen, methane and a broad range of other Volatile Organic Compounds. Syngas is considered to be a renewable fuel.

Fluidised Bed Pyrolysis

CPI: Steve Donegan, Gustavo Valente
Caterpillar Inc.: Jalaja Repalle

1. Abstract

This pyrolysis model takes a set feed, initially specified as wood. The feed is assumed to breakdown in the pyrolysis process to a bio oil and a char residue. The heat for the process comes from recirculating sand. The sand is heated from the combustion gases created when the char is burned

2. Description

The feed is assumed to of the correct particle size for the process, between 3 and 45 mm. The composition of the bio oils are taken from a literature study. Any oil composition can be input. If as a result of laboratory research, a correlation for the bio oil composition can be developed this will be applied to the output stream.

The composition of the Char is determined from an elemental balance on the system. As stated if either the feed elemental composition or the bio oil produced changes, the char will adjust.

An estimation of the heat required to drive the process (pyrolysis is essentially an endothermic process) is also made. The heats of formation of the products are subtracted from those of the feed materials. This is the heat then needed to be used in the process. In this case the re-circulating sand. The amount of sand re-circulating is estimated from the heat needed for the process and an assumed temperature drop of the sand when in the reactor. The energy of combustion of the Char is calculated from an NREL correlation

$$HHV = 146.58C + 568.78H - 51.53(O+N) - 6.58A + 29.45S \text{ (NREL report)}$$

By using the Wt% of the elements in the char, a heat of combustion in BTU/lb can be calculated. The temperature is then calculated using an estimated specific heat capacity.

This correlation comes from a report from the NREL (listed in the references section of this model). The correlation was based in a design throughput of 550 dry tons/day.

This model will need refining as and when laboratory data is received. The model shows that the whole process can have an excess of energy when the Char is combusted.

3. Assumptions

- Particles size treatment has been carried out
- Moisture content of 50%
- Removal of non combustible materials such as metals and glass or very wet materials
- Shredding / milling waste fractions to smaller particle size
- Particle size for the process between 3 and 45 mm is assumed
- Raw waste is dried to reduce moisture content as the Pyrolysis process is not designed to process wet waste

4. Inputs/Outputs

Inputs	**Units**
Waste type	Poplar, Pig slurry
Feedstock feedrate	kg/h
Moisture content	%
Gasification op temperature	^oC
Outputs	
Sand mass flowrate	kg/h
Water mass flowrate	kg/h
Syngas mass flowrate	kg/h
Syngas enthalpy	kJ/h

5. Example

```
1: Poplar
2: Pig Slurry
Please choose waste type from the above list: 2
*****************************
Feedstock Name: Pig Slurry
Units:  Wt %
C:  47.9
H:  7.6
N:  5.9
S:  1.2
O:  37.4
Ash:    0.0
*****************************
Please enter moisture content in input feedstock (%): 5
Please enter feedstock feedrate (Kg/hr): 12546
Please enter gasification operating temperature(815C-1000C): 889
*****************************
Sand Mass Flow Rate (Kg/hr):    326196.0
Water Mass Flow Rate(Kg/hr):    5018.4
*************Syn Gas Mass Flow Rates (Kg/hr)**********

SynGasMassRate =

    DrySyngasmass_scfmplbmol: 14.1330
         DrySyngasmass_m3pkg: 0.8805
           DrySyngasFlowrate: 1.1047e+004
                          CO: 5.5111e+003
                         CO2: 2.5750e+003
                         CH4: 1.1354e+003
                        C2H4: 547.0128
                        C2H6: 32.7129
                          H2: 235.5548
                        C2H2: 51.5615
                         Tar: 166.1512
                         H2S: 146.6847
                         NH3: 839.5084
                       Water: 5.6457e+003
                        Sand: 326196
                        Char: 1.3054e+003
                           C: 4.6141e+003
                           O: 5.0219e+003
                           H: 775.2238
                       Units: 'kg/hr'
```

```
*************Syn Gas Enthalpies (KJ/hr)*

SynGasEnthalpy =

       CO: 4.7830e+006
      CO2: 2.2348e+006
      CH4: 4.0313e+006
     C2H4: 1.2948e+006
     C2H6: 9.8080e+004
       H2: 2.8157e+006
     C2H2: 6.5091e+004
      Tar: 1.6256e+005
      H2S: 1.1573e+005
      NH3: 1.3247e+006
    Water: 2.3893e+007
     Char: 7.3126e+005
     Sand: 2.4450e+008
```

6. References

- ENVIROS “Assessment of North East England’s waste to energy industrial solutions” ONE Northeast, February 2009
- M. Ringer, V. Putsche, and J. Scahill, “Large-Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis“ NREL/TP-510-37779, November 2006

7. Glossary

- **Char:** The remains of solid biomass that has been incompletely combusted, such as charcoal if wood is incompletely burned.
- **Combustion:** The transformation of biomass fuel into heat, chemicals, and gases through chemical combination of hydrogen and carbon in the fuel with oxygen in the air.
- **Feedstock:** Any material feed into the system which is converted to another form or product.

- **Gasification:** A chemical or heat process to convert a solid fuel to a gaseous form.
- **Gasifier:** A device for converting solid fuel into gaseous fuel.
- **Heating value:** The maximum amount of energy that is available from burning a substance.
- **Pyrolysis:** The thermal decomposition of biomass at high temperatures in the absence of air. The end product of pyrolysis is a mixture of solids (char), liquids (oils), and gases (methane, carbon monoxide, and carbon dioxide) with proportions determined by operating temperature, pressure, oxygen content and other conditions.
- **Syngas:** Is a mixture of combustible gases that constitutes carbon monoxide, hydrogen, methane and a broad range of other Volatile Organic Compounds. Syngas is considered to be a renewable fuel.

Anaerobic Digestion Model Report

CPI: Steve Donegan, Gustavo Valente
Caterpillar Inc.: Jalaja Repalle

1. Abstract

There are many different types of anaerobic digester design and operating methodology. They operate in batch or continuous modes and at different temperature regimes (**mesophilic** or **thermophilic**). The model at present looks at the anaerobic digester as a black box which will be modified to fit the mesophilic and the thermophilic digester models.

2. Description

The model is governed by the Buswell (1952) equation:-

CcHhOoNnSs + 1/4(4c - h - 2o +3n + 2s) H2O → 1/8(4c - h + 2o +3n + 2s)CO2 + 1/8(4c + h - 2o -3n - 2s)CH4 + nNH3 + sH2S

This is an empirical equation based aropund an elemental analysis of the feed consituents. The NNFCC produced a report titled “A DETAILED ECONOMIC ASSESSMENT OF ANAEROBIC DIGESTION TECHNOLOGY AND ITS SUITABILITY TO UK FARMING AND WASTE SYSTEMS” in their calculations they use a biogas yield based on historical data and the type of feed stock (such as cow slurry). It is proposed that this project validates the Buswell equation with data from actual processes and modifies if necessary.

This gives a theoretical production of biogas constituents for a given feed together with other contaminants when an elemental balance is performed. The model uses a few factors to account for the fact that not all the feed material is capable of biological degradation and that not all of the biologically available material will be processed. Typical values are shown below, these are simply multiplied by the theoretical values to give the biogas production potential of the feed.

The remaining amounts are then collected as slurry called digestate.

A value for the residence time can be input into the flowsheet and a volume based on a simple T=V/Q calculation to give the vessel volume is used. This value is used to estimate heat loss from a simple Q=UA ΔT calculation. This can be advised as the unit heating requirements.

Hygienisation of the feed is also required if the process uses organic wastes as feedstock. This consists of raising the temperature of the medium up to at least 70^{o}C for at least 1 hour.

3. Assumptions

- Not all of the biologically available material will be processed
- The temperature of the feedstock is set at 10 °C (Ambient Temperature)

- Hygienisation temperature is carried out at 70°C
- Volatile solids (Organic dry matter) 0.62 kg/kg of total solids
- Biogas yield is assumed to be 60% kilograms per kilogram of Volatile solids
- The aspect ratio of the Digester is assumed to be 4:1 height to diameter

4. Inputs/Outputs

Inputs	**Units**
AD temperature	[35-50ºC] Mesophilic [50-70ºC] Thermophilic
Feedstock feedrate	kg/h
Outputs	
Residence time	Days
Heat loss	kW
Syngas mass flowrate	kg/h
Sludge mass flowrate	kg/h
Water mass flowrate	kg/h

5. Example

```
Please enter anaerobic digester temperature(35C-50C): 40
2: Pig Slurry
Please choose waste type from the above list: 2
*****************************
Feedstock Name: Pig Slurry
Units:  Wt %
C:  47.9
H:  7.6
N:  5.9
S:  1.2
O:  37.4
Ash:    0.0
*****************************
Please enter feedstock feedrate (Kg/hr): 1254
*****************************
AD Temperature (C): 40.0
Residence Time (days)   20.0
Heat Loss to Atmosphere (KW)    104.4
**************AD Outputs (Kg/hr)*********
CO2:    187.0
CH4:    80.0
NH3:    16.6
H2S:    14.5
*******************************************
Total Sludge (Kg/hr) :  511.9
Water (Kg/hr):  444.0
*******************************************
```

6. References

- The National Non food crops centre “A detailed economical assessment of anaerobic digestion technology and its suitability to UK farming and waste systems” Defra funded project NNFCC April 2008
- Fabian Monnet “An introduction to anaerobic digestion of organic wastes” REMADE November 2003
- R.J. Spiegela,*, J.L. Prestonb “Technical assessment of fuel cell operation on anaerobic digester gas at the Yonkers, NY, wastewater treatment plant” National Risk Management Research Laboratory, US Environmental Protection Agency (EPA), December 2002
- Charles Banks “Optimising anaerobic Optimising anaerobic digestion Evaluating the Potential for Anaerobic Digestion to provide Energy and Soil amendment” University of Reading, March 2009

7. Glossary

- **AD:** Anaerobic Digestion
- **Aerobic:** Depending on free oxygen or air
- **Biogas:** Mixture of gases produced by anaerobic digestion minly composed of methane (50 – 70%) , carbon dioxide (30 – 50%) and minor other componds (H2S, NH3…)
- **Biomethane:** Pure methane produced from biogas
- **Digestate:** Nutrient-rich material left following anaerobic digestion
- **Digester:** The reactor in which anaerobic digestion takes place
- **Feedstock:** Any material feed into the system which is converted to another form or product.
- **Fibre:** The solid part of digestate
- **Inorganic:** Material of mineral origin such as metal or glass
- **Methane:** A colourless, odourless gas with the formula CH_4
- **Mesophilic:** A type of anaerobic digestion operating between 35ºC and 40°C.
- **Organic:** Material which comes from animal or plant sources
- **Silage:** Fermented, high moisture fodder made from crops
- **Slurry:** A semi-liquid mixture of manure and water
- **Thermophilic:** A type of anaerobic digestion that operates at about 55°C

Plasma Gasifier and Plasma Cleaner Model Report

CPI: Tom Malik, Steve Donegan, Gustavo Valente
Caterpillar Inc.: Jalaja Repalle, Zane van Romunde

1. Abstract

This is a model of a plasma gasifier or cleaner of processed fuel, where the plasma obtained through electrical energy is used to completely gasify the volatile parts of the feeds, the remaining part emerging as slag. The exit conditions from the model are assumed to be at chemical equilibrium at 1000ºC. The plasma energy required to carry out the process is calculated, as well as the composition balance which is based on the equilibrium constraints together with the ultimate analysis of the input feeds.

2. Description

The Plasma gasifier model converts a mixture of feedstocks, steam, Oxygen and Nitrogen to syngas and slag. Heating is provided to the gasifier through the plasma energy as well as reactions with Oxygen. The amount of oxygen needs to be kept at sufficient levels so as to produce syngas, rather than combustion products. The steam participates in the reactions. It is assumed that the plasma helps to create equilibrium conditions at the exit and these are represented by three simultaneous reactions (water gas shift, methane decomposition and primary water gas shift). Two of these three reactions are endothermic, while the water gas shift reaction is exothermic. It is assumed that the plasma is capable of cleaning up any char and residues and converting them to syngas both due to the higher temperature present and the catalytic effect of the ionic species created by the plasma. The average exit temperature (fixed at 1000ºC) before any downstream cooling is, however not as high as the plasma temperature, as not all the gas necessarily flows through the plasma itself. What is significant is that it is at chemical equilibrium at the exit condition. Thus the outputs from the gasifier are the syngas and slag. Amounts of Oxygen and Nitrogen entering the model can be controlled separately, to allow for any variation from the air composition due to requirements from the plasma. The C, H and O components of the fuel are represented in terms of ultimate analysis per C atom and can represent a mix of primary fuels or partially processed fuels that need cleaning.

Plasma cleaning model is essentially the same model as the plasma gasifier model. To simulate cleaning scenarios, the fuel inputs should be given in the form of CHxOy, i.e., per C atom, and should include contributions from condensate as well as gaseous sources, other than steam, O_2 and N_2. The number of steam molecules in feed per C atom is specified as an input. The total amount of nitrogen required for the batch should also be specified. The amount of O_2 required is worked out by setting the remaining fraction of C in the exit gases, usually to set to a very small positive number, i.e., relating to complete gasification.

3. Assumptions

- A gasifier exit temperature T (1000^{o}C) is assumed. Different temperatures could be applied but will require new values of the equilibrium constants for the three reactions.
- The ultimate analysis of the fuel is used to determine the gasifiable fuel per C atom and is represented as CH_xO_y.
- The number of moles of H_2O, O_2 per atom of C is specified as an input.
- The amount of Nitrogen in the total batch feed is specified as number of moles.
- The composition of syngas is determined from the atom balances on C, H and O as well as the three simultaneous equilibrium relationships. For these, the equilibrium constants are provided as inputs to the model.
- The amount of one of the syngas components required by the user at the exit can be set, e.g. the amount of Hydrogen required in terms of actual number of moles for the entire batch.
- The Nitrogen is assumed to remain inert during the processing and helps to relate the actual throughput in mole and mass terms of each component to that per C atom. This allows a consistent mass balance to be obtained.
- The settings of the model can be used to give a small positive value to the exit C amount. This ensures consistency in mass balance that may no longer be there if it was allowed to go to large negative values. However, in order to fix the exit C amount, it is required to free one of the other variables. An appropriate one is the moles of O_2 added per C atom of fuel.
- All the non volatiles emerge from the reactor as fused slag and thermal energy is used up to heat them up to the exit temperature. No char remains in the products.
- The energy balance is carried out from the difference between exit system enthalpy and input system enthalpy as well as the heat of reaction. The latter is obtained from the heats of formation of individual components present. The difference between the two values is the energy required to be imparted from the plasma.
- The actual power required in terms of MW is worked out from the total energy required and an assumed time for the processing to be carried out.
- For the Plasma cleaner model, there may already be some syngas present in the feed and its amount and composition is taken into account. However, the exit conditions are still determined by the equilibrium constraints and the model works in the same manner. The plasma energy required will be reduced due to the smaller gasification workload involved.

4. Inputs/Outputs

The system is constrained both by the mass balance (atomic balance) requirements as well as the equilibrium conditions present. Hence, it is only required to set the following apart from the molecular weights of all the components. The exit composition is calculated. Slag is put in separately and impacts on the energy balance.

The outputs give the composition as well as the energy balance and the plasma energy requirements.

Plasma gasifier

Inputs	Units
Waste type	Poplar, Pig slurry
Moisture content	%
Fuel mass	kg
N_2 mass	kg
Slag mass	kg
Process duration	Hrs
Outputs	
Syngas mass	kg
Power required	kW

Plasma cleaner

Inputs	Units
Fuel type	Type 1, Type 2
Moisture content	%
Fuel mass	kg
N_2 mass	kg
Slag mass	kg
Process duration	Hrs
Outputs	
Syngas mass	kg
Power required	kW

5. Examples

Plasma gasification

```
1: Poplar
2: Pig Slurry
3: Rape Straw
Please choose waste type from the above list: 2
****************************
Feedstock Name: Pig Slurry
Units:  Wt %
C:  47.9
H:  7.6
N:  5.9
S:  1.2
O:  37.4
Ash:    0.0
****************************
Please enter moisture content in input feedstock (%): 5
Please enter input fuel mass in Kgs: 12456
Please enter N2 mass in Kgs:  1254
Please enter slag amount in the process (Kg):  1235
Please enter plasma gasification process duration in hrs:  12
---------Masses In (Kg)------------------
Feedstock (CHxOy):  12456.0
H2O:    467.6
O2:     1793.4
N2:     1254.0
slag:   1235.0
---------Masses Out (Kg)------------------
CH4:    320.6
CO:     9882.9
CO2:    12.2
H2:     4446.3
N2:     1254.0
H2O:    56.4
C:      4.5
slag:   1235.0
---------------------------------------------
Power Required (KW):    2977.0
```

Plasma cleaning

```
1: Fuel Type1
2: Fuel Type2
Please choose waste type from the above list: 1
*****************************
Fuel Name:  Fuel Type1
Units:  Wt %
C:  50.9
H:  6.0
O:  41.9
*****************************
Please enter moisture content in input fuel (%): 5
Please enter input fuel mass in Kgs: 123654
Please enter N2 mass in Kgs:  1235
Please enter slag amount in the process (Kg):  1235
Please enter plasma gasification process duration in hrs:  12
---------Masses In (Kg)------------------
fuel (CHxOy):   123654.0
H2O:    4302.5
O2:     15881.7
N2:     1235.0
slag:   1235.0
---------Masses Out (Kg)------------------
CH4:    3179.6
CO:     96557.5
CO2:    121.2
H2:     43435.1
N2:     1235.0
H2O:    559.4
C:      43.8
slag:   1235.0
---------------------------------------------
Power Required (KW):    28901.9
```

6. References

- Mountouris, E. Voutsas, D. Tassios, "Solid Waste Plasma Gasification: Equilibrium Model development and exergy analysis", Energy Conversion and Management, 47, 2006, 1723-1737.
- Mountouris, E. Voutsas, D. Tassios, "Plasma Gasification of sewage sludge: Process Development and Energy Optimisation", Energy Conversion and Management, 47, 2006, 1723-1737.
- Ivan Imris et al., "Energy recovery from waste by the plasma gasification process", Archives of Thermodynamics, Vol. 26 (2005), No.2, 3-16.

7. Glossary

- **Slag:** The nonvolatile component of the feeds that may be fused together at the exit temperature conditions.
- **Char:** The remains of solid biomass that has been incompletely combusted, such as charcoal if wood is incompletely burned.
- **Combustion:** The transformation of biomass fuel into heat, chemicals, and gases through chemical combination of hydrogen and carbon in the fuel with oxygen in the air.
- **Feedstock:** Any material feed into the system which is converted to another form or product.
- **Gasification:** A chemical or heat process to convert a solid fuel to a gaseous form. The breaking down of hydrocarbons at high temperatures, by carefully controlling the amount of oxygen.
- **Plasma:** This is the fourth state of matter e.g. as obtained in lightning between electrostatically charged clouds or under controlled conditions of electrical discharge in the laboratory. The controlled conditions are used in plasma gasifiers to help impart energy as well as create conditions that lead to complete gasification and equilibrium at exit.
- **Gasifier:** A device for converting solid fuel into gaseous fuel.
- **Heating value:** The maximum amount of energy that is available from burning a substance.
- **Syngas:** Syngas is a gas mixture containing carbon monoxide, hydrogen and other trace gases. It is generated by gasifying fossil fuels or biomass. Syngas from biomass is used as a fuel, for hydrogen production, or as a precursor to synthetic diesel.

Oil Scrubber Model Report

CPI: Steve Donegan, Gustavo Valente
Caterpillar Inc.: Jalaja Repalle

1. Abstract

The syngas produced from waste to energy technologies can also contain volatilised heavy metals such as mercury, cadmium and lead, as well as chlorine and sulphur.

Once the syngas has been cooled the heavy metals can be removed using activated carbon, and the acid gases are removed using a caustic solution in a scrubber.

Light tars can be removed with oil scrubbing. The Absorber is operated above the water dew point to avoid mixing of tar and water. The product gas after the scrubber is “tar-free”. The Absorber scrubbing oil can be regenerated in a Stripper, which is operated with air. The Stripper can be equipped with a condenser to minimise oil losses. The stripper air can be returned to the combustor section of the gasifier where the tars can be reused or destroyed.

2. Description

The syngas is fed into the oil scrubber where the impurities are washed out of the gas into the scrubbing oil producing clean gas. The scrubber is supplied constantly with fresh oil.

3. Assumptions for this model

- The heat capacity of the liquid is assumed to be 2 kJ/kg/°C
- The density of the oil is assumed to be 800kg/m^3
- Particulate removal Efficiency is set to 70%. This value is set arbitarily and can be changed. The project is not performing detailed design on equipment. The factors that affect the removal of particulates are the scrubbing fluid recirculation rate the droplet size and the gas superficial velocity.
- There is a 10 degree temperature rise in the oil during scrubbing due to heat exchange between gas and oil

4. Inputs/Outputs

Inputs	Units
Gas vol. flowrate	m^3/h
Particulate concentration	mg/m^3
Inlet gas temperature	ºC
Outlet gas temperature	ºC
Scrubbing oil temperature	ºC

Outputs	
Oil temperature rise	^oC
Scrubbing efficiency	kg/h
Outlet gas particulate concentration	mg/m^3

5. Example

```
Please enter gas volume flow rate (m3/hr): 12546
Please enter input gas particulate concentration (mg/m3): 1254
Please enter inflow gas temperature (C): 12
Please enter outflow gas temperature (C) (should be lesser than inflow temp): 10
Please enter scrubbing liquid temperature (C): 12
**********************************
Oil temperature rise (C):   10.0
Scrubbing oil mass flow rate(Kg/s)  0.5
Output gas particulate concentration (mg/m3))   11.0
**********************************
```

6. References

No references were required for this model. This model is based on simple chemical engineering principles for the design of a scrubber unit.

7. Glossary

- **Scrubber**: Device used to remove some particulates and/or gases from industrial exhaust streams. A liquid is used wash the impurities from the stream.
- **Syngas:** Syngas is a gas mixture containing carbon monoxide, hydrogen and other trace gases. It is generated by gasifying fossil fuels or biomass. Syngas can either be directly burned in a CHP system, used as a fuel for hydrogen production, or as a precursor to synthetic hydrocarbons such as methane, diesel etc.
- **Gasification:** The breaking down of hydrocarbons at high temperatures by carefully controlling the amount of oxygen.

Molten Carbonate Fuel Cell Model Report

CPI: Azhar Juna, Gustavo Valente
Caterpillar Inc.: Jalaja Repalle

1. Abstract

The fuel cell model takes an input of hydrogen fuel gas together with oxygen and carbon dioxide form the air into water, power and heat. The heat of reaction is used to maintain system temperature and hence once up to temperature the model requires no additional energy input. The model assumes that the reaction is 50% efficient. Excess heat produced is not used in this model. An overall mass balance is also presented.

2. Description

The model is based on the molten carbonate variety of fuel cell technology (MCFC). A molten carbonate fuel cell is an electrochemical system which converts hydrogen fuel gas into water, power and heat, without combustion.

The model is split into two main parts to represent the cathode reaction and the anode reaction. At the cathode side, oxygen and carbon dioxide from the air react with the addition of 2 electrons from the electrical circuit to forms a CO_3^{2-} carbonate ion. This carbonate ion passes through the molten carbonate electrolyte to the anode side where it reacts with the hydrogen fuel to form water, carbon dioxide, power and heat. Air in excess to the stoichiometric requirements is used.

In order for the MCFC to function, it is necessary to operate it at a temperature typically in the region of 600-700ºC. Initially this heat must be provided from an external source, such as electricity or a gas burner. Once the fuel cell is up to temperature, the heat of reaction is sufficient to maintain its operating temperature.

3. Assumptions

- A fuel cell operating temperature T is assumed to be 600ºC.
- It is assumed that the system is at temperature and that no additional heat is required. No allowance is made for energy required to raise the system to temperature initially.
- It is assumed that the balance of the efficiency figure is converted into heat which is lost to the environment, system etc. For example if efficiency was set to 50%, then 50% of the fuel is converted to power and 50% to heat. If the waste heat were to be captured, an overall efficiency of 89-90% could be achieved as quoted in literature.
- The fuel used is pure hydrogen.
- No allowance is made for the use of hydrocarbon fuel gases directly or indirectly through a reformer.

- Assumed that the composition of air is 79% N_2, 20% O2 and 1% CO_2

4. Inputs/Outputs

Inputs	**Units**
H_2 feedrate	Kg/h
Fuel cell efficiency	%
Outputs	
Electrical power	kWh
Thermal heat	kWh

5. Example

```
Please enter H2 feed rate in (Kg/Hr):1254
Please enter fuel cell efficiency (between 0 and 1):.6
Fuel Cell Output Electric Power (KWh)   25054.9
Fuel Cell Output Thermal Heat (KWh) 16703.3
```

6. References

- Wolf Vielstich, Arnold Lamm, Hubert A. Gasteiger "Handbook of Fuel Cells – Volume 4 – Fundamentals, Technology and Applications"
- Ovonic Hydrogen Conversion Chart, Ovonic Hydrogen Systems LCC
- Larminie, Dicks "Fuel Cell Systems Explained" 2nd Edition.

7. Glossary

- **MCFC:** Molten Carbonate Fuel Cell.
- **Cathode:** Electrically positive electrode which air is applied to.
- **Anode:** Electrically negative electrode which fuel (hydrogen) is applied to.
- **Electrolyte:** Molten mixture of alkali metal carbonates which is electrically isolating but conducts carbonate ions when at temperature.
- **Reformer:** A system which catalytically converts hydrocarbon fuels into a hydrogen rich fuel stream and carbon oxides (CO & CO_2).

Gas Turbine Model Report

Jalaja Repalle, Caterpillar Inc
Mark Hughes, Solar Turbines Incorporated

1. Abstract

The gas turbine model simulates turbine performance based on fuel Wobbe index. Gas turbines manufactured by Caterpillar's Solar Turbines division were used in the simulations. Turbine models used included Taurus 60, Mars 100, and Titan 130, which are ISO rated at 5.7, 11.3, and 15.0 MW each. The simulation model interpolates the turbine's output power for the given fuel Wobbe index based on logarithmic relationship between Wobbe index and power output.

2. Description

Solar Turbines leads the industrial gas turbine industry in the use of non-standard fuels, having put over a hundred turbines in the field over the past twenty years. The criteria used to select the Solar gas turbine models for this study included the following:

- Ability to burn low to medium quality fuels (in terms of energy content).
- Turbine size/rate of fuel consumption in an economical range for this application.
- Proven experience on hydrogen-containing fuels.

Note that it is currently not possible to burn typical gasifier-produced fuels in a dry, low NOx combustion system. To meet expected emissions limits, it will be necessary to employ post-combustion exhaust treatment systems such as SCRs and CO catalysts. Water injection may also be necessary, depending on the fuel composition, to reduce NOx to reasonable levels prior to the SCR such that its removal percentage is reduced.

3. Assumptions

- Due to combustion dynamics and fuel gas pressure requirements, syngases with a Wobbe index of less than 300 were eliminated from consideration.
- Wobbe index and turbine power output vary in logarithmic relation (proven through parametric analysis).

4. Inputs/Outputs

Inputs	**Units**
Gas wobbe index	[300-850]
Turbine type	Taurus 60 Mars 100 Titan 130
Outputs	
Turbine output power	kW

5. Validation

Scenario1:

```
Please Enter wobbe Index between 300 and 850:700
4:   Taurus 60
6:   Mars 100
7:   Titan 130
Enter Turbine Type from above list:6
Gas Turbine Output Power (KW)    11085.5
```

Scenario2:

```
Please Enter wobbe Index between 300 and 850:600
4:   Taurus 60
6:   Mars 100
7:   Titan 130
Enter Turbine Type from above list:4
Gas Turbine Output Power (KW)    5663.7
```

6. References

- Solar Turbines Website and Engine Performance Tool
  http://mysolar.cat.com/
  (note: access to Solar's turbine performance tool is subject to prior approval by Solar Turbines Incorporated)

7. Glossary

- **Wobbe Index:** Lower heating value (in Btu/SCF) divided by the square root of the gas's specific gravity.
- **Taurus 60:** Industrial gas turbine manufactured by Solar Turbines Incorporated having an ISO rated output of 5.75 MW.
- **Mars 100:** Industrial gas turbine manufactured by Solar Turbines Incorporated having an ISO rated output of 11.29 MW.
- **Titan 130:** Industrial gas turbine manufactured by Solar Turbines Incorporated having an ISO rated output of 15.0 MW.

Gas Engine Model Report

Jalaja Repalle, Caterpillar Inc
Bryan Silletti, Caterpillar Inc

1. Abstract

The gas engine model is based on using a methane (CH_4) equivalent of the gas mixture. Gas Engines manufactured by Caterpillar were used in the simulations based on the landfill gas and low energy gas configurations currently used in the marketplace. The gas engine models used included the G3520C, the G3516, and G3412 low energy models, rated at 2MW, 1MW, and 375kW respectively. The simulation model provides the engine output for the given CH4 number.

2. Description

Caterpillar is a leader in gas engine industrial and power generation applications and in the use of non-standard fuels, particularly with landfill gas. Currently, Caterpillar has over 420MW in operation in the UK alone. The criteria used to select the Caterpillar gas engine models for this study included the following:

- Ability to burn low to medium quality fuels (in terms of energy content)
    - High efficient, less flexible gas engine – G3520C
    - Low efficient, more flexible gas engine – G3516
    - Low efficient, more flexible gas engine – G3412
- Engine size/rate of fuel consumption in an economical range for this application.
- Proven experience on low energy fuels

While the engine models selected are able to run on high H_2 fuels, extensive de-rating of the engine is required and reduces the overall financial viability of these systems. Currently, a CH4 equivalent number is used as a surrogate for the alternative fuel and a more developed technique will be required

3. Assumptions

- A methane (CH4) equivalent number can be generated from the various gaseous fuels generated from the processing and pre-processing steps
- Full rating is achieved with the current methane numbers through timing and control modifications

4. Inputs/Outputs

Inputs	**Units**
CH_4 Equivalence	[30-140]
Turbine type	G3520C G3516 G3412
Outputs	
Output power (kW)	[375-2000]

5. Example

```
Please enter Gas Methane Number (between 0 and 300):
250
Engine Type                            Performance Number
G3520C Coal Seam (500/350mg NOx)       DM8631
G3520C Coal Seam (500/250mg NOX)       DM8632
Land Fill Gas (G3520C LE)              DM8647
Non-Land Fill Gas (G3520C LE)          DM8648
Pipeline Natural GasG3516 LE           DM5158
Low Energy Gas (G3516)                 DM0761
Low Energy Gas (G3412 LE)              DM0762
Pipeline Natural Gas (G3412C)          DM5450
Pipeline Natural Gas (G3412 TA)        DM5449
Please enter Engine Performance Number from above list:
DM8631
****Results at 100%, 75%, 50% Loading Conditions**********
Genset Power (KW):  1966,    1474,    983
Heat Rejection to Jacket (KW): 624,     534,     420
Heat Rejection to Exhaust (KW):     1264,    761,     761
```

6. References

- Caterpillar Gas Engine Specification Sheets: http://www.cat.com/power-generation/literature