AUSTRALIAN MEAT PROCESSOR CORPORATION

Review and cost benefit analysis of Torrefaction technology for processing abattoir waste

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1.0 Executive summary

Lycopodium Process Industries (Lycopodium) was engaged by the Australian Meat Processor Corporation (AMPC) to undertake an independent review of the value proposition that torrefaction of waste streams from the meat processing (specifically paunch, manure and anaerobic digester sludge) presents to the industry. The two end uses for the torrefied biomass considered were:

1) a bio-based coal substitute

2) a fertilizer/soil conditioning biochar product.

The technology assessment was largely based on the outcomes of a report prepared for AMPC by ideas* Pty Ltd (ideas*) entitled, 2013/3009 Torrefaction of animal waste for beneficial use, reduced emission and cost reduction.[1] which presented findings from a laboratory-scale trial in which solid waste samples from a large beef abattoir were processed. The findings of the report, including key processing assumptions and outputs from the ideas*/Torreco process, were cross-checked with published scientific literature.

The outcomes of the technology review can be summarised as follows:

- The processing conditions that Torreco have used to torrefy the waste samples are unconventional compared with other torrefaction technologies in that the heating rates are faster (up to 90°C/min vs <50°C/min), the feed moisture content is higher (up to 90%w/w vs <20%w/w), the process temperature is higher (370°C to 385°C vs 200°C to 320°C), and the solids residence time is lower (4 to 8 min vs 30 to 60 min). The novelty of the process along with some gaps in the product analysis (such as torrgas production rates, mass loss of input solids and gross calorific value of the torrefied products) make it difficult to close the mass and energy balance or verify the outputs of the process against those derived from standard process conditions. The outcomes of the cost-benefit analyses undertaken for the Torreco process should therefore be assessed within the context of these uncertainties. This is not to say that the Torreco process is not technically feasible, however, as there is some indication in the literature that the Torreco processing conditions described may favour high char production rates and reasonable retention of the energy and nutrient content of the biomass – a scenario which is preferable when looking to maximise the value of the torrefied product as a bio-based coal substitute or fertilizer.

- The capital estimate that was presented in the ideas* report for a two (2) ton (wet) per hour torrefaction system was reviewed and found to lie within the accuracy range expected at the concept stage. For scenarios where all or part of the torrefied material is to be sold as a granulated biochar or fertiliser product, the additional expense of a 6,000 ton per year granulation facility is estimated at $2.1 million.

- The operating expense estimates submitted by ideas* are believed to be underestimated both in terms of the power and heating costs required to the run the process. In particular, there is a heavy reliance on the availability of waste heat from the exhaust of existing boiler systems which the author believes to be implausible due to limitations around the temperature of the exhaust gases and potential impact on boiler operations.

Further to the technology review, a cost-benefit analysis (CBA) of the ideas*/Torreco torrefaction process was undertaken. The CBA considered production of a bio-based coal substitute and/or a granulated biochar from solid meat processing waste streams and looked at how the process compares to other technologies such as combustion, pyrolysis, gasification and anaerobic digestion that also act to reduce on-site waste management costs and recover energy and/or nutrients from these solid waste streams. The CBA was based on a two (2) ton (wet) per hour torrefaction system operating at a 1,300 head per day beef processing facility and with the feed composed of two thirds paunch waste and one third manure – having a combined solids content of 44%w/w. It was assumed that a maximum of 50% of the requisite heat energy could be supplied by excess from the boiler.

The results of the CBA indicate the following:

- The commercial viability of the Torreco technology is highly dependent on both the cost of delivering energy to the process and the value that can be realised from the torrefied material.
- If used to produce a biochar product only, the torrefaction system compared favourably against pyrolysis, gasification, combustion and anaerobic digestion of paunch wastes when similar assumptions regarding the value of coal, biochar and Australian Carbon Credit Units (ACCUs) were used.
- The estimated greenhouse gas (GHG) abatement potential for the scenario in which the torrefied biomass is used to replace 20% of a site's coal-based energy requirements is approximately 2,091 T (CO2-e) per year. When the torrefied material is used only as biochar for soil conditioning the GHG abatement potential drops to about 160 T (CO2-e) per year.
- Assuming that the torrefied material is used to substitute 20% of a site's coal-based energy requirements while the rest is sold as biochar the 20-year net present value (NPV) ranges from -$5,063,656 to -$1,673,831, the internal rate of return (IRR) ranges from -0.4% to 1.8% and the simple payback period ranges from 15.5 to 19.1 years depending on the value realised for the biomass and ACCUs.
- Assuming that all of the torrefied material is used as a biochar product the NPV ranges from -$3,855,407 to $11,239,034, the IRR ranges from -5.0% to 32.2% and the simple payback period ranges from 3.1 to 36.0 years depending on the value realised for the biomass and ACCUs. Biochar values in order of $330 per ton are required to reduce the simple payback period to less than 3 years.

Recommended further steps include:

- Repeat laboratory scale trials on typical meat processing solid wastes to confirm the:
  - percentage volatilization of organic material across torrefaction process
  - higher and lower heating value of the torrefied product produced

- torrgas composition and calorific value to determine value as a heat source for process
- process energy requirements
- ability of the torrefied material to meet the fuel specifications for solid fuel boilers
- consideration of potential odour issues associated with torrefaction of these materials.

- Confirm the following regarding the proposed demonstration site:
  - Quantities of the various forms of solid waste produced and that these are in line with Torreco's assumption and produced at a sufficient amount overall to run a 2 wet ton per hour torrefaction system.
  - Availability of waste heat of suitable quality and quantity to drive the Torreco process and, if not, the ability to provide access to an alternative energy source such as LPG or natural gas.
  - Current and projected purchase price of coal.
  - Current and projected coal usage.
  - Current coal delivery system to boiler, whether any modifications would be required to accommodate torrefied biomass and, if so, what these are likely to cost.
  - Current and future waste disposal methods and costs.
- Re-evaluate the viability of the demonstration scale project based on the outcomes of the previous two groups of activities.
- Potentially apply for co-funding from industry groups or the government in order to improve the project economics, reduce the project risk and thereby enable a demonstration scale system to be built which can confirm process costs, outputs and the market value of the torrefied material produced.

2.0 Introduction

The Australian red meat processing industry produces substantial quantities of organic solid wastes as a result of its operations every year. These organic wastes originate from various activities within a processing operation and includes; manure from the truck wash and holding pens, paunch and gut contents, solids from primary treatment, and biological sludge from waste water treatment [2]. Traditionally, handling and disposal/treatment of these organic wastes has resulted in significant ongoing costs for the processor. Recognising that there is substantial chemical energy and potentially valuable nutrients present within these organic waste streams, the Australian Meat Processor Corporation (AMPC) commissioned a number of studies aimed at assessing the technical and economic feasibility of using various processing routes, such as combustion, gasification, pyrolysis, and anaerobic digestion – to produce energy and/or fertilizer products from these waste streams [1, 3-7].

AMPC engaged Innovation Development Engineering Administration Services Pty Ltd (ideas*) to complete a study to evaluate torrefaction of these solid waste streams. Activities undertaken as part of this study included[1]:

- Collection of manure and paunch samples from a large beef processing facility in Queensland and anaerobic digester sludge (ADS) from a large beef processing facility in New South Wales.
- Torrefaction of the latter samples within a pilot scale torrefier in order to assess the operation of the process and the suitability of the torrefied material produced to be on-sold as a bio-based coal substitute or fertilizer/soil conditioner.
- Develop a mass and energy balance for the process as well as a nutrient analysis.
- Undertake a capital and operating expense assessment for implementation of torrefaction technology at a large beef processing facility in Queensland.

Following the completion of the study by ideas*, AMPC engaged Lycopodium Process Industries Pty Ltd to undertake an independent review of the technology and findings. Lycopodium also undertook a cost benefit analysis for implementing the technology at the beef facility in Queensland based on the outcomes of ideas* report as well as an estimate of the potential Scope 1 and 2 emissions reductions. The findings of these activities are presented within this report.

3.0 Torrefaction Overview

Torrefaction is often referred to as 'mild pyrolysis' – where pyrolysis is a thermal treatment process that is applied to organic material (usually biomass) in the absence of oxygen and under approximately atmospheric pressures [8, 9]. The torrefaction process is traditionally characterised by slow heating rates (typically <50°C/min), relatively long solid residence times (30 to 90 minutes) and pyrolysis temperatures in the range of 200°C to 320°C [8].

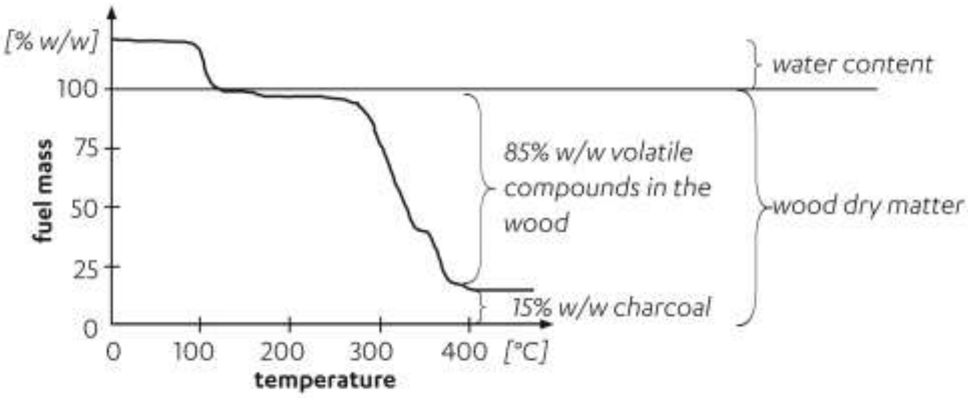


Figure 1. Typical thermal gravimetric analysis of wood undergoing pyrolytic decomposition (From [8])

During torrefaction, as the organic material is slowly brought to higher temperatures, the residual moisture present in the waste feed is driven off and (above approximately 200°C) the organic material then begins to undergo thermal decomposition (Figure 1). During this decomposition various reactions take place and different types of volatiles are released. The release of these volatiles results in mass and chemical energy in the solids being transferred to the gas phase. The amount of mass and energy from the original biomass which is retained in the torrefied biomass is strongly dependent on torrefaction temperature, reaction time, and biomass type [10]. Under typical processing conditions, however, the input biomass loses about 30% of dry mass but only 10% of its energy. This phenomenon results in energy densification (i.e. 30% higher MJ/kg [8]).

Table 1. Fuel properties of woodchips, wood pellets, torrefied biomass, TBPs and bituminous coal (From [11, 12])

PROPERTIES	WOOD	WOOD PELLETS	TORREFIED BIOMASS	TORREFIED PELLETS	CHARCOAL	COAL
Moisture content (% wt)	30–45	7–10	3	1–5	1–5	10–15
Calorific value (MJ/kg)	9–12	15–16	19.9	20–24	30–32	23–28
Volatiles (% db)	70–75	70–75		55–65	10–12	15–30
Fixed carbon (% bd)	20–25	20–25		28–35	85–87	50–55
Bulk density (kg/l)	0.2–0.25	0.55–0.75	0.23	0.75–0.85	~0.20	0.8–0.85
Volumetric energy density (GJ/m3)	2.0–3.0	7.5–10.4	4.7	15.0–18.7	6–6.4	18.4–23.8
Dust	Average	Limited	High	Limited	High	Limited
Hygroscopic properties	Hydro-philic	Hydro-philic	Hydro-phobic	Hydro-phobic	Hydro-phobic	Hydro-phobic
Biological degradation	Yes	Yes	No	No	No	No
Milling requirement	Special	Special		Classic	Classic	Classic
Handling requirements	Special	Easy		Easy	Easy	Easy
Product consistency	Limited	High		High	High	High
Transport cost	High	Average		Low	Average	Low

The primary goal of torrefaction has therefore historically been the desire to produce an upgraded solid fuel with better handling and combustion properties. The proposed benefits of torrefaction include [9]:

- increased energy density
- low moisture content
- better grindability
  - fibrous and tenacious nature of biomass which makes grinding/milling difficult is significantly reduced due to breakdown of hemicellulose matrix and depolymerisation of cellulose. The grindability, uniformity of particle size and flow characteristics are therefore enhanced leading to higher potential for fuel substitution within existing coal-type boilers[12].
- biomass goes from hydrophilic to hydrophobic
  - easier storage, reliable moisture content and less biological degradation.
- ability to produce a torrefied biomass pellet (TBP) with an energy content of 19 to 22 MJ/kg

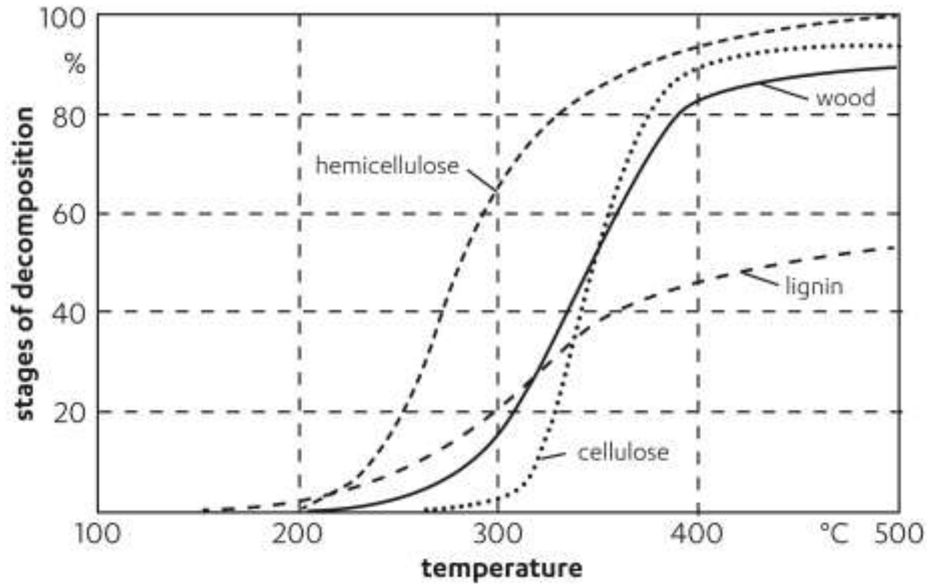
Recently a number of companies, such as Torreco and Agri-Tech Producers LLC, have also suggested that torrefied biomass may be utilized as a ‘biochar’ with potential soil conditioning and/or nutrient delivery qualities [13]. The economic and agricultural value of this biochar, however, has yet to be fully established[14]. As Sohi et al point out, much of the evidence used to assess biochar function to date rests on studies made using charcoal [15]. While there is historical evidence of the value of charcoal in soil management, feedstock, pyrolysis temperature and possibly other pyrolysis conditions effect char characteristics that influence how it functions in the soil [16]. Of these parameters, it has been established that the highest treatment temperature (HTT; the maximum temperature which the biomass is subjected to in the pyrolysis reactor) has the greatest overall influence on the final product characteristics. Therefore, biochar produced via torrefaction style conditions with a particular organic material may differ significantly from biochar produced with other pyrolytic conditions and/or organic material. Proposed benefits of biochar application to soils include:

- increased water holding capacity
- increased nutrient uptake efficiency
- improved cation exchange capacity (CEC)
- adsorption of toxic elements
- mineralisation of soil organic matter
- encouragement of beneficial micro-organisms
- reduction of soil acidity.

In order to better understand the torrefaction process it helps to understand the key components of the biomass that is typically fed to the process. Biomass tends to be formed primarily of organic polymers collectively referred to as lignocellulose and smaller amounts of minerals and other inorganic and organic compounds. The lignocelluloses fraction is broken into three main groups – hemicelluloses, cellulose and lignin. The relative contribution of lignocelluloses to the overall biomass and the composition of its constituent parts varies between sources of biomass. Under typical torrefaction conditions, however, the major biomass constituent that is volatilized is hemi-cellulose which decomposes between 200°C to 300°C in two steps[17]:

- Depolymerisation (typically occurring at temps up to 250°C) – low mass loss
- Decomposition to char, steam, CO, CO2 and light volatiles – higher mass loss.

Cellulose and lignin are more stable and require greater energy to degrade. This aspect of torrefaction is well illustrated in



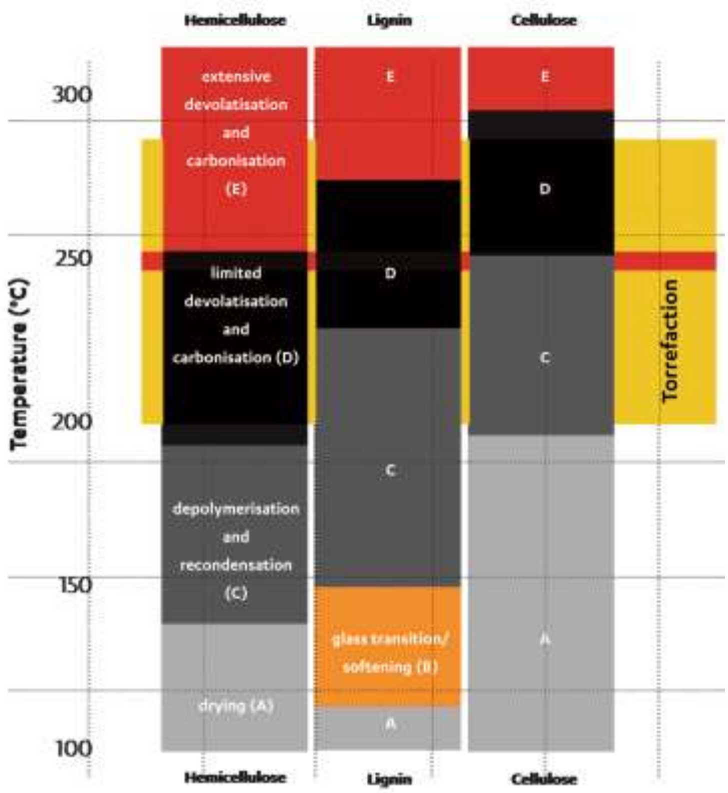


Figure 2 and

Figure 3.

Torrefaction of red meat processing wastes provides an interesting feed stream in that paunch, manure and anaerobic digester solids have a reduced content of lignocellulosic material (in particular, hemicelluloses) due to the fact that the organic material has already undergone a certain degree of decomposition within the gut of the animal or within the anaerobic digester. Dhangana et al [18], however, have undertaken torrefaction studies using wastes low in lignocelluloses (such as chicken litter, digested sludge and undigested sludge) which indicated that torrefaction of these wastes results in a similar energy densification to that of typical lignocellulosic material.

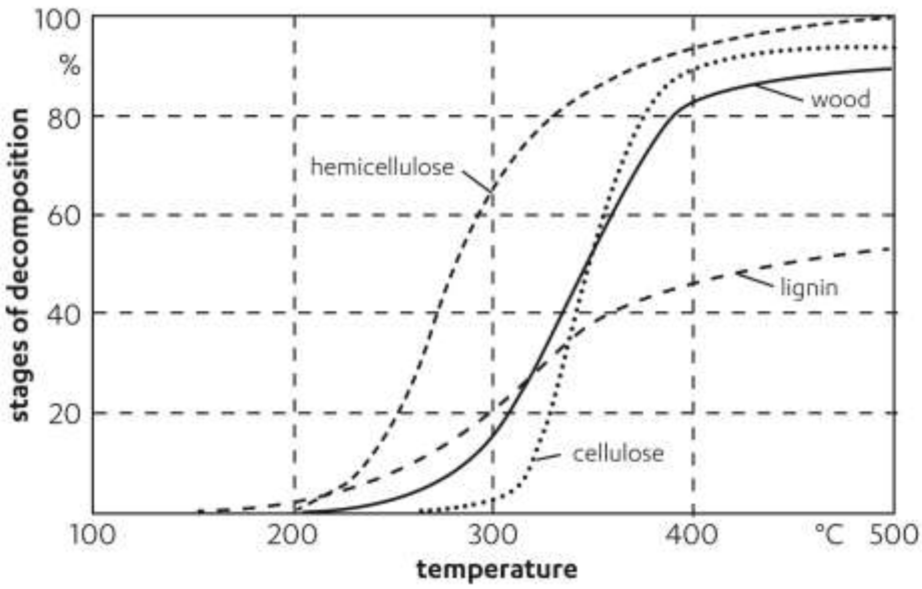


Figure 2. Thermal decomposition of lignocelluloses fractions in wood (From [8])

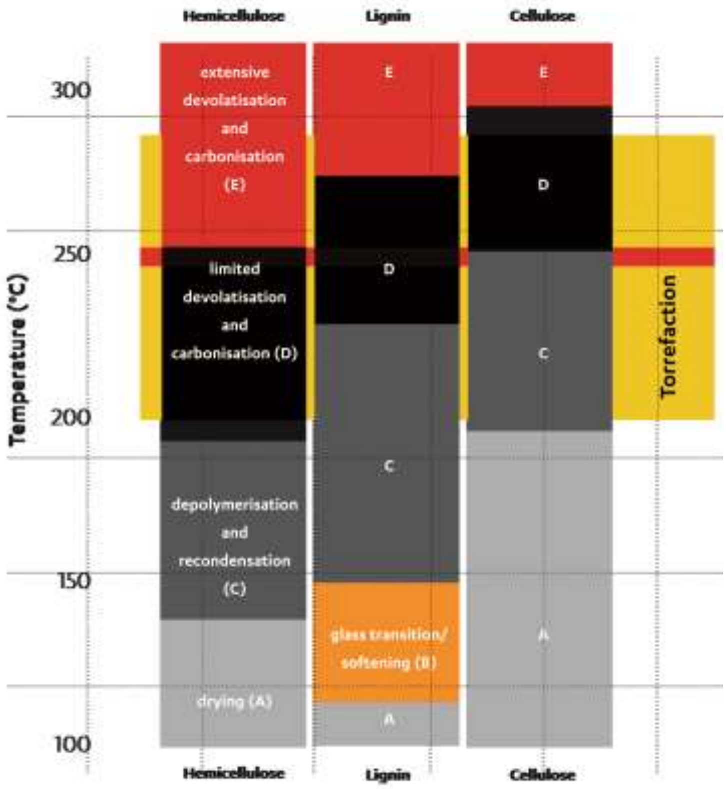


Figure 3. Physiochemical changes in biomass during torrefaction (From [9])

With respect to larger scale systems, torrefaction processes can be designed for direct or indirect heating of the torrefaction chamber. Typical process flow sheets for each scenario are presented in Figures 4 and 5.

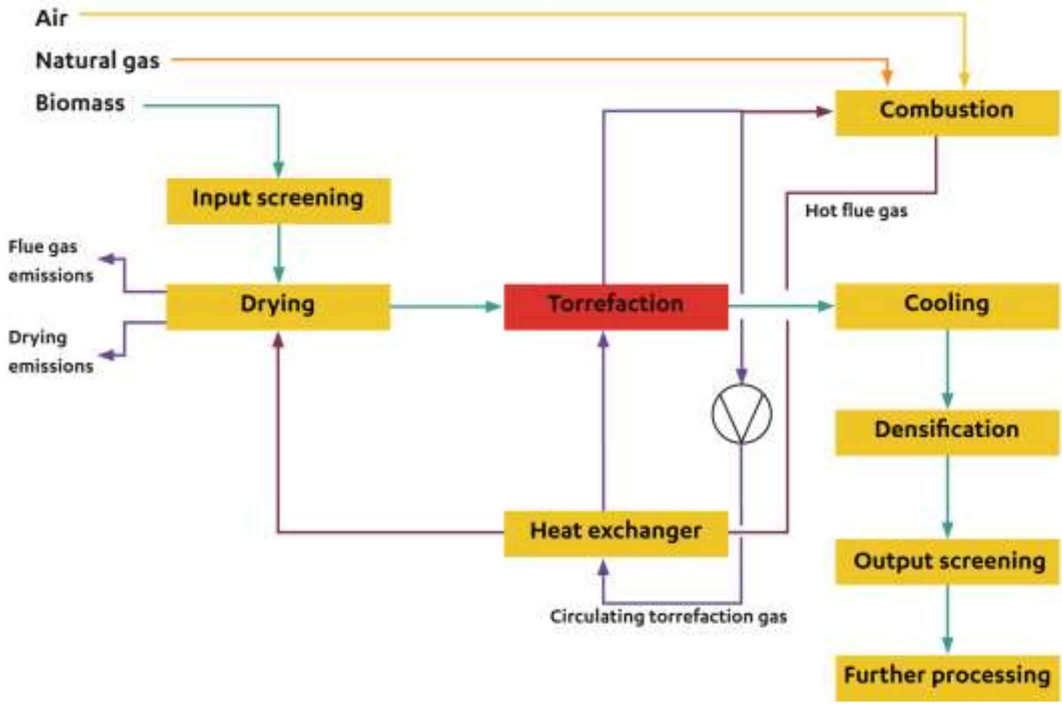


Figure 4. Typical process flow sheet – Direct heating (From [8])

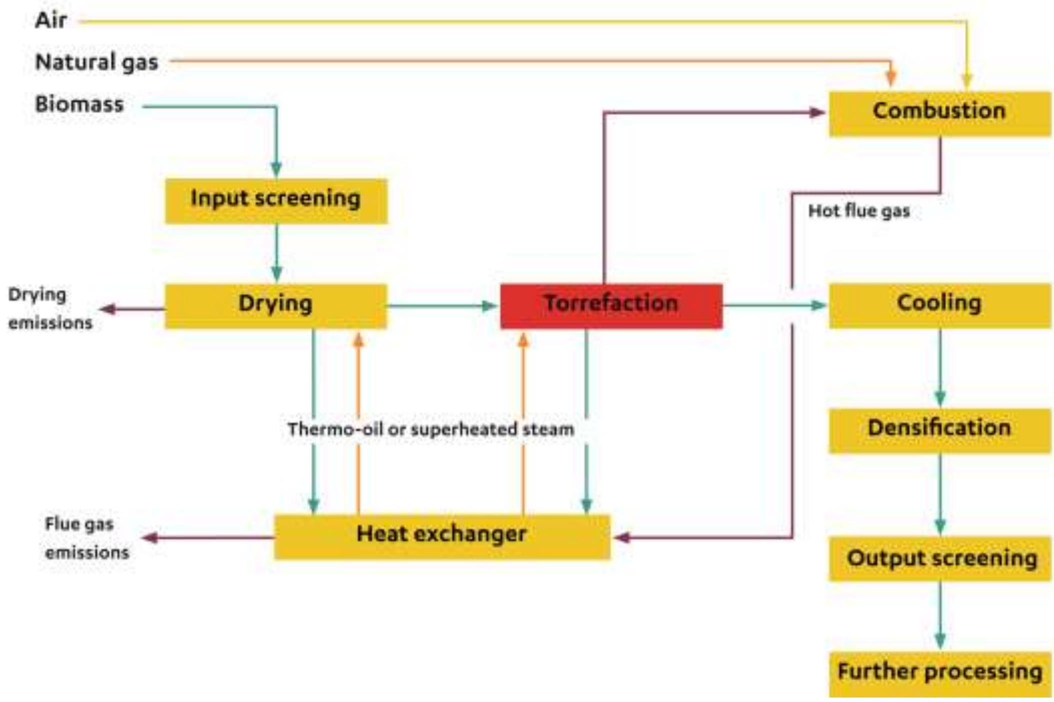


Figure 5. Typical process flow sheet – Indirect heating (From [8])

While the process flow sheets in

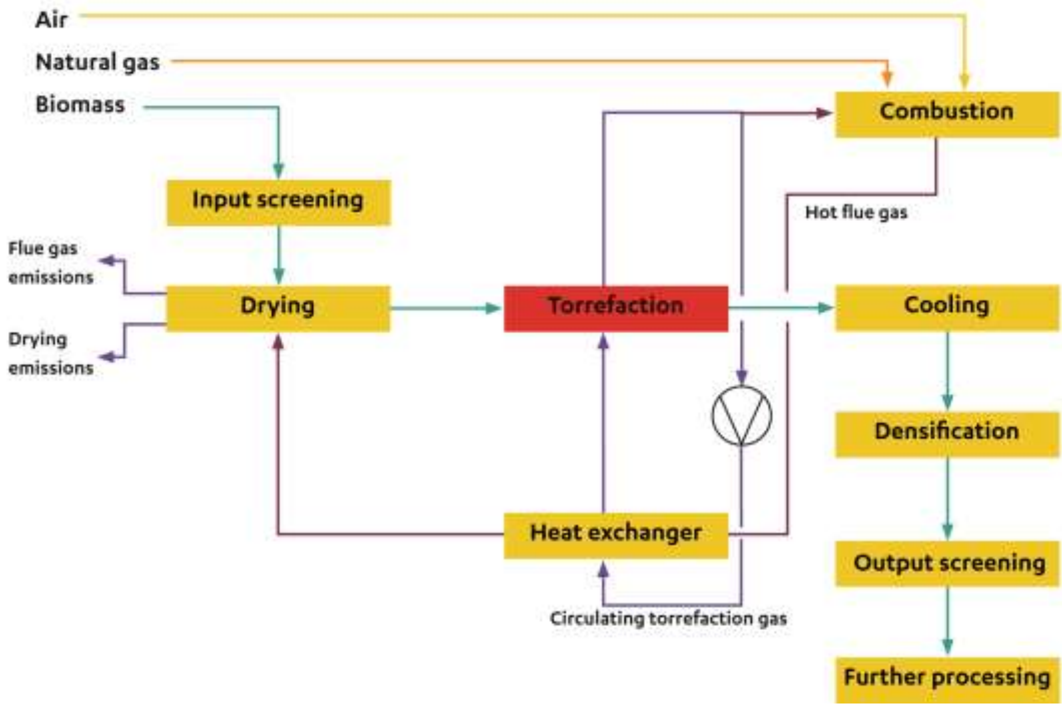


Figure 4 and

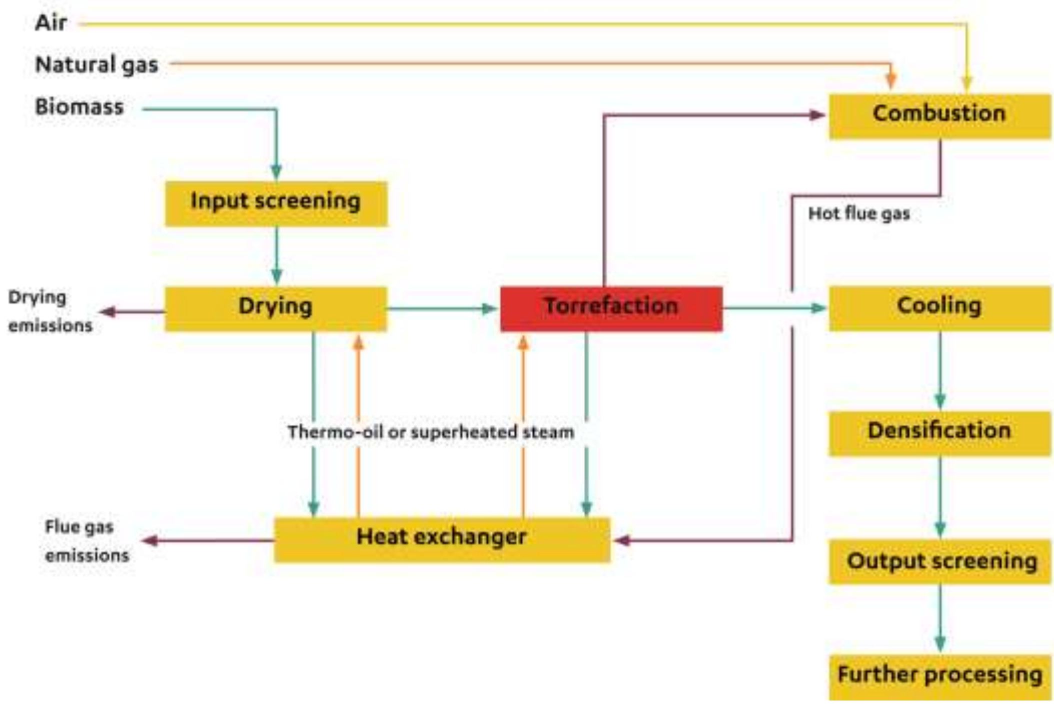


Figure 5 show the torrefaction gases going directly to combustion, there are compounds within this gas stream which are condensable. Through cooling of the gas stream these compounds may be removed and (particularly through removal of water) provide for more efficient combustion of the torrgas. The groups of components that are found in the solid, liquid and gas components after torrefaction of biomass are presented in Figure 6.

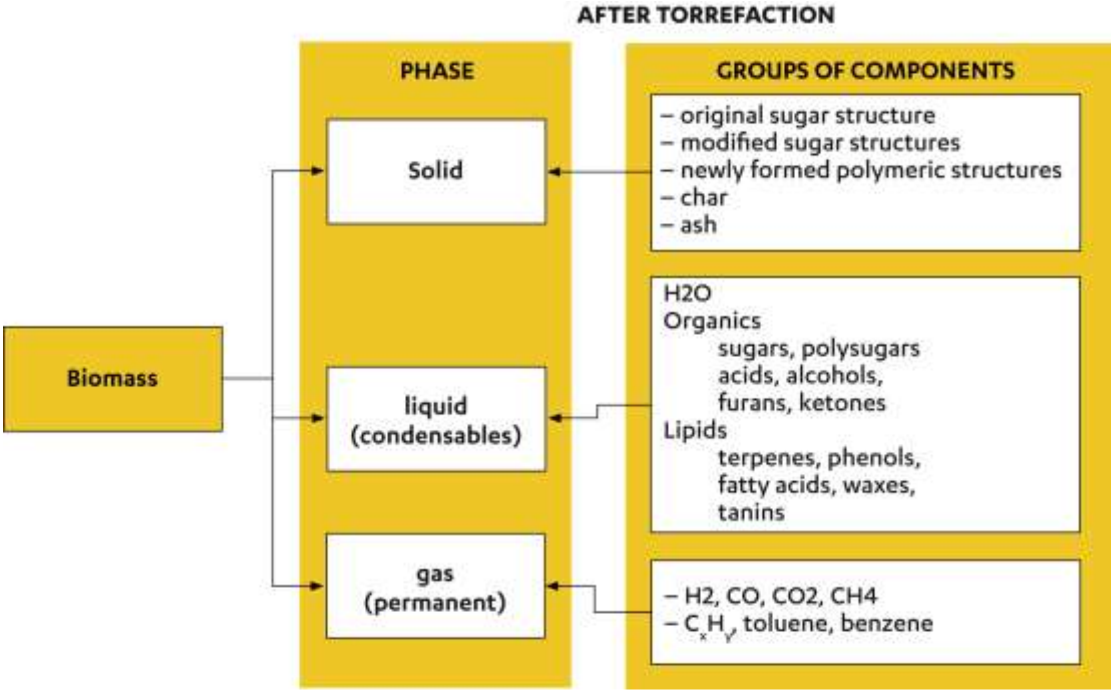


Figure 6. Torrefaction product analysis (From [9])

Potential environmental, health and safety concerns associated with torrefaction process include the:

- dust produced by the torrefaction process is considered to have a similar fire hazard risk as charcoal (which has been known to spontaneously combust). The volatiles potentially present in the biochar also present a fire hazard. Suitable care is therefore required to minimise dust accumulation and the combustion risk may require active management through addition of fire retardants or handling within an inert atmosphere. Handling of biochar in Australia is classified under UN Number 1362 (activated carbon), Hazard Class: 4.2, Packing Group III [19].
- depending on the feed stock and pyrolysis conditions, the torrefied biomass may also contain crystalline silica or other materials which require limited exposure.
- condensable and permanent components of the gas may contain compounds which require safe handling and/or specialist waste treatment or disposal methods.
- leeching characteristics of compounds from biochar is not yet fully understood and may be of concern depending on the feed stock and process conditions [9, 19, 20]

4.0 Technology comparison

AMPC has commissioned a number of previous studies into the energy and nutrient recovery technology options for meat processing wastes. Amongst these have been, slow pyrolysis, gasification, combustion and anaerobic digestion. Table 2 summarises the various processing conditions involved with each of these technologies and briefly comments on the relative advantages and disadvantages of each.

Torrefaction has the particular advantage of retaining a large portion of the embedded chemical energy and nutrient content of the biomass within the solid ‘biochar’ fraction that exits the process. Other forms of pyrolysis – fast and slow – result in lower biochar output and higher proportions of liquid and gas products. Both of the latter fractions often require upgrading to be effectively utilised.

Table 2. Comparison of Typical Processing Conditions and Outputs from Various Technology Options for Recovering Energy and/or Nutrients from Organic Wastes. (Based on data taken from [1,15, 21-23])

		PROCESS TEMP.	OXYGEN LEVEL[1]	TYPICAL FEED MOISTURE	HEATING RATE	SOLIDS RESIDENCE TIME	SOLID FRACTION	LIQUID (BIO-OIL)	GAS				
TECHNOLOGY		°C	%	WT%	°C/MIN	MINS	WT%	WT%	WT%	PRODUCTS	CAN BE FURTHER PROCESSED TO:	ADVANTAGES	DISADVANTAGES
Torrefaction (Conventional)		200-320	0	<20	<50	30 to 60	75	20	5	Biochar, syngas, condensables	Energy pellets, granulated soil conditioner/ fertiliser	High biochar production	Limited end use of products and unproven markets[3].
Torrefaction (Torreco Process)		370-385	0	~45 to 50	~45 to 90	4 to 8	90[2]	6[2]	4[2]	Biochar, syngas, condensables	Energy pellets, granulated soil conditioner/ fertiliser	Maximum biochar production	Minimal energy in torrgas to drive torrefier, therefore potentially reliant on other energy sources. Very little operational data available.
Pyrolysis	**Slow**	450-550	0	<35	1 to 30 (15 to 20 typical)	10 to 60	35	30 (70% water)	35	Biochar, syngas, bio-oil	Soil conditioner, syn-diesel	Produces roughly even amounts of bio-char, bio-oil and syngas	Multi-product mix leads to additional handling and processing costs.
	Fast	450-550	0	<12	Up to 500	Seconds	12	75 (25% water)	13	Bio-oil, syngas, biochar	Syn-diesel	High bio-oil yields, low syngas	Bio-oil is rich in oxygenated compounds, 10 to 25 Wt % water, highly corrosive (pH ~ 2), not distillable, unstable (ageing = polymerisation of bio-oil compounds), and immiscible with hydrocarbons. Therefore requires clean up or processing for further use.
Gasification		700-1200	50	<50		Seconds to minutes	10	5% tar (5% water)	85	Syngas, Ash/char	Methanol, hydrogen, syn-diesel	Multiple pathways for syngas. Can be transported and combusted in gas boilers or modified gas engines. Less flue gas produced.	Syngas contains condensable tars which can be problematic in cogeneration
Combustion		850-1000	200	<40		Seconds to minutes	5		95	Heat energy, ash		Maximum energy release from biomass.	Energy must be consumed at point of combustion.
Anaerobic digestion (mesophilic)		37	0	85 to 97	n.a.	1 to 30 days	40	n.a.	60	Digested sludge, treated effluent	Composted potting mix, Liquid fertiliser	Ability to process high moisture biomass, reduced solids production	Biological process can be difficult to control and performance can be rapidly affected by changes in feed stock or contaminants.

[1] Percentage relative to theoretical stoichiometric oxygen requirements

[2] Due to insufficient data, the relative solid, liquid and gas yields from the Torreco process have been assumed based on results presented by Atienza-Martinez et al [24] for torrefaction of sewage sludge at 320°C for 3.6 minutes.

[3] Applies similarly to all technologies producing biochar, bio-oil and bio-solids streams.

5.0 Technical review of torreco process

In order to better define the inputs to the cost benefit analysis for a demonstration scale torrefaction project based on the Torreco process, it was first necessary to undertake a detailed review of the outcomes presented in the ideas* report regarding the torrefaction of manure and paunch from the large beef processing facility in Queensland and ADS from the large beef processing facility in NSW.

Torrefaction conditions

As outlined in Table 2, the processing conditions that Torreco have used to torrefy the waste samples are unconventional in that the heating rates are faster (up to 90°C/min vs <50°C/min), the feed moisture content is higher (up to 90%w/w vs <20%w/w), the process temperature is higher (370°C to 385°C vs 200°C to 300°C), and the solids residence time is lower (4 to 8 min vs 30 to 60 min). As discussed previously, torrefaction/pyrolysis conditions are known to have a distinct impact on the characteristics of the solid, liquid and gaseous fractions produced. Therefore the performance of the torrefied material as a coal substitute or biochar-like soil conditioner/fertiliser product may not be very well described by the existing literature and industry experience with products derived from torrefaction using traditional means. The temperature of the Torreco process is particularly unusual and only one other (non peer-reviewed) reference was found for torrefaction of biomass in this temperature range [13].

For the purposes of the cost benefit analysis, it has been assumed that the torrefied product will be suitable for use as either a coal substitute or a biochar-like material but it is recommended that these properties are confirmed through further testing.

Mass and energy balance

As indicated in the note that accompanies Table 2, there was not sufficient data presented in the ideas* report to allow for closure of the mass and energy balance around the torrefier. Specifically, the starting biomass concentration within each of the torrefied feeds was not determined, nor was the amount and calorific value of the torrgas produced. The calorific value of the starting biomass was also not determined, while the gross calorific values (GCVs) presented for the torrefied biomass were calculated using a formula that requires quantification of the carbon, nitrogen, hydrogen and oxygen content of the fuel source. The oxygen content, which would have the effect of reducing the GCV, was not determined for the torrefied materials assessed. The true GCVs for the latter materials are therefore likely to be lower than those presented in the ideas* report.

The lack of data meant that, in order to undertake the CBA, it was necessary to assume values for the relative solid, liquid and gas yields from the Torreco process. The novelty of the processing conditions, however, also meant that there was very little data within publicly available literature to draw upon. Under typical processing conditions the percentage of the input biomass that is volatilized to torrgas and condensable material is around 25%w/w to 30%w/w. A study conducted by Atienza-Martinez et al [24] on the torrefaction of sewage sludge, however, suggests that the Torreco processing conditions described may favour high torrefied solids production rates – a scenario which is preferable when looking to maximize the value of the torrefied product as a bio-based coal substitute or fertilizer. The yield assumptions, presented in Table 2 as 90% solid, 6% condensable liquid and 4% syngas, have therefore been based on results presented by Atienza-Martinez et al for torrefaction of sewage sludge at 320°C for 3.6 minutes[24]. With respect to the GCV of the feed to the demonstration scale torrefaction system, a value of 21 GJ/ton was assumed and derived from an equal mass contribution (1/3) within the feed of grain fed paunch, grass fed paunch and manure using the GCV numbers presented in the report (i.e. Combined GCV = 24.3/3 + 23.7/3 +14.8/3 GJ/ton).

It should be noted that each of these assumptions is likely to have a positive impact on the economics of the project. It is recommended that further laboratory scale testing is undertaken using the relevant meat processing wastes in order to verify these assumptions and adjust the outputs of the CBA according to any differences seen

Capital estimate

The capital estimate of $2.7 million that was presented in the ideas* report for a two wet ton per hour torrefaction system was reviewed and found to lie within the accuracy range expected at the concept stage. This estimate, however, does not consider the potential need for tail gas scrubbing to handle possible odor issues. For scenarios where all or part of the torrefied material is to be sold as a granulated biochar or fertiliser product, the additional expense of a 6,000 ton per year granulation facility is estimated at $2.1 million. The estimate for the granulation facility is an installed price based on budget equipment pricing provided by FEECO International Australasia and adjusted for scale.

For the CBA it has been assumed that the cost of a granulation facility is required for the both the scenario where the torrefied material is used to provide 20% of facility's coal energy needs (as the remainder is to be sold as granulated biochar) and that the torrefied material used as a coal substitute can be used in existing boilers without modification. As discussed in AMPC report A.ENV.0111 there are numerous issues that may be encountered within boilers utilizing biomass-derived fuels (i.e. differences in ash fusion/melting temperatures which cause fouling of boiler tubes, high particulate carry-over, and increased corrosion) and it is therefore recommended that this latter assumption be verified through further testing [5].

Operating and maintenance expense estimate

The operating expense estimates submitted by ideas* are believed to be underestimated both in terms of the power and heating costs required to the run the process. In particular, there is a heavy reliance on the availability of waste heat from the exhaust of existing boiler systems which Lycopodium believes to be implausible due to limitations around the temperature of the exhaust gases and potential impact on boiler operations.

With respect to the availability of waste heat, boilers are typically designed to maximize thermal efficiency and therefore installations attempt to extract as much heat as possible which results in low stack temperatures – typically 200°C to 300°C. Due to potentially aggressive corrosion issues, however, stack temperatures must be kept high enough to avoid condensation of water vapors. For coal fired boilers, due to the presence, even in low quantities, of sulfurous compounds within the coal (which act to raise the dew point temperature and increase corrosion potential due to acids formed), the lowest stack temperature that is usually recommended is 200°C. Assuming then, that the stack temperature is actually running significantly above 200°C then there is potential for the torrefaction process to make use some of this heat but in some senses it isn't really 'free' as the plant could also elect to install an economizer on this exhaust system to help pre-heat the feed water to boiler and enhance the efficiency. Given that the Torreco process aims to operate at 370°C to 385°C, the potential to use waste heat is further limited as the boiler exhaust is very unlikely to be able to supply heat at these temperatures unless the existing boiler is operating very inefficiently. It is possible that the torrgas produced could be burnt to provide additional heating for the process and potentially make up some of the shortfall but without information regarding volumes produced and calorific values it is difficult to quantify.

For the purposes of the CBA it was assumed that the very best that could be achieved was that 50% of the heat required for the torrefaction process was derived from a combination of waste heat and torrgas. Whether this is truly possible would require further analysis of the boiler arrangement at a target demonstration site and a better understanding of the energy value of the torrgas produced from the process.

With respect to power consumption, based on prior experience with similar motorized systems and comparison with a similar system at larger scale, Lycopodium's engineers believe that the power consumption figures presented for the torrefaction process and associated balance of plant are somewhat low. A system built by Agri-Tech Producers LLC which can process approximately 10 wet tons per hour (i.e. five times the size of the process considered) and contains similar unit operations requires approximately 225 kW of power to run it [25] while 10 kW has been allowed for the Torreco system. Lycopodium believes that the energy consumption would be closer to 45 kW and this is the value that has been used for the majority of scenarios considered within the CBA. For the sake of comparison, the 10 kW figure has also been used in a couple of scenarios to demonstrate the impact on the value proposition.

In undertaking the CBA for the torrefaction technology, it was assumed that for the scenarios where torrefied material was used to replace 20% of the coal demand at the site that there was no grid-supplied natural gas supply available (or they would already be using it) and therefore the additional energy required to run the torrefaction process was supplied with LPG. For scenarios where only a biochar product was produced then it was assumed that natural gas could be available and this was what was used to supply the remainder of the process energy requirements.

Greenhouse gas emissions abatement potential

Lycopodium reviewed the GHG emissions abatement potential of the torrefaction project and would agree with the assessment made by ideas* that the worst case emissions factor for combustion of the torrefied material would be 5.20 kg CO_2-e/GJ. Given that bituminous coal has an emissions factor of 88.43 kg CO_2-e/GJ [26] then the overall abatement potential for replacement of coal with torrefied material is approximately 83.23 kg CO_2-e/GJ.

The Scope 1 and 2 emissions factors used in undertaking the CBA are summarised in Table 3. Avoided emissions from the reduction in nitrogen application through the use of torrefied material as a fertiliser were not considered.

Table 3. Summary of Emissions Factors used in CBA (Include CO_2, CH_4 AND N_2O factors)

DESCRIPTION	VALUE	UNITS	REFERENCE
Coal Combustion	88.43	kg CO_2-e/GJ	[26] Table 2.2.2
Composting of Solid Wastes	0.046	t CO_2-e/t waste treated	[26] Section 5.2.2
Combustion of Biochar	5.2	kg CO_2-e/GJ	[26] Table 2.2.2
Combustion of Natural Gas	51.33	kg CO_2-e/GJ	[26] Table 2.3.2A
Combustion of LPG	59.9	kg CO_2-e/GJ	[26] Table 2.4.2A
Power Usage	0.82	kg CO_2-e/kWh	[26] Table 7.2 QLD grid

The 'sale' value for any Australian Carbon Credit Units (ACCUs) generated under this project within the Emissions Reduction Fund has been assumed to be $6/ t CO_2-e. The contract length has been assumed as 5 years.

Solid waste availability

The 2 wet ton per hour demonstration scale system that is put forward in the ideas* report would require a feed at approximately 44 wt% solids to produce 20 tons per day of torrefied material. Operating for 24 hours per day for 250 days per year this equates to a requirement of approximately 5,280 ton per year of dry organic material ideas* have assumed that the feed consists of one third each of grain fed paunch waste, grass fed paunch waste and manure. Therefore the total amount of paunch waste required per year is approximately 3,520 dry tons and approximately 1,760 dry tons of manure. It is recommended that the availability of these volumes of waste materials are available at the selected demonstration site and, if necessary, the demonstration system be scaled back to suit.

For the purpose of conducting the CBA it has been assumed that the requisite amounts of waste material are available on site.

6.0 Cost benefit analysis of Torreco process

Cost benefit analyses of various scenarios for converting meat processing solid waste to energy and/or agricultural products were conducted on the basis of earnings before interest, taxes, depreciation, and amortization (EBITDA). Three different technology options were compared in the CBA – torrefaction, direct co-combustion (paunch waste only), and anaerobic digestion (paunch waste only). The last two scenarios were based on information supplied in previous industry reports for projects A.ENV.0099 [6] and A.ENV.0110 [3]. Due to the negative results of previous cost benefit studies into gasification and slow pyrolysis of solid meat processing wastes [5] these two technologies were not considered here.

Many of the general assumptions made in these analyses have been described in Section 5 or as a note to Table 4. Further assumptions made include:

- cost of waste disposal is $15/ton at 44wt% solids (i.e. matches feed concentration and volume sent to torrefaction system). Based on previous values used in MLA/AMPC reports [3]
- cost/value of electricity used/generated is $0.17/kWh
- cost of natural gas is $7/GJ
- cost of LPG is $2/kg
- no cost for disposal of condensable material from torrefaction process
- 250 operating days per annum
- plant lifetime is 20 years
- discount rate is 7%
- capital spent in first year and 100% production realised from Year 2 onwards
- facility processes approximately 1300 head per day and is capable of producing waste quantities required.

In scenarios where it is assumed that some of the torrefied material produced is used as a bio-based coal substitute, the revenue from the torrefied material (either as savings to existing coal usage on-site or through sale into the solid energy market) is determined on a calorific basis. That is, the value of torrefied material is determined based on the number of tons of bituminous coal replaced. For example, if the yearly production of torrefied material was 5,106 tons then, because of the difference in energy content (21 GJ/t torrefied material versus 27 GJ/t bituminous coal) the equivalent amount of coal that would be displaced by this product would be approximately 3,971 ton per year. It is for the latter tonnage of material that the $/t value of the torrefied material has been applied.

The range of potential values for the torrefied biomass as a coal substitute was based on, a) current thermal coal prices of approximately $80/ton [27] and b) value for coal assumed in previous AMPC reports at around $120/ton [3, 5].

The range of potential values for the torrefied biomass as a biochar/fertilizer substitute was based on, a) low value presented in ideas* report of $45/ton, b) high value presented in ideas* report of $100/ton and, c) value for biochar assumed in previous AMPC report of $300/ton [5].

The outcomes of different scenarios run as part of the CBA are presented in Table 4 while the effect of the value of the biochar on the overall payback period for the project is shown in

Figure 7. The key points to note from these CBA comparisons are:

- the commercial viability of the Torreco technology is highly dependent on both the cost of delivering energy to the process and the value that can be realised from the torrefied material.
- the torrefaction system compared favourably against pyrolysis, gasification, combustion and anaerobic digestion of paunch wastes when similar assumptions regarding the value of coal ($120/ton), biochar ($300/ton) and ACCUs ($23/ton) were used.
- the estimated greenhouse gas (GHG) abatement potential for the scenario in which the torrefied biomass is used to replace 20% of a site's coal-based energy requirements is approximately 2,091 T (CO_2-e) per year. When the torrefied material is used only as biochar for soil conditioning the GHG abatement potential drops to about 160 T (CO_2-e) per year.
- assuming that the torrefied material is used to substitute 20% of a site's coal-based energy requirements while the rest is sold as biochar the 20-year net present value (NPV) ranges from -$5,063,656 to -$1,673,831, the internal rate of return (IRR) ranges from -0.4% to 1.8% and the simple payback period ranges from 15.5 to 19.1 years depending on the value realised for the biomass and ACCUs.
- assuming that all of the torrefied material is used as a biochar product the NPV ranges from -$3,855,407 to $11,239,034, the IRR ranges from -5.0% to 32.2% and the simple payback period ranges from 3.1 to 36.0 years depending on the value realised for the biomass and ACCUs. Biochar values in order of $330 per ton are required to reduce the simple payback period to less than 3 years.

From information presented in Table 4 it is also shown that the average cost of producing a torrefied biomass from meat processing waste is approximately $25 per ton of product when it is assumed that the majority of heat to drive the process is provided by the exhaust gas from existing boilers and that power required is 10 kW. If natural gas or LPG are required to provide 50% of the system's heat needs and the system requires 45 kW of power to run, then the cost of producing the torrefied biomass goes up to approximately $43 per ton and $93 per ton respectively. If natural gas is used to supply 100% of the heating needs then the cost is $54 per ton.

Table 4. Summary of cost benefit analysis scenario outcomes.

SCENARIO DETAILS															
Scenario No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Technology Employed		Torreco Process	Torreco Process	Torreco Process	Torreco Process	Torreco Process	Torreco Process	Torreco Process	Torreco Process	Torreco Process	Torreco Process	Raw Paunch Co-firing[1]	Raw Paunch Co-firing[1]	Anaerobic Digestion[2]	Anaerobic Digestion[2]
Scenario Description		Co-firing 20%	Co-firing 20%	Co-firing 20%	Co-firing 20%	Biochar only	Biochar only	Biochar only	Biochar only	Biochar only	Biochar only	New boiler	New boiler	Biogas for heat	Biogas for CHP
Value as Coal Substitute		Low	Low	High	High	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	High	Low	High	High
Value as Biochar		Low	Low	Medium	Medium	Low	Medium	Medium	Medium	High	High	n.a.	n.a.	$150/t biosolids	$150/t biosolids
ERF Income included		Yes	No	No	Yes	No	No	No	No	No	No	Yes ($23/t, 20 yr contract)	Yes ($6/t, 5 yr contract)	No	Yes
Torrefaction Heat Source		Waste Heat	50% LPG	50% LPG	50% LPG	100% Nat. Gas	100% Nat. Gas	50% Nat Gas	50% Nat Gas	100% Nat. Gas	50% Nat. Gas	n.a.	n.a.	n.a.	n.a.
Low/High Power Use Assumption		Low	High	High	Low	High	High	High	Low	High	Low	n.a.	n.a.	n.a.	n.a.
INPUTS	**Units**														
Capacity of waste processing facility	T (wet)/hr	2	2	2	2	2	2	2	2	2	2	1.67	1.67	14,814.8	14,814.8
Operational hours	hrs/day	24	24	24	24	24	24	24	24	24	24	10	10	24	24
Operating days per year	days/yr	250	250	250	250	250	250	250	250	250	250	250	250	365	365
Energy use of waste processing facility	kW	10	45	45	10	45	45	45	10	45	10	n.a.		52.4	52.4
Energy content - coal	MJ/kg	27	27	27	27	27	27	27	27	27	27	20	20	27	27
Energy content - biochar	MJ/kg	21	21	21	21	21	21	21	21	21	21				
Value of torrefied material as coal substitute	$/T	$80	$80	$120	$120	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	120	80	120	120
Value of torrefied material as biochar	$/T	$45	$45	$100	$100	$45	$100	$100	$100	$300	$300			150	150
Sawdust price	$/T	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	35	35		
Value of ACCUs	$/T CO_2-e	6	n.a.	n.a.	6	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	23	6	0	0
ERF ACCU sale contract length	yrs	5	n.a.	n.a.	5	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	20	5		
CAPEX	$	$4,800,647	$4,800,647	$4,800,647	$4,800,647	$4,800,647	$4,800,647	$4,800,647	$4,800,647	$4,800,647	$4,800,647	$1,975,000	$1,975,000	$10,961,826	$11,759,123
OPEX & Maintenance Costs	$/yr	$152,780	$501,006	$501,006	$442,287	$303,817	$303,817	$244,609	$187,133	$303,817	$187,133	$4,800	$4,800	$262,436	$324,480
OUTPUTS	**Units**														
Torrefied Material Produced	T/yr	5,106	5,106	5,106	5,106	5,106	5,106	5,106	5,106	5,106	5,106				
Torrefied Material used to replace coal use	T/yr	1,105	1,105	1,105	1,105										
Estimated GHG abatement	T (CO_2-e)/yr	2,091	2,091	2,091	2,091	2,091	160	160	160	160	160	7,645	7,645		
Value of carbon abatement	$/yr	$12,545			$12,545	$12,545						$175,833	$45,869		
Revenue from biochar/biosolids	$/yr	$180,073	$180,073	$400,162	$400,162	$229,787	$510,638	$510,638	$510,638	$1,531,915	$1,531,915			$685,714	$685,714
Waste disposal costs avoided	$/yr	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$96,430	$96,430	$180,000.00	$180,000
Power costs avoided	$/yr														$703,160.31
Coal costs avoided	$/yr	$88,381	$88,381	$132,571	$132,571							$348,000	$232,000	$101,989	$44,195
Sawdust costs	$/yr											$159,250	$159,250		
Average cost of processing biomass	$/T	$29.92	$98.11	$98.11	$86.61	$59.50	$59.50	$47.90	$36.65	$59.50	$36.65	$56.57	$56.57	$57.41	$70.98
Average value of converting biomass[3]	$/T	$90.28	$87.82	$142.03	$142.03	$80.25	$135.25	$135.25	$135.25	$335.25	$335.25	$213.88	$129.07	$211.69	$352.86
Net yearly income/savings	$/yr	$308,219	-$52,552	$224,273	$282,992	$105,971	$386,822	$446,029	$503,506	$1,408,098	$1,524,782	$1,524,782	$210,249	$705,267	$1,288,590
COST BENEFIT ANALYSIS OUTPUTS															
Net Present Value	$	-$1,582,471	-$4,994,209	-$2,393,345	-$1,826,148	-$3,425,752	-$750,107	-$178,197	$376,995	$9,114,848	$10,241,950	$2,560,965	-$82,206	-$3,432,213	$1,457,218
Internal Rate of Return	%	1.8%	n.a.	-1.6%	0.8%	-6.6%	4.7%	6.5%	8.1%	29.1%	31.6%	23%	6%	2%	9%
Simple Payback Period	yrs	15.58	n.a.	21.41	16.96	45.30	12.41	10.76	9.53	3.41	3.15	4.33	9.39	15.54	9.13

[1] Scenario 11 details sourced directly from AMPC report A.ENV.0110. Scenario 12 is essentially the same but applies current estimates regarding value of coal and ACCUs and incorporates shorter projected contract lengths for ACCU purchase under ERF.

[2] Two Stage Anaerobic Digestion, 4 day residence time stage one, 20 day residence time stage two, $1000/m^3$ vessels, $500/m^3$ ancillaries, 0.2 kWh/m^3.d power consumption, 5% maintenance, 0.35 FTE operator at $75,000 p.a,, 0.25 m3/kg VS methane production, 0.9 methane conversion factor, 0.86 VS/TSS, 64% methane in biogas, 40% electrical energy efficiency, 65% capture of residual heat energy, 60% TSS reduction, 30% moisture content in digested solids.

[3] Includes value derived from sale of product, waste disposal costs avoided, power costs avoided, coal costs avoided and revenue from ACCUs.

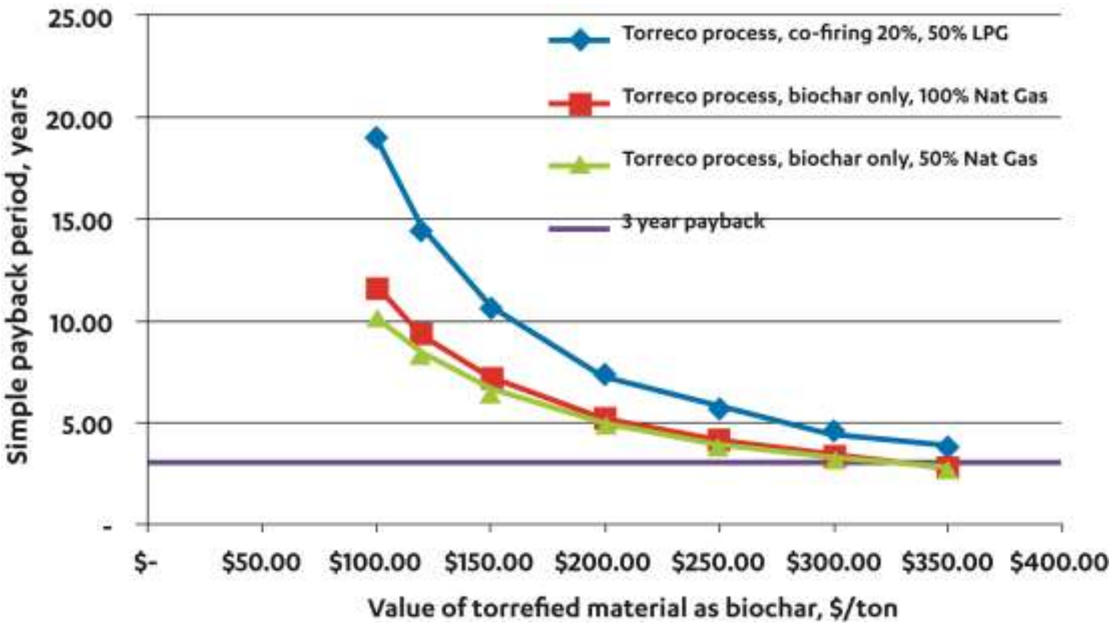


Figure 7. Effect of sale price of torrefied material as biochar on simple payback period for the project.

7.0 Conclusions and recommendations

The Torreco process utilizes novel torrefaction conditions which make it difficult to assess alongside conventional expectations for the project outputs. Given that there was also a lack in the information captured during recent laboratory trials which prohibited an accurate mass and energy balance it is therefore recommended that laboratory trials are repeated and this information is captured. With respect to capital the information supplied in the ideas* report was within the level of accuracy to be expected at this stage of project development. It is believed that the operational costs, however, have been underestimated.

A cost-benefit analysis of the Torreco process based on some necessary (potentially favorable) assumptions concluded that the value proposition of the Torreco process is highly dependent on both the cost of delivering energy to the process and the value that can be realized from the torrefied material. However, when similar assumptions regarding the value of coal, biochar and ACCUs) were used, the Torreco system compared favorably against pyrolysis, gasification, combustion and anaerobic digestion of paunch wastes. The estimated greenhouse gas (GHG) abatement potential for the scenario in which the torrefied biomass is used to replace 20% of a site's coal-based energy requirements is approximately 2,091 T (CO_2-e) per year. When the torrefied material is used only as biochar for soil conditioning the GHG abatement potential drops to about 160 T (CO_2-e) per year.

Assuming that the torrefied material is used to substitute 20% of a site's coal-based energy requirements while the rest is sold as biochar the 20-year net present value (NPV) ranges from -$5,063,656 to -$1,673,831, the internal rate of return (IRR) ranges from -0.4% to 1.8% and the simple payback period ranges from 15.5 to 19.1 years depending on the value realised for the biomass and ACCUs. Assuming that all of the torrefied material is used as a biochar product the NPV ranges from -$3,855,407 to $11,239,034, the IRR ranges from -5.0% to 32.2% and the simple payback period ranges from 3.1 to 36.0 years depending on the value realised for the biomass and ACCUs. Biochar values in order of $330 per ton are required to reduce the simple payback period to less than 3 years.

Recommended further steps include:

- Repeat laboratory scale trials on typical meat processing solid wastes to confirm:
  - percentage volatilization of organic material across torrefaction process
  - higher and lower heating value of the torrefied product produced
  - torrgas composition and calorific value
  - input energy requirements
  - the ability of the torrefied material to meet the fuel specifications for the existing boiler at the proposed demonstration site.
- Confirm the following regarding the proposed demonstration site:

- quantities of the various forms of solid waste produced and that these are in line with Torreco's assumption and produced at a sufficient amount overall to run a 2 wet ton per hour torrefaction system
- availability of waste heat of suitable quality and quantity to drive the Torreco process and, if not, the ability to provide access to an alternative energy source such as LPG or natural gas
- current and projected purchase price of coal
- current and projected coal usage
- current coal delivery system to boiler, whether any modifications would be required to accommodate torrefied biomass and, if so, what these are likely to cost
- current waste disposal methods and costs.

- Re-evaluate the viability of the demonstration scale project based on the outcomes of the previous two groups of activities.
- Potentially apply for co-funding from industry groups or the government in order to improve the project economics, reduce the project risk and thereby enable a demonstration scale system to be built which can confirm process costs, outputs and the market value of the torrefied material produced.

8.0 REFERENCES

1. Stefanutti, R., *Torrefaction of Animal Waste for Beneficial Use, Reduced Emissions and Cost Reduction*, A.M.P.C. Ltd, Editor. 2014.
2. MLA, *Waste Solids Environmental Best Practice Manual*. 2012, Australian Meat Processor Corporation.
3. Bridle, T., *Use of Paunch Waste as a Boiler Fuel*, M.L.A. Limited, Editor. 2011: North Sydney.
4. Bridle, T., *Waste to energy: Alternative uses for paunch waste and DAF sludge/Waste pyrolysis review*, M.L.A. Limited, Editor. 2011.
5. Bridle, T., *Pilot testing pyrolysis systems and reviews of solid waste use on boilers*, M.L.A. Limited, Editor. 2011, Meat & Livestock Australia Limited: North Sydney.
6. Jensen, P., Batstone, D., *Solids digestion pilot study at Teys Bros Beenleigh (Extension)*. 2012, Meat & Livestock Australia Limited.
7. MLA, *Pilot testing pyrolysis systems and reviews of solid waste use on boilers*. 2011.
8. Schorr, C., M. Muinonen, and F. Nurminen, *Torrefaction of Biomass*. 2012. p. 1-55.
9. Bergman, P.C.A., et al., *Torrefaction for biomass co-firing in existing coal-fired power stations*, ECN, Editor. 2005.
10. Bergman, P.C.A. and J.H.A. Kiel, *Torrefaction for biomass upgrading*, in *14th European Biomass Conference & Exhibition*. 2005, Energy research Centre of the Netherlands (ECN): Paris.
11. Nunes, L.J.R., J.C.O. Matias, and J.P.S. Catalão, *A review on torrefied biomass pellets as a sustainable alternative to coal in power generation.* Renewable and Sustainable Energy Reviews, 2014. **40**(0): p. 153-160.
12. Tumuluru, J.S., et al., *A Review on Biomass Torrefaction Process and Product Properties*, in *Symposium on Thermochemical Conversion*. 2011, U.S. Department of Energy: Oklahoma State University, Stillwater, OK.
13. Hopkins, C., *Torrefaction to Improve Biomass for Energy and Biofuels Production and Carbon Sequestion* in *International Bioenergy & Bioproducts Conference*. 2011, NC Cooperative Extension: Atlanta.
14. Sohi, S., et al., *Biochar, climate change and soil: A review to guide future research*, E. Krull, Editor. 2009, CSIRO Land and Water Science. p. 64.
15. Sohi, S.P., et al., *A Review of Biochar and Its Use and Function in Soil*, in *Advances in Agronomy*, D.L. Sparks, Editor. 2010, Elsevier Inc. Academic Press: Burlington. p. 47-82.
16. Gaskin, J.W., et al. *Potential for Pyrolysis Char to Affect Soil Moisture and Nutrient Status of a Loamy Sand Soil*. in *Georgia Water Resources Conference*. 2007. Athens, Georgia: Georgia Institute of Technology.
17. Di Blasi, C. and M. Lanzetta, *Intrinsic kinetics of isothermal xylan degradation in inert atmosphere.* Journal of Analytical and Applied Pyrolysis, 1997. **40–41**(0): p. 287-303.
18. Dhungana, A., A. Dutta, and P. Basu, *Torrefaction of non -lignocellulose biomass waste.* The Canadian Journal of Chemical Engineering, 2012. **90**(1): p. 186-195.
19. Blackwell, P., G. Riethmuller, and M. Collins, *Biochar Application to Soil*, in *Biochar for Environmental Management: Science and Technology*, J. Lehmann and S. Joseph, Editors. 2009, Earthscan: London, UK. p. 207.

20. Tay, V., et al., *Leaching properties of a biochar derived from a Western Australia pine plantation*, in *Chemeca 2013: Challenging Tomorrow*. 2013, Engineers Australia: Barton, ACT. p. 857-862.
21. Sims, R.E.H., *The Brilliance of Bioenergy: In Business and In Practice*. 2013: Taylor & Francis.
22. Bridgwater, A.V., P. Carson, and M. Coulson, *A comparison of fast and slow pyrolysis liquids from mallee.* International Journal of Global Energy Issues, 2007. **27**(2): p. 204-216.
23. Ronsse, F., et al., *Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions.* GCB Bioenergy, 2013. **5**(2): p. 104-115.
24. Atienza-Martínez, M., et al., *Sewage sludge torrefaction in a fluidized bed reactor.* Chemical Engineering Journal, 2013. **222**(0): p. 534-545.
25. www.agri-techproducers.com. *Torre-Tech 5.0 Specifications Sheet (corrected)*. 2014.
26. *National Greenhouse and Energy Reporting System Measurement*, I. Department of Industry, Climate Change, Science, Research and Tertiary Education, Editor. 2013, Commonwealth of Australia. p. 665.
27. Infomine. *1 Month Coal Prices and Price Charts*. 2014; Available from: http://www.infomine.com/investment/metal-prices/coal/1-month/.