PYROPOWER Summary, Insights, Observations & Conclusions

SEAI RDD Funded Project

Premier Green Energy Operations Ltd

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Introduction

The concept of the inevitability and finality of waste creation in connection with production and consumption is no longer broadly accepted. The new norm is encompassed within terminology such as, circular economy, zero waste, re-use, and recycling. Indeed, all these terms can be attributed to the ideal of achieving a world largely without waste and incorporating a responsible attitude to primary resources, secondary raw materials, products and the environment.

EU and Irish waste policy (and corresponding regulations) target a hierarchical scheme for the treatment and recovery of products from waste materials; this includes recovery of energy from wastes and residues where they cannot be efficiently or economically be recycled or re-processed. In this context, Premier Green Energy Operations Ltd. (PGE) has developed an innovative, continuous, pyrolysis-based advanced thermal treatment (ATT) system to recover energy from a wide variety of dry organic wastes and residues, that is designed to be deployed at moderate scale (0.5 - 4 MWe/hr). However, while steady state production of an energy-rich syngas has been proven at pilot scale for several feedstocks, the challenge of conditioning syngas to crack entrained condensable compounds, e.g. tars and oil vapours, largely remains as a barrier to commercialisation and widespread deployment.

The objective of the PYROPOWER project was to design and fabricate a syngas conditioning system, modelling and testing the process to validate performance in a gas engine, utilising three different biomass waste feedstocks. The selected materials were; (a) refuse derived fuel (RDF) blended with wood, (b) dried dairy sludge blended with wood, and (c) forestry brash. PYROPOWER will demonstrate the suitability of waste-derived syngas, emanating from the integrated ATT and syngas conditioning unit, as an effective energy carrier for continuous power generation in a 60kWe gas engine electrical generator.

Considerable volumes of solid residues including forestry brash, dried dairy/sewage sludges and refuse derived fuel (RDF) are generated in Ireland annually, but are rarely valorised for their energy potential even though the technologies to do so are available. These wastes are of low energy density and have a low monetary value hence transporting them is uneconomical and is not favoured by the EU waste hierarchy (i.e un-supporting of the Proximity principle).

In this context, advanced thermal treatment (ATT) is a technically and environmentally attractive option for energy recovery from such waste materials. Feedstock is heated to 650°C-800°C in an oxygen deficient atmosphere, fractionating it into a flammable syngas, bio-oil or hydrocarbon vapour and a valuable char. ATT eliminates bio-hazard concerns, while lack of oxygen avoids formation of excessive NOx, SOx and other contaminants that may otherwise arise from combustion based processes. Accordingly it is an ideal process for energy recovery and volume reduction for non-recyclable wastes that might otherwise be sent for landfill disposal.

However, efficient energy recovery requires a syngas conditioning system that minimises coking, cracks long chain hydrocarbon tars into smaller, lighter permanent hydrocarbon gaseous molecules, increases calorific value and removes particulates and moisture. This results in a syngas of sufficient quality to meet minimum gaseous fuel specifications published by major engine manufacturers. PYROPOWER will develop and test an ATT integrated syngas conditioning system to address current technological deficiencies which hamper ATT deployment as part of a renewable and sustainable energy solution.

Project Summary

The PYROPOWER project was subdivided into two work packages; the initial work package incorporated engineering and modelling studies to ensure that the residence time, temperature ranges, mixing behaviour and the proportion of additive injections were appropriate for comprehensive syngas thermal cracking and conditioning. In particular, it addressed the amount of oxidant needed to realise sub-stoichiometric syngas cracking, along with establishing the general operating conditions, by examining thermochemical reactions, turbulence intensity and mixture conditions. It also addressed the design and sizing of the syngas conditioning units in a manner that ensures appropriate removal of particulate matter, moisture and contaminants, thus conditioning syngas to a specification that is compatible with combustion in gas engines. In addition, it entailed fabrication of selective components for integration into the existing pilot-scale plant and which were required for iterative testing upon the selected range of feedstock materials during the second work package.

The objectives of the second work package of the PYROPOWER project were twofold; (a) testing and integration of the 60kWe gas engine with the gas train and (b) performance of iterative system feedstock trials for process validation. Successful completion of the initial objective entailed a collaborative approach from PGE personnel and external consultants to implement and integrate the previously specified gas train with the gas engine. This required provision of a relatively small level of gas storage capacity in the gas pipeline to act as buffer storage, which facilitated function testing of the gas engine on syngas derived from pyrolysation of virgin woodchip. The testing regime necessitated the installation of an electrical load bank to accept and dissipate electrical power generated by the 60kWe gas engine.

In the context of PGE's performance of iterative feedstock trials, the selected conversion technology is Advanced Thermal Treatment (ATT), via pilot-scale pyrolysis. ATT technologies are all those thermally based technologies applied to the processing of waste streams and biofuels for resource recovery, energy extraction and power generation. ATT technologies are most often employed in the thermal treatment of relatively dry biomass or wastes with a significant biogenic fraction. Pyrolysis is an endothermic process incorporating the thermochemical degradation of organic material at elevated temperatures in the absence of air; the primary outputs are syngas and char.

In the context of performing iterative feedstock trials for process validation, it was imperative to initially establish fuel characteristics of an untreated woodchip material sample. Fuel characteristics are analysed and assessed through proximate and ultimate analysis of an untreated wood sample, while its energy value is established as its calorific value. **Table 1** illustrates the corresponding values for a representative sample of locally sourced, untreated Sitka spruce woodchip as utilised by PGE Operations in fuel trials.

Properties	Unit	Value			Method
		As received	Dry	Dry ash free	
Fuel Properties – Proximate Analysis					
Moisture Content	wt%	51.90	-	-	
Ash Content	wt%	1.00	2.08	-	
Volatile Matter	wt%	40.40	84.00	85.78	
Fixed Carbon	wt%	6.70	13.92	14.22	Calculated
Fuel Properties – Ultimate Analysis					
Carbon	wt%	23.55	48.96	50.00	Measured
Hydrogen	wt%	2.78	5.78	5.90	Measured
Nitrogen	wt%	0.09	0.20	0.20	Measured
Oxygen	wt%	20.68	42.99	43.90	Calculated
Total (with Halides)	wt%	100	100	100	Calculated
Fuel Properties – Calorific Values					
Gross Calorific Value (HHV)	MJ/kg	9.40	19.53	19.95	
Net Calorific Value (LHV)	MJ/kg	7.51	18.25	18.63	

Table 1 – Fuel Characteristics of Sitka Spruce Woodchip Feedstock
Source: ECN Phyllis / Premier Green Energy Operations Ltd

Having established woodchip fuel characteristics, it was then necessary to establish gas composition data from pyrolysation of this material for comparative purposes. In that context, typical gas composition is outlined in both **Table 2** and **Chart 1**, and emanates from gas chromatography composition analysis of pyrolysed Sitka spruce woodchip feedstock conducted In November 2017. In this feedstock conversion trial run, syngas samples were automatically taken and analysed at regular intervals to establish a representative pattern of syngas elemental compositions.

Gas Chromatography Gas Compositional Analysis of Sitka Spruce Woodchip

Summary Analysis Sitka Spruce Woodchip Gas Composition, November 2017												
Sample	**Air Input Lt/min**	**HHV**	**CH4**	**CO2**	**C2H4**	**C2H6**	**C2H2**	**H2S**	**H2**	**N2**	**CO**	**O2**
Wood Sample Gas Online 1	400	0.01	0.00	0.05	0.0000	0.0000	0.0001	0.000000	0.05	78.43	0.00	21.46
Wood Sample Gas Online 2	400	7.68	6.12	11.64	0.3439	0.0076	0.2268	0.000000	14.34	42.41	24.23	0.70
Wood Sample Gas Online 3	400	7.74	6.21	11.89	0.3543	0.0080	0.2327	0.000000	14.08	42.66	24.56	0.00
Wood Sample Gas Online 4	440	7.62	6.35	11.93	0.3307	0.0071	0.2308	0.000000	13.55	43.73	23.86	0.00
Wood Sample Gas Online 5	440	7.44	6.33	12.16	0.3122	0.0066	0.2376	0.000000	13.77	44.80	22.39	0.00
Wood Sample Gas Online 6	440	7.35	6.02	12.27	0.3161	0.0069	0.2436	0.000000	13.80	44.79	22.56	0.00
Wood Sample Gas Online 7	440	7.45	6.35	12.09	0.3001	0.0066	0.2372	0.000000	13.82	44.83	22.36	0.00
Wood Sample Gas Online 8	440	7.36	5.84	12.19	0.2930	0.0065	0.2366	0.000000	13.70	44.29	23.44	0.00
Wood Sample Gas Online 9	440	7.40	6.07	12.25	0.3084	0.0069	0.2413	0.000000	14.04	44.47	22.62	0.00
Wood Sample Gas Online 10	440	7.60	6.56	11.94	0.3209	0.0071	0.2367	0.000038	13.93	44.10	22.73	0.17
Wood Sample Gas Online 11	440	7.66	6.61	11.83	0.3195	0.0072	0.2356	0.000000	14.02	44.08	22.89	0.00

Table 2 - Gas Chromatography Gas Compositional Analysis of Sitka Spruce Woodchip (November 2017)
Source: Premier Green Energy Operations Ltd

Gas Chromatography Gas Compositional Analysis of Sitka Spruce Woodchip

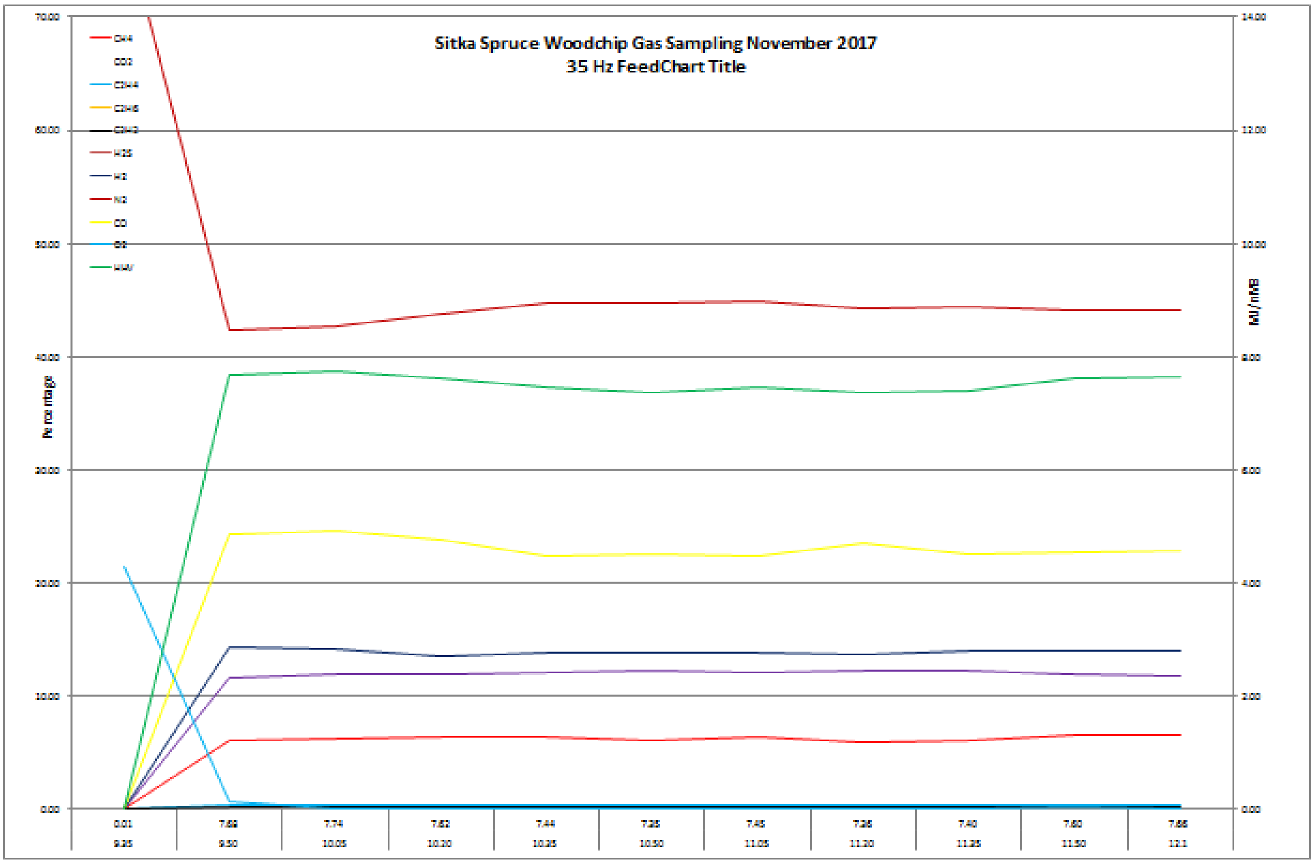

Chart 1 - Gas Chromatography Gas Compositional Analysis of Sitka Spruce Woodchip (November 2017)
Source: Premier Green Energy Operations Ltd

Table 2 and **Chart 1** demonstrate the gross calorific value (GCV), expressed as Higher Heating Value (HHV) of syngas derived from pyrolysation of untreated sitka spruce woodchip. The GCV would typically fall within the range from 6.5 to 9.0 MJ/Nm^3 for all samples analysed after the gas cracking tower. Bag samples taken prior to the gas cracker would typically demonstrate "Raw" syngas HHV in the range of circa 10.0 - 15.0 MJ/Nm^3. In the context of energy content, the key elemental contributors to syngas as an effective energy carrier are methane, hydrogen and carbon monoxide respectively. However, it should be noted that the variability in calorific value (CV) of syngas samples is linked to changes in ambient air moisture levels and in testing methodology. In addition, CV variations are reflective of the volume of pre-heated air injection into the gas thermal cracking vessel; this air volume acquires its heat from a bespoke recuperator.

By volume, dry air contains circa 78% nitrogen, an inert gas. **Table 2** and **Chart 1** demonstrate content of syngas samples; the typical content of nitrogen falls within the range of 30% - 50% of the elemental composition of all syngas sampled post thermal cracker vessel. Hence, nitrogen has dilution impact upon the energy content of all the other compositional elements of the syngas. This dilution is somewhat further increased by the elemental composition of nitrogen entrained in the actual wood samples, but the key dilution factor remains the volume of pre-heated air injection into the thermal gas cracking vessel.

Dried Dairy Sludge Pyrolysis Testing

A series of feedstock conversion trial runs, utilising a 50% blend by mass of untreated woodchip and dried dairy sludge were conducted during November 2017. However, for reasons of commercial sensitivity, PGE Operations have been requested to preserve the confidentiality of this information. Nevertheless, both conversion trial runs clearly demonstrated that this blend of feedstock is an effective energy carrier with sufficient calorific value to generate renewable electricity and nutrient-enriched biochar.

Forestry Brash Pyrolysis Testing

Prior to the initiation of pyrolysis testing, it was initially necessary to establish fuel characteristics through proximate and ultimate analysis of a forestry brash sample. The results of this exercise are outlined hereunder in **Table 3**.

Properties	Unit	Value			Method
		As received	Dry	Dry ash free	
Fuel Properties – Proximate Analysis					
Moisture Content	wt%	22.80	-	-	
Ash Content	wt%	3.06	3.97	-	
Volatile Matter	wt%	63.62	82.41	85.82	
Fixed Carbon	wt%	10.51	13.62	14.18	Calculated
Fuel Properties – Ultimate Analysis					
Carbon	wt%	38.84	50.31	52.39	Measured
Hydrogen	wt%	3.54	4.59	4.78	Measured
Nitrogen	wt%	0.86	1.12	1.13	Measured
Oxygen	wt%	30.84	39.95	41.60	Calculated
Total (with Halides)	wt%	100	100	100	Calculated
Fuel Properties – Calorific Values					
Gross Calorific Value (HHV)	MJ/kg	15.43	19.98	20.17	
Net Calorific Value (LHV)	MJ/kg	13.90	18.73	18.63	

Table 3 – Fuel Characteristics of Forestry Brash Feedstock
Source: ECN Phyllis / Premier Green Energy Operations Ltd

The results demonstrate some divergences from the fuel analysis of untreated Sitka spruce woodchip on an "as received" basis largely arising from discrepancies in moisture content. However, fuel characteristics are noticeably similar on a dry basis.

A feedstock conversion trial run was conducted in November 2017, utilising forestry brash; the outcome, as illustrated in **Table 4** hereunder, demonstrates that the average profile of gas constituents from pyrolysation of forestry brash is broadly similar to those exhibited by syngas from pyrolysation of untreated Sitka spruce, albeit generally at lower concentration levels, especially in relation to hydrogen and methane content. In addition, energy dilution elements, carbon dioxide and nitrogen, were higher in forestry brash than in woodchip. Nevertheless, it is demonstrably clear that syngas from forestry brash pyrolysation is an effective energy carrier with sufficient calorific value to generate renewable electricity and usable biochar.

Summary Analysis From Forestry Brash Gas Composition, November 2017

Sample	Time	Air Input Lt/min	HHV	CH4	CO2	Ethylene	Ethane	Acetylene	H2S	H2	N2	CO	O2
Average Sample Gas Values		427	7.61	6.83	11.81	0.36	0.01	0.21	0.00	14.41	44.55	22.02	0.00

Table 4 – Average Gas Chromatography Gas Compositional Analysis of Forestry Brash (November 2017)
Source: Premier Green Energy Operations Ltd

Refuse Derived Fuel (RDF) Pyrolysis Testing

Before commencing pyrolysis testing, fuel characteristics were determined through proximate and ultimate analysis of an RDF sample, and are presented in **Table 5**, herewith.

Properties	Unit	Value			Method
		As received	Dry	Dry ash free	
Fuel Properties – Proximate Analysis					
Moisture Content	wt%	32.30	-	-	
Ash Content	wt%	10.83	16.00	-	
Fuel Properties – Ultimate Analysis					
Carbon	wt%	31.60	46.68	55.57	Measured
Hydrogen	wt%	4.20	6.20	7.39	Measured
Nitrogen	wt%	0.50	0.74	0.88	Measured
Sulfur	wt%	0.20	0.30	0.35	
Oxygen	wt%	20.24	29.89	35.58	Calculated
Total (with Halides)	wt%	99.87	99.80	99.77	Calculated
Fuel Properties – Calorific Values					
Gross Calorific Value (HHV)	MJ/kg	14.01	20.69	24.63	
Net Calorific Value (LHV)	MJ/kg	12.30	19.33	23.02	

Table 5 – Fuel Characteristics of Refuse Derived Fuel (RDF) Feedstock
Source: ECN Phyllis / Premier Green Energy Operations Ltd

The analysis demonstrates significant divergences from the fuel analysis of untreated Sitka spruce in relation to moisture content on an "as received" basis. In addition, carbon and hydrogen content are significantly higher in RDF compared to their equivalent content in untreated Sitka spruce. Furthermore, both the gross and net calorific values for RDF, expressed as higher and lower heating values respectively, are considerably higher in RDF compared to untreated Sitka spruce. A feedstock conversion trial run was conducted in January 2018, utilising a blend of 50% Sitka spruce woodchip and 50% refuse derived fuel (RDF) on a volumetric basis; on a mass basis the ratio would have been circa 3 : 1.

Prior to conducting this trial run, a modification had to be made to the pilot-scale plant fuel feed secondary hopper, with the integration of a fuel feeding "rake" to prevent bridging of the extremely light "flock" RDF material above the infeed screw feeder to the retort. When feedstock bridges over the infeed screw feeder, it prevents a constant and even flow of material into the conversion chamber and undermines the ability to consistently generate syngas and char. The average gas compositional analysis from pyrolysation of blended woodchip and refuse derived fuel (RDF) feedstock is illustrated in **Table 6** hereunder.

Summary Analysis From RDF Gas Composition, January 2018

Sample	Time	Air Input Lt/min	HHV	CH4	CO2	Ethylene	Ethane	Acetylene	H2S	H2	N2	CO	O2
Average Sample Gas Values		413	7.97	7.28	12.09	0.39	0.01	0.21	0.00	14.67	42.96	22.39	0.00

Table 6 – Average Gas Chromatography Gas Compositional Analysis of RDF (January 2018)
Source: Premier Green Energy Operations Ltd

The table illustrates that the profile of gas constituents from pyrolysation of RDF is broadly similar to those exhibited by syngas from pyrolysation of untreated Sitka spruce, albeit generally at higher concentration levels, especially in relation to hydrogen and methane content. In general, the higher concentration of these elements is not unexpected due to the presence of plastics in the RDF feedstock, which typically have significantly higher CV than wood. However, while incorporation of plastics in the feedstock typically leads to a reduction in the proportion of char volume, it enables generation of higher gas yields. The results demonstrate that syngas from RDF pyrolysation is an effective energy carrier with more than adequate calorific value to generate renewable electricity and biochar, although at a lower volume of the latter.

Key Insights, Observations & Conclusions

PYROPOWER, an SEAI RDD funded project incorporating testing and integration of a 60kWe gas engine with the pilot-scale pyrolysis plant gas train, and performance of iterative feedstock trials for process validation, has generated numerous insights, observations and conclusions; these include the following:

- The feedstock trials demonstrate that pyrolysis provides an alternative, elegant and environmentally-friendly solution to the treatment of an array of dry biogenic material residues that is preferable to the current practice of land-spreading;
- Performance of feedstock conversion trials on three selected feedstocks via the pilot-scale plant confirm that the technology is capable of generating an energy-rich syngas which, when conditioned, has sufficient calorific value to generate renewable and sustainable electricity in an effective and efficient manner. The technology also has the capacity to simultaneously produce a valuable, nutrient-enriched biochar;
- Deployment of advanced thermal treatment pyrolysis offers a methodology for energy and nutrient recovery, contributing significantly to decarbonisation of energy, enhanced recovery and recycling of nutrients and endangered raw materials, such as phosphorous, and can mitigate major environmental impacts of waste disposal;
- The conversion technology operates at its most effective level when the process is in continuous, uninterrupted mode at an appropriate scale;
- Although the introduction of pre-heated air to the thermal cracker vessel is a necessary process step, it leads to dilution of all other energetic components of the syngas;
- Further research will be required prior to commercial deployment, especially in relation to monitoring and control of emissions to ensure compliance with the relevant EU Directive;

- Additional engineering solutions will be required to optimise electrical generation efficiency and to boost thermal energy recovery to meet the high efficiency criteria of the CHP Directive; however, observations of the trials would strongly suggest that thermal losses can be dramatically reduced at higher rates of feedstock conversion, e.g. in excess of 1000 Kg per hour;
- Decoupling of waste production and related impacts from economic growth is critical to transitioning to resource efficiency, environmental preservation, and the circular economy;
- Deployment of advanced thermal treatment pyrolysis and complementary technologies, at an appropriate scale, can underpin EU and Irish waste policy and corresponding regulations which target a hierarchical scheme for the treatment and recovery of products from waste materials in compliance with the proximity principle;
- In a commercial deployment project, the thermal energy required to sustain the pyrolysis conversion process would be supplied by combusting syngas from thermal processing of the output char in lieu of electrical heating elements.
- Evidence from the feedstock trials would suggest that a far wider range of residues from Ireland's agri-food, marine, forestry and municipal waste sectors (AMFM) may potentially be exploited for energy recovery via pyrolysis and other complementary technologies;