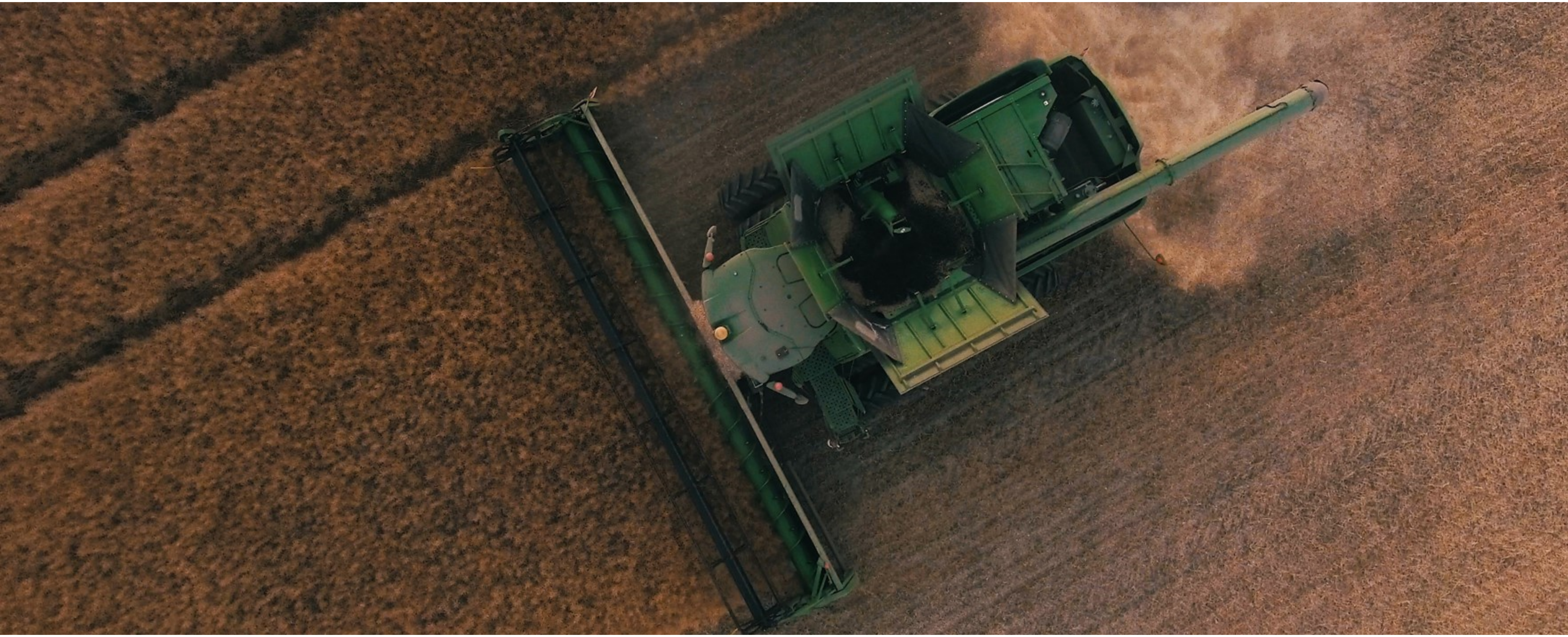
Advanced Thermal Treatment for Agricultural Residues

Agriculture Victoria, Department of Energy, Environment and Climate Action

12 September 2023



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This report has been prepared specifically for and under the instructions and requirements of the Department of Energy, Environment and Climate Action ("the Client" or DEECA) under an Appointment dated 16 March 2023 in connection with the development of a financial assessment tool to assess thermal treatment options for agricultural residues in Victoria (the "Project").

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Executive Summary

NEED

Arup was engaged by Agriculture Victoria (DEECA) to develop a financial tool for Victorian Primary Producers aimed at assessing the advanced thermal treatment (gasification and pyrolysis) of agricultural residues. The Australian Biomass for Bioenergy Assessment uncovered hundreds of thousands of tonnes of agricultural residues that are and could be made available for generating renewable energy on-farm.

Prospective agricultural residues for gasification or pyrolysis include straws (from cereal crops such as barley, corn, rice, wheat) and other harvest residues (such as grains, seeds, shells, husks, bagasse, pulp). Woody residues, referring to the woody parts of trees such as trunks and branches, from horticulture and forestry can be used to supplement more seasonal agricultural residues and are beneficial due to the minimal presence of sulphur and heavy metals.

TECHNOLOGY REVIEW

A literature review was conducted to identify commercially available gasification and pyrolysis technologies, their feedstock requirements, equipment capacities and efficiencies (yields), capital and operating costs, and the value of marketable products, for technologies available globally and within Australia. The data provided default or benchmark values for the tool so that farmers can quickly assess the potential value of their residues with respect to:

- Energy cost savings via heat and/or electricity generation
- Enhanced soil health from biochar application
    - Reduced dependence on fertilisers
    - Increased water retention
    - Increased soil carbon
- Additional revenue streams
    - Wood vinegar (pyrolysis by-product) helps plant growth and acts as natural pesticide
    - Carbon credits (e.g., CO_2 Removal Certificates)

Adding biochar to soil produces net negative emissions because carbon dioxide taken from the atmosphere during plant growth is stored as soil carbon (0.3 – 1.4 t-CO_2 per tonne of biomass treated, based on a life-cycle assessment compared burning crop residues).

MARKET ENGAGEMENT

Stakeholder input into the development of the financial tool targeted technology providers, users and potential users. Input was sought from Victorian farmers (target end users of the tool), Australian technology providers, and representatives of industry groups. The input was garnered via an online survey and followed up by targeted interviews. The engagement found rising interest in using crop and biomass residues to:

- Offset high or volatile energy and gas prices
- Provide on-demand renewable electricity as a competitive alternative to solar and wind
- Benefit from lost opportunity for converting agriculture resource into energy
- Enable more environmentally sustainable solutions for agriculture residue management
- Contribute to both economic and environmental goals.

Gasifier and pyrolyser capacities, along with indicative costs and product yields were supplied by technology providers, corroborating the data reported in the literature. Case studies for recent Australian projects have also been outlined. The main challenge with gasification and pyrolysis projects from technology providers was seen to be securing a long-term supply of biomass feedstock, which needs to be relatively dry (less than 25% moisture) and sized to approximately 5-20mm prior to gasification or pyrolysis.

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1. Introduction

Purpose and Methodology

The main purpose was to develop a financial tool to help farmers assess advanced thermal treatment of their agricultural residues to reduce energy costs, add revenue and improve environmental outcomes.

Purpose

Arup was engaged by Agriculture Victoria (DEECA) to develop a financial tool engaging with stakeholders for Victorian Primary Producers. This is aimed at assessing the advanced thermal treatment (gasification and pyrolysis) of agricultural residues.

Prospective agricultural residues for gasification or pyrolysis include straws (from cereal crops such as barley, corn, rice, wheat) and other harvest residues (such as grains, seeds, shells, husks, bagasse, pulp). Woody residues, referring to the woody parts of trees such as trunks and branches, from horticulture and forestry can be used to supplement more seasonal agricultural residues and are beneficial due to the minimal presence of sulphur and heavy metals.

Study methodology

A technology review, stakeholder engagement and life cycle analysis were undertaken to inform the design and functionality of the financial tool. The approach taken is outlined below. The detailed findings and analyses are described in the body of this report.

Technology Review

A literature review was conducted to identify commercially-available gasification and pyrolysis systems, their feedstock requirements, equipment capacities and efficiencies (yields), capital and operating costs, and the value of marketable products, for technologies available globally and within Australia.

Stakeholder Engagement

Stakeholder input into the development of the financial tool was garnered via an online survey, followed up by targeted interviews, with Victorian farmers (targeting end users of the tool), Australian technology providers, and representatives of industry groups.

Gasifier and pyrolyser capacities, along with indicative costs and product yields were sought from technology providers, to corroborate the data reported in the literature. The main challenges and drivers of gasification and pyrolysis projects was also sought from technology providers.

Life Cycle Analysis

A lifecycle carbon assessment of gasification and pyrolysis of residues compared burning crop residues in the field was undertaken. Two base scenarios were assessed:

1. Gasification and electricity generation with heat recovery; and
2. Pyrolysis to produce biochar and bio-oil (or wood vinegar).

The Financial Tool

The feasibility assessment tool will enable Agriculture Victoria, service providers of primary producers, and relevant experts to understand the potential opportunity to undertake feasibility assessments for individual farms for onsite gasification and pyrolysis of agricultural residues and/or wood waste.

The tool was developed with a dashboard to act as the main user interface, presenting key outputs and allowing users to change key inputs to better understand the key drivers of a processed project. It also includes sections for more knowledgeable users to input project specific parameters, and calculation tabs that profile out expected cashflows in terms of capital expenditure (capex), operational expenditure (opex), lifecycle costs and revenues, and viability metrics such as payback period, rate of return and emissions abated.

A User Guide was incorporated in the tool that provides step-by-step instructions for how users can input key data, run scenarios, and interpret results.

Project context

There is opportunity for horticultural and other broadacre producers to produce valuable energy products by leveraging emerging gasification and pyrolysis technology and currently underutilised biomass material such as straw and other agricultural residues.

Victorian agriculture industry overview

Importance of the Victorian agriculture industry

As Australia's second largest agricultural producer, Victorian gross value of agricultural production was around $15.9 billion in 2021-22 (22% of the national gross value of agriculture production)[6]. There are over 150,000 people employed across the agriculture production and food and beverage manufacturing production sectors[1].

Grain crops, such as wheat, barley and canola, represent the largest contributor to the gross value of agricultural production, delivering 20% of the total value to the Victorian economy ($3.55 billion total in 2020-21)[1]. Grain production is also the third largest employer in the agricultural sector, with more than 4,000 businesses employing nearly 10,000 people across the state.

Victorian grain producers provide a sizeable contribution to the state's economy, but there is significant opportunity for them to capture even greater value for their products. By capitalising on advanced thermal treatment technologies, underutilised biomass material such as excess straw and other agricultural residues can be converted into synthesis gas (syngas) to generate energy (electrical/thermal) or chemicals. Advanced thermal treatment technologies include combined heat & power (CHP), Fischer-Tropsch synthesis, methanol synthesis and dimethyl ether (DME) synthesis.

Managing agricultural waste on Victorian cereal farms

Straw is a by-product of cereal plants after the grain and chaff have been removed. Victoria produces (on average) approximately 3.4 million dry tonnes of straw per year, as a by-product of grain (or cereal) crops[2, 3].

Crop stubble from the harvest of cereal crops includes straw, some of which preferably remains on the soil surface after harvest to help with[4]:

- protection from soil erosion,
- conservation of soil moisture, and
- conservation of organic matter to assist with crop yields.

However, excess crop stubble is an ongoing issue for farmers because it can obstruct sowing equipment and harbour weeds, pests and diseases[5]. To manage this issue, crop stubble is often burned, however this is problematic in terms of the smoke produced and the energy released from the straw being wasted.

Straw can also be utilised for animal bedding, animal feed, and for compost[4] or baled and compressed for export. There is scope to recover energy from this straw. Other dry agricultural residues, such as legume stubble, almond husks, and tree clippings, are also important biomass sources that could be exploited for energy. Conventional energy recovery is well established for bagasse, grape marc, almond husks and wood waste, typically by direct combustion of biomass in boilers to produce heat and steam. Large steam-based CHP systems, which burn grape marc (Australian Tartaric Products[8]) or almond husks (Select Harvest[9]), also have the capacity to produce electricity.

Managing wood waste and forestry residues

The Australian forestry industry generates millions of tonnes of wood residues every year as a by-product of harvesting and sawmilling operations. Harvest residues consist of stumps, branches, bark, crown material and tree heads and butts. They are typically left in forests to maintain forest and soil health for subsequent plantings but can also be burnt off.

There is limited information available regarding the amount of harvest residues currently produced in Australia. One contributing factor is that a significant portion of these residues are left in forests and therefore not included in estimates of log harvest or production.

Nevertheless, according to ABARES in Victoria it is estimated around 1.84 million tonnes (Mt) of harvest residues was available in 2016-17[10]. Sawmill residues are typically already utilised onsite or otherwise for other purposes[10] and have therefore been excluded from the total amount of woody biomass potentially available. Onsite uses for sawmill residues includes in a kiln for drying or other uses such as pulp and paper, landscaping, animal bedding, etc.

Besides having enormous potential as a resource, wood waste also offers other benefits such as its low ash content and high calorific value, which makes it a valuable option as a renewable energy source.

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Overview of gasification and pyrolysis

New technologies are providing opportunities for undervalued farm waste. Gasification and pyrolysis on farms can promote circular economy outcomes and deliver key benefits to Victorian producers such as energy savings, heat production, soil health, additional revenue streams, and a reduced environmental impact.

Gasification and pyrolysis technology overview

Technology overview

New technologies are emerging that allow farmers to realise non-traditional agricultural benefits by using agricultural residues to capture bioenergy. These advanced biomass thermal treatment technologies include pyrolysis and gasification, as well as more advanced thermochemical and thermo-catalytic processes.

In the case of crop stubble, instead of allowing undesirable smoke to be released when burning crops, the excess material can be treated in a controlled manner to produce useful bioenergy products. Gasification or pyrolysis of excess straw residues provides the opportunity for farmers to capture this energy, while contributing to soil health for improved productivity.

Pyrolysis is used to break down organic matter at relatively low temperatures (300-700ºC)[2, 6]. The process is completed without oxygen. The decomposition products are a mixture of syngas, bio-oil (pyrolysis-oil), and biochar[2].

Gasification is a process which produces primarily syngas and biochar via incomplete combustion of biomass[2, 3]. Gasification also produces a small amount of bio-oil[2]. Gasification takes place at temperatures greater than 750°C and with limited amounts of oxygen[2].

The conditions for gasification and pyrolysis (such as heating rate, temperature, residence time, humidity, oxygen, particle size) affect the relative proportions of gas, liquid, and solid fractions, and can be optimised to suit the application.

Potential beneficial reuses of straw on Victorian farms

Typical farming practices vary greatly by region, driven by factors such as rainfall and soil type. The amount of rainfall and soil type affect crop yields and farming practices (such as no-till, ploughing-in, burning). This in turn affects the availability of excess straw.

Around two-thirds of straw produced is collected, and 25-75% of this amount may be used for animal feed or bedding. Based on this, there is estimated to be up to ~1.7 Mt of straw per year available for gasification or pyrolysis[1]. This equates to ~23.8 PJ (~23.8 million GJ) of thermal energy compared with the 214 PJ of natural gas consumed in Victoria in 2020[8]. Annual residue quantities is dependent on several factors and varies from year to year based on crop yield, animal bedding and feed demands, other competing uses such as land application, as well as sporadic factors such as pestilence and disease outbreaks.

The use of gasification and pyrolysis on farms can deliver key benefits to Victorian producers such as[2]:

- Energy savings from heat or electricity generation
- Enhanced soil health from biochar application
- Additional revenue streams
- Reduced dependence on fertilisers
- Reduced environmental impact
- Increased soil carbon
- Wood vinegar is a by-product of pyrolysis and is considered as a natural pesticide.

Potential emissions reduction

Gasification and pyrolysis present an opportunity to reduce on-farm emissions due to:

- Avoiding emissions that would ordinarily result from usual methods of managing excess straw (e.g. burning)[2, 5].
- Decreasing electricity/gas consumption from the grid by utilising the valuable syngas product to generate electricity or heat[2].
- Using the produced biochar to reduce fertiliser consumption[2].

Victorian producers need the tools to understand how these technologies could impact their business

New and emerging technologies are presenting innovative solutions to tackling sustainable energy and climate challenges in the agriculture industry. Farm/business owners need to understand how these technologies may benefit their businesses were they to implement them, including an understanding of the financial and operational implications to them. A robust and easy-to-use tool is needed to ensure that Victorian producers have access to the information that they need.

> *" [There is] increasing interest amongst farmers in addressing climate change and utilising their wastes. Higher energy costs are also driving interest in on-farm energy production."*
>
> **Daryl Scherger, Victorian Bioenergy Network**

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Overview of gasification and pyrolysis

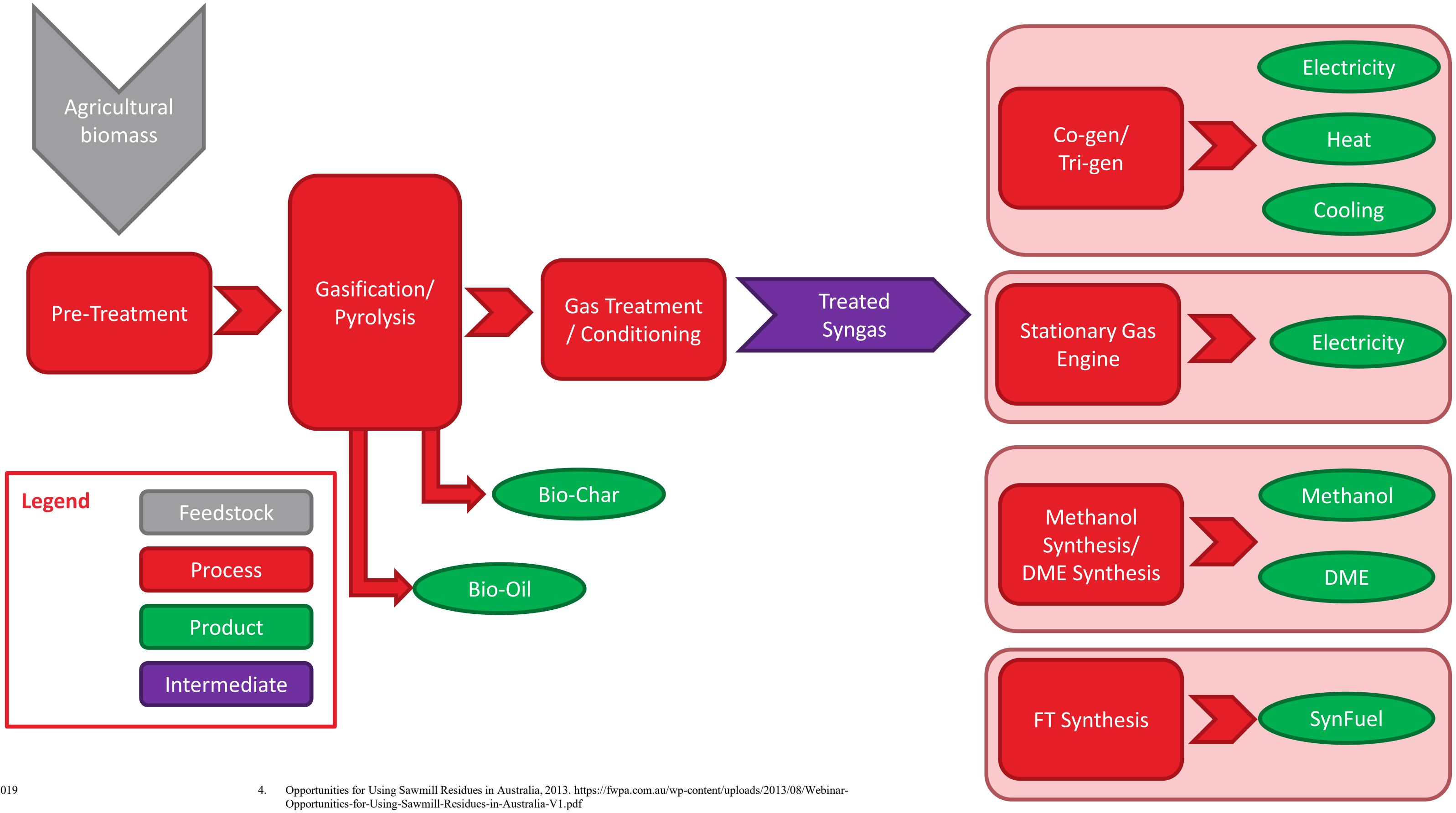
Pre-treatment of agricultural biomass and treatment of produced syngas from gasification/pyrolysis is important to producing a refined and useful syngas product. Syngas can be utilised for heat and electricity generation via CHP, as well as for production of chemicals and liquid fuels.

Gasification process overview

Gasification of agricultural residues captures energy, soil conditioning and circular economy benefits from the recovery of what otherwise might have been wasted agricultural by-products or residues. A process overview is shown adjacent. The following steps are involved to convert biomass into useful bioenergy products:

- **Pre-treatment** to improve biomass quality[1].
- **Gasification/Pyrolysis** which produces a mixture of syngas, biochar and bio-oil[2].
- **Gas treatment/conditioning** to remove undesired impurities and refine the syngas product.
- **Advanced thermal treatment** of the treated syngas for heat, cooling, and electricity generation, or for synthesis of methanol or liquid fuels[2, 3, 4].

This study seeks to explain these various components of the gasification and pyrolysis process and summarise key drivers and challenges these technologies face for on-farm implementation. Relevant commercial uptake examples of pyrolysis and gasification are also identified, both in Australia and internationally.



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2. Technology Review

Gasification and pyrolysis feedstock

Agricultural residues are sought-after biomass feedstocks for gasification due to their cost-effectiveness and availability.

Biomass types and storage

Biomass types, specification and availability

Raw biomass of all types can be used for pyrolysis/gasification. Biomass is categorised based on its source into the following classifications:

- Agricultural biomass (e.g., crop or horticultural residues)
- Woody biomass (e.g., forestry and timber residues)
- Marine biomass
- Human and animal effluent
- Industrial waste biomass.

Woody biomass and agricultural biomass are the focus of this report.

Woody biomass generally refers to the woody parts of trees such as trunks and branches (excluding leaves, bark and roots), and is widely utilised for conversion into viable products through thermal treatment due to the minimal presence of sulphur and heavy metals.

Agricultural biomass includes straws (from cereal crops such as barley, corn, rice, wheat) and other residues (such as grains, seeds, shells, husks, bagasse, pulp), as outlined in this report.

Various studies demonstrate that the gasification/pyrolysis products are heavily influenced by the biomass material's chemical makeup, moisture content and inorganic species (such as silica, aluminium, iron, calcium, sodium, potassium). Moreover, the amount of energy extracted corresponds directly to moisture content and varies depending on the other mentioned factors. A list of example feedstock sources is shown in Table 2 with their typical form, moisture content, lower heating value (LHV), and the estimated amount available in Victoria in a typical year (with average rainfall).

Victoria produces approximately 3.4 million dry tonnes of straw per year, as a byproduct of grain (or cereal) crops. This is based on information from *Sustainability Victoria – Assessment of Victoria's Biogas Potential (2021)* and around two-thirds of straw production is collected, and 25-75% of this amount may be used for animal feed or bedding. Based on this, there may be up to 1.7 Mt of straw per year available for gasification or pyrolysis[1]. Based on information from *Future opportunities for using forest and sawmill residues in Australia (2018)*, there may also be up to 1.84 Mt of woody biomass available (e.g., stumps, branches and bark)[3].

> *"Wood residues with minor contamination with [non-fluorine & non-chlorine] plastics will be okay. Not CCA [treated timber]."*
>
> **Peter Burgess, Rainbow Bee Eater**

Suitability of feedstock depends on various factors, including the availability and cost of the feedstock (including collection, transport and storage), moisture content, particle size (particularly for woody biomass), and chemical composition (such as silica, potassium, chlorine).

Table 2: Feedstock sources for gasification and pyrolysis[1, 2, 3, 9]

Category	Source	Amount available in Victoria (million tonnes p.a.)	Moisture content (%)	LHV (MJ/kg)	Bulk density (kg/m^3)
Agricultural residues	Straw, Chaff (Dried, harvested /baled)	1.7	10-25	13-15	15 – 200
Woody biomass	Harvest residues (e.g. stumps and bark).	1.84	15-20	14-15	150 – 265
	Horticultural residues	0.18			

> *"Lignocellulosic biomass produces high grade biochar with low ash. Agricultural straw produces less biochar. We are learning all the time, and all feedstocks have a fit, place or use."*
>
> **Andrew Wells, Earth Systems**

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Gasification and pyrolysis feedstock

Pre-treatment of agricultural residues through size reduction and drying processes improves the quality of the raw material prior to gasification.

Biomass pre-treatment and storage

Pre-processing and pre-treatment of feedstock

Pre-treatment of biomass often includes cleaning, drying, screening, and sizing the biomass to produce a refined feedstock with improved characteristics for gasification or pyrolysis[1].

The choice of an appropriate pre-treatment method is dependent on multiple factors, such as the characteristics of the collected biomass (such as size, dryness, contamination), the technology utilised in the gasification/pyrolysis process (such as the type of gasifier or pyrolyser), and the desired quality of the syngas or biochar.

Straw has a relatively low bulk density (~40 kg/m^3) compared with wood residue (~250 kg/m^3), meaning straw is more expensive to transport and larger storage facilities are required when compared to wood chips. Baling straw can increase the bulk density to ~100 kg/m^3 [4] extending viable collection distances and reducing storage volume. There are gasification systems that have been developed to take whole bales, although his aspect of gasification and pyrolysis systems can be quite bespoke.

In the case of wood chips, further size reduction may be required to achieve the desired size for gasification or pyrolysis depending on the wood chip source and the type of gasifier.

Pre-treatment options prior to gasification/pyrolysis include:

- **Size reduction:** The degree of biomass screening, crushing, shredding or milling is contingent upon the specific feedstock characteristic required by the gasifier. For instance, a fixed bed gasifier can accommodate particles in the range of several tens of millimeters in size, whereas an entrained flow gasifier is only capable of handling biomass in the micron size range[3]. Small particle sizes with high surface area allows high heat transfer rates, which is crucial for fast pyrolysis where high liquid fraction yields are desired. In these cases, a particle size range of 1-2mm is usually recommended[2]. Slower heat transfer rates are acceptable for gasification or carbonisation, targeting high gas yields or solid yields respectively, and so larger particle sizes (5-20mm) are usually recommended.
- **Drying:** The moisture content of the biomass is sometimes well in excess of what the facility is designed for, particularly for green woody residues. In such cases, biomass needs to be dried to an appropriate level. This is often done economically by natural drying (passive drying) during storage. Active drying can rapidly dehydrate the biomass down to the desired moisture content using the excess heat produced during gasification or pyrolysis via exothermic reactions. The most common dryer types are rotary dryers, flash dryers, fluidised-bed dryers and belt dryers. The particle size, particle density, initial moisture content and drying temperature strongly influence the drying time[2]. Drying with waste heat is complex and care must be taken to avoid fires and control particulate emissions.
- **Other pre-treatment options** include screening (to remove stones and sand), washing, alkali treatment, steam treatment, and compression treatments such as pelletising or briquetting.

> *"Pre-Dryer System … takes the excess high-grade heat we produce in our self-sustaining process and helps reduce feedstock moisture content prior to pyrolysis"*
>
> **Andrew Wells, Earth Systems**

Gasifiers and pyrolysers manufacturers/installers currently available in Australia recommend particle sizes in the range 5-20 mm and are relatively flexible in terms of feedstock type, accepting a range of crop, harvest and woody residues.

Low feedstock moisture content (less than 25%) is usually also required, with some technologies requiring moisture contents less than 15%.

Some suppliers require straw to be pelletised, which involves drying to low moisture contents (typically less than 10%) and size reduction (to less than 2mm) prior to compression through a pellet press. Pelletising greatly increases the bulk density of the biomass (~650 kg/m^3). Biomass compression into pellets and briquettes (as shown in exhibit A & B) is used to make haulage and storage easier and more economical, but obviously increases plant capital cost and process complexity. As such, it is perhaps more suited to larger scale operations.

Exhibit A: pellets

Exhibit B: briquettes

Biomass storage

Storage of biomass material is important to provide protection from moisture and preserve the biomass material. Biomass can be stored via several methods such as outdoor storage in piles, in silos, or in a bunker[11]. Bunkers are enclosed storage areas which can be above or below ground. Silos are another type of enclosed storage method. Outdoor above ground storage in piles is a more economical storage option for large amounts of biomass[11].

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Advanced thermal treatment process and its products

Gasification and pyrolysis convert woody biomass and agricultural residues into useful products such as syngas and biochar. The economic viability of such systems is influenced by availability of a quality low-cost feedstock and potential cost savings from electricity and heat generation.

Biomass gasification and pyrolysis technology

Gasification and pyrolysis technology overview

Biomass gasification refers to the thermochemical conversion of ligno-cellulosic biomass (the woody parts of plants) at elevated temperatures and with a controlled deficiency of oxygen into a syngas (gas containing hydrogen and carbon monoxide) and biochar (solid containing mostly carbon). The conversion process typically involves the following stages at increasing temperatures[1, 8]:

- Drying
- Thermal decomposition; torrefaction and pyrolysis
- Partial combustion of some gases, vapours and char
- Gasification (and/or reforming) of decomposed products.

Decomposition produces a mixture of gas, liquid (bio-oil or pyrolysis-oil), and solid (biochar) phases. The heating rate and reaction temperature dictates the relative proportion of each product. Slow heating produces **mostly biochar**, with low peak temperatures (200-300℃) producing a torrefied char and higher peak temperatures and times (>400℃) producing charcoal. Fast heating rates **targets bio-oil production** with liquid yield being optimised by (i) very high heating rate, (ii) reaction temperature within the range of 425-600°C, and (iii) short gas residence time by rapid quenching of the gas produced[1, 2]. The size of the biomass can limit the maximum heating rate, due to the low thermal conductivity of wood. Fast-pyrolysis, flash-pyrolysis, and ultrarapid-pyrolysis are commonly used terms to differentiate between different heating rates and the peak temperatures. Fast pyrolysis and higher temperature generally produces a higher porosity biochar than carbonisation[1].

The bio-oil or pyrolysis-oil produced is a mixture of tars, condensable hydrocarbons, and water. It has value as a biofuel, where its high energy density and ease of transport make it a promising alternative to petroleum fuel for power generation. Furthermore, bio-oil is biodegradable, neutralises CO_2 and greenhouse gases, and produces considerably fewer NOx and SOx emissions when burned in engines compared to petroleum-based fuels. It can also be refined to produce wood vinegar.

To **target syngas production**, the pyrolysis gases are generally held in contact with the biochar for longer and heated to higher temperatures (700-1000°C)[2, 5]. A gasification medium is typically introduced to react with solid carbon and heavier hydrocarbons, converting them to lighter gases like carbon monoxide and hydrogen. Partial combustion (oxidation) of char and gases provides heating to the process.

The syngas composition and heating value depend greatly on the amount and type of gasifying medium (air, steam or oxygen). Gasification of wood chips using air as the gasifying medium typically produces a syngas with lower heating value (LHV) of 5-6.5 MJ/Nm^3 , which is relatively low compared to ~36 MJ/Nm3 for natural gas. This syngas consists mostly of nitrogen (~40-50%), hydrogen (~20-25%) and carbon monoxide (~15-30%), as well as smaller amounts of CO_2 (~5-15%) and CH_4 (~1-3%) [1, 3]. Nitrogen in the gasifying air dilutes the fuel gases – CO and H_2. The heating value of the syngas can be increased to 10-18 MJ/Nm^3 using steam, or to 12-28 MJ/Nm^3 by using oxygen as a gasifying agent[1]. Heating value can also be increased by syngas recirculation or syngas upgrading to remove inert gases. These further steps add complexity and cost.

Gasification of 1 tonne of biomass typically produces 2,500m^3 of syngas, the equivalent of ~340 litres of diesel fuel, and ~1.2 MWh of electricity in a gas engine-genset.

The most common type of commercial gasifiers are fixed bed gasifiers, which are usually either updraft or downdraft. Updraft gasifiers, where the syngas is drawn from the top of the reactor, can operate with wetter biomass with up to 60% moisture content (wet basis), but are known to produce syngas with the most tar (see page 13 on syngas purification)[8]. Downdraft gasifiers must operate with biomass with less than 25% moisture content, but their main advantage is the production of syngas with low tar content for IC engines [3, 7].

> *"Technology is only getting better, getting a locked-in long-term supply of biomass is the big challenge"*
>
> **Adam Riley, Advanced Energy Tech**

A summary of the indicative product proportions dependent on the type of thermal treatment and process conditions is shown in Table 3.

Table 3: Gasification/pyrolysis thermal treatment example product proportions[1, 4]

Process	Residence time	Bio-oil	Biochar	Syngas
Gasification	Long	~5%	5-20%	~85%
Fast pyrolysis / indirect liquefaction	Short (seconds)	<70%	<20%	<20%
Slow pyrolysis / carbonisation	Long (minutes to hours)	20-40%	<50%	20-40%

The cost of gasification plants varies depending on the size, feedstock type, and final product outputs (e.g., heat and electricity)[2]. Indicative plant costs for gasification, as well as pyrolysis and incineration, are shown in Table 6.

Influential economic factors

Economic factors which can influence the economic viability of installing such plants include[2]:

- Availability of a low-cost feedstock with low moisture content and high energy density
- Research shows that the current biochar market in Australia is small and fragmented.
- Cost savings from electricity or heat generation
- Value of renewable energy certificates or carbon credits
- Potential cost savings from water and fertiliser efficiency gains.

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Advanced thermal treatment process overview and products

Syngas purification involves removing undesired impurities and refining the gas before producing heat and electricity via a CHP process. This process is critical to remove impurities which can pose a risk to downstream equipment, ash handling, and emissions.

Syngas purification / clean-up overview

Syngas purification

Synthesis gas or syngas is the key product of biomass gasification/pyrolysis and mostly comprises carbon dioxide, carbon monoxide, hydrogen, methane, ethane, ethylene, propane, sulphur oxides, nitrogen oxides, and ammonia. Other constituents can arise from incomplete gasification or incomplete degradation of organic or inorganic compounds.

Incomplete gasification and carryover of impurities in biomass feedstocks result in contaminants in syngas, which are mainly classified as solid particulates (such as unconverted char and ash), inorganic impurities (such as halides, alkali, sulfur compounds, nitrogen compounds), as well as organic impurities (such as tars, aromatic compounds, and carbon dioxide). These contaminants can cause downstream issues such as corrosion, clogging/fouling, and catalyst deactivation.

The type of impurities present varies based on the gasification method employed and the type of biomass utilised as the feedstock and the degree of gas clean-up must be appropriately matched to its intended use as shown in Table 4.

Syngas cleaning technologies can be classified as hot gas clean-up or cold gas clean-up based on the condensation temperatures of various species present in the syngas. Usually, cold gas cleaning uses water sprays where contaminants are absorbed in water droplets and condense with water at the exit where temperature is low (<100°C). Hot gas cleaning techniques take place at elevated temperatures (>300°C), where many alkalis condense. Other hot gas technologies occur at very high temperatures of 1000°C or above. Significant contaminants and relevant cleaning technologies are discussed in Appendix B and are summarised for some contaminants in Table 5.

Among organic impurities, tar is the least desirable. There are three main options for tar removal such as:

- scrubbing with an organic liquid (e.g., bio-diesel)
- catalytic cracking by nickel-based catalysts; or
- olivine sand and high-temperature cracking.

To remove inorganic impurities effectively, they should be removed sequentially. Water quenching is used to remove char and ash particles, followed by hydrolysis to convert COS and HCN to H_2S and NH_3. Ammonia and halides are then washed with water, and H_2S is removed by adsorption with the wash water. Finally, solid or liquid adsorbents are used to remove carbon dioxide from the gas.

There are some emerging technologies such as combined ceramic filtration and catalytic filtration which is more economical option for the commercial small-scale treatment.

With highly efficient catalyst at moderate temperatures (<600 °C) to remove both tars and particulates in a single step, it simplifies the gas cleaning process and reduces the need for multiple treatment stages. However, their manufacturing cost can be relatively high, and they necessitate frequent cleaning and maintenance to prevent clogging and maintain the catalysts.

Cleaning has two aspects: removing undesired impurities and conditioning the gas to get the right ratio of H_2 and CO for the intended use.

It is important to ensure that syngas cleaning residues are handled and disposed of properly based on the type and quantity of waste generated, as well as the local regulations and environmental considerations.

Residues commonly found would include ash, carbon, spent catalysts, wastewater, organic liquids, etc. which should be properly disposed of or recycled.

For instance, a wet scrubber containing organic liquid such as bio-diesel could be utilised to cool down the hot syngas and extract heavy tar molecules. The bio-diesel, once depleted, could be repurposed as fuel for electricity generation or mobile equipment.

The purified syngas can be used for many purposes, most notably in a stationary gas engine to generate electricity, which requires the least stringent syngas purity. Table 4 lists typical Syngas purity requirements for end-use applications.

Table 4: Syngas cleaning requirements for some typical end applications[6, 7]

Contaminants	Internal Combustion Engine (mg/m³)	Methanol Synthesis (mg/m³)	FT Synthesis (mL/L)	Gas Turbine (mL/L)
Tars (condensable)	-	*No data available*	<0.01	-
Tars (heteroatoms, BTX)	<100	<0.1	<1	-
Particulates (soot, dust, char, ash)	<50 (PM_{10})	<0.02	Not detectable	<0.03 (PM_5)
Alkali	1-2	-	<0.01	<0.024
Nitrogen (NH_3, HCN)	-	<0.1	<0.02	<50
Sulphur (H_2S, COS)	<700	<1	<0.01	<20
Halides (primarily HCl)	-	<0.1	<0.01	1

Note: all values are at Standard Temperature & Pressure (STP) unless explicitly specified.

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Advanced thermal treatment process overview and products

Syngas is a valuable product which has a wide range of uses such as for heat, cooling, and electricity generation. It can also be used to manufacture a variety of liquid fuels with other conversion technologies. However, these are unlikely to be suitable for farm deployment.

Syngas uses

Electricity via gas engine genset

Syngas can be utilised as a fuel in a stationary gas engine, where it undergoes combustion and energy conversion to drive a generator, producing electricity. Electrical conversion efficiency is typically in the range 20-30%[3, 4, 9, 12, 13].

Electricity via Rankine Cycle (steam or ORC)

The syngas can be combusted in a boiler to produce steam, which can drive a steam turbine, or similar ORC-based (Organic Rankine Cycle) power plant, to generate electricity[2]. The overall electrical efficiency of such a system can be expected to be lower than a gas engine genset, at ~17%[6, 8]. Combustion of syngas instead of direct combustion of straw can reduce problems with corrosion, boiler fouling and ash melting due to its high alkali and halide content[1, 2].

Co-generation

Overall energy recovery efficiency can be improved by recovering useful heat from engine exhausts and cooling circuits – known as Combined Heat & Power (CHP) or co-generation. The recovered heat is commonly in the form of steam or hot water, which can subsequently be used for heating or cooling purposes. The benefit of CHP (and Tri-generation) is its very high efficiency (+80%). This configuration is shown in the diagram Figure 1.

Some heat is typically used to initiate and sustain the gasification or pyrolysis process. Some electricity could be used for microwave-assisted gasification/pyrolysis, although this technology has not been widely implemented in Australia.

Tri-generation

Trigeneration, also known as combined cooling, heat, and power (CCHP), involves utilising the heat produced by a cogeneration plant to generate chilled water for air conditioning or refrigeration. This is accomplished by connecting an absorption chiller to the CHP system.

Liquid biofuels

Syngas can also be converted into liquid fuels such as methanol, dimethyl ether (DME), synthetic natural gas (SNG) via Fischer-Tropsch (FT) or similar processes[8, 9]. The FT process takes place at temperatures between 200 - 350°C and produces a FT crude which can be upgraded to various types of liquid fuels that replace fossil-based equivalents (diesel, kerosine, petrol)[8]. These conversion processes typically require much higher syngas purity than gas engines (see Table 4).

Globally, several commercial scale SNG or liquid fuel production facilities (from biomass gasification) have been announced but none are yet operational[14].

These alternative products are currently unsuitable for farm-scale deployment due to lack of commercial readiness (lack of commercial examples using biomass-derived syngas), specialty skills required for operation, and the process plant is best suited to large scale operations (economies of scale)[14].

Potential future opportunities

Most gasification/pyrolysis processes are flexible and can handle various feedstocks, including potential new residues not currently utilised for syngas production. Additionally, if feedstock volumes increase, the gasification/pyrolysis technology is modular to some extent and could be expanded, and common infrastructure (such as electricity connection, materials handling and storage, stack/pretreatment area) could be leveraged to allow for processing capacity expansion. Gasifiers used for co-generation could be upgraded in the future with new technologies, for example to produce liquid fuels via the FT process.

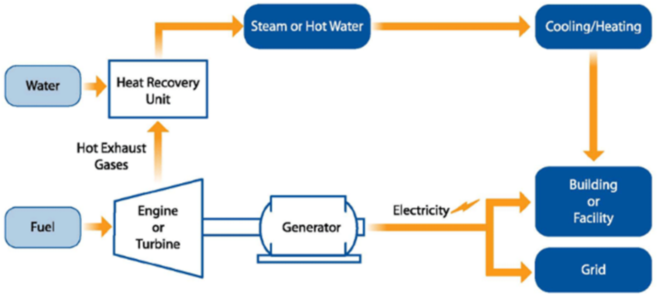

Figure 1: Example CHP configuration #1 - Combustion engine with heat recovery unit. Image sourced from United States Environmental Protection Agency (EPA) [4]

Case Study: *Holla Fresh* are a culinary herbs grower located in Tantanoola in South Australia, who installed a Rainbow Bee Eater (RBE) ECHO2 pyrolyser in 2018 (commissioned 2019).

- Feedstock source: Van Schaik's BioGro, a nearby organics composting business, who supply crop & timber waste at zero cost and in return take the biochar and blend it with compost.
- Biomass input: ~500 kg/hr biomass
- Products:
    - 100 kW_e electricity via syngas combustion in a gas engine
    - 700-800 kW_{th} hot water from boiler used for heating their glasshouses (~3.8Ha)
    - 250 kg/hr horticultural CO_2 from flue gas used in glasshouse to enhance growth rates
    - 0.6 t-CO_2/hr of CO_2 Removal Certificates (CORCs*)
- Payback period: anticipated to be 4-6 years

Ref: [10,11, 12]

*CO_2 Removal Certificates (CORCs) are created under an EU Framework for removing and storing non-fossil carbon from the atmosphere. They can be traded Business-to-Business directly or on B2B marketplaces such as NASDAQ's Puro.earth.

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Advanced thermal treatment process overview and products

Gasification/pyrolysis plants can contribute to regional self-sufficiency and deliver key benefits to Victorian producers such as energy savings, heat production, and biochar for improved soil health. While high upfront costs currently pose a challenge, energy markets and incentive schemes are continually improving the business case.

Key drivers and implementation challenges

Key drivers, benefits, and opportunities

The use of gasification in agriculture can contribute to regional self-sufficiency and increase on-farm energy resilience, security and grid stability. Victorian farmers can benefit through:

- **Energy savings:** Syngas produced from gasification provides a supplementary or alternative fuel source for agricultural operations such as heating, cooling, and motive power, which can reduce expenditure on grid electricity, diesel, LPG or other fuels[1, 5].
- **Energy security and resilience:** Gasifier-gensets have a relatively short start up time and a wide load range, offering on-demand renewable electricity generation. This source of renewable electricity is a genuine alternative to intermittent solar/wind once energy storage is factored in. On-demand renewable electricity generation can be used to either replace grid power or to reduce supply tariffs by reducing maximum power draw from grid or by reducing power consumption from grid during peak periods.
- **Grid support**: Gasifiers have the capability to generate power as needed, even exceeding on-site demands, should the distribution network service provider necessitate it.
- **Soil health:** Biochar can be beneficial for soil health by decreasing nitrate leaching, decreasing nitrous oxide emissions (up to 38%), increasing retention of soil moisture and nutrients (nitrogen, phosphorous), and increasing potassium availability in soil[1, 3, 4, 7, 9]. Biochar differs to compost, which tends to provide short-term benefit (e.g., 12-18 months), by create enduring physical soil property and agronomic benefits (moisture holding, nutrient holding, microbial holding, improved cation exchange capacity) for hundreds of years. Soil applications, especially where food production is enhanced, can represent highest value use of biochar[9]. See Holla Fresh case study on *page 15* , where biochar is blended with compost.
- **Additional revenue streams:** Carbon credits (ACCUs) could be generated through avoiding the release of carbon emissions, or renewable energy certificates (RECs) could be obtained if electricity is generated[1]. Note that both carbon credits and RECs may not be able to be produced at the same time. Additionally, fuel switching under the Victorian Energy Upgrade (VEU) scheme is an eligible process (see https://www.esc.vic.gov.au/victorian-energy-upgrades-program/activities-offered-under-veu-program/project-based-activities).

  Biochar could be sold for non-soil applications including carbon-based filtration, metallurgical reductants, and as animal feed additives, to improve animal health and reduce enteric methane production[9, 10]. The Australian Biochar Industry Roadmap 2023 demonstrates and explains the huge potential for growth of biochar use in Australia[10].
- **Reduced dependence on fertilisers:** Biochar can aid with the retention of soil nutrients and can decrease the amount of fertiliser needed[1, 2, 4].
- **Cost savings:** Associated cost savings from onsite energy generation, offsetting energy from the grid(s), water and fertiliser savings from biochar's water and nutrient holding capacity.
- **Reduced environmental impact of business as usual:** Gasification or pyrolysis of residues can avoid the particulate emissions (smoke) associated with crop burning or reduce methane emissions associated with rotting biomass (e.g., burnt-out Kangaroo Island Plantations[8]).
- **Carbon sequestration:** Gasification/pyrolysis are both potentially methods of carbon sequestration through the proper application of biochar to the soil or sub-soil.

Table 6 below shows the CAPEX and OPEX ranges for gasification and pyrolysis units, based on the range provided by the suppliers (see Appendix A).

Within the Gasification-Cogen unit, the amount of electricity generated from the syngas would fall within the range of 0.7 to 1.1 MWh per tonne.

Biochar and bio-oil can also be sold at wholesale (gate) prices of ~$20-100 per tonne for biochar and ~$0.05-0.50 per litre for bio-oil. The price for bio-oil can vary based on factors such as its calorific value and the value of crude oil / diesel[1].

Implementation barriers and challenges

There are several challenges to implementing on-farm gasification systems that must be managed. These include:

- **Technology readiness**: Some commercially-ready technology options are available for on-farm gasification systems. There are also several Australian technologies in development, such as from Renergi and Wildfire Energy, which may provide better efficiencies and therefore improved commercial viability when compared to traditional systems; of course, emerging technologies have associated risk.
- **Commercial viability**: Best returns are likely to arise where multiple economic benefits can be realised such as combined heat and power, ACCU/REC/CORCs, soil benefits, reduced fertiliser/water, etc. This adds complexity to investment decisions, financing, and implementation[1].
- **Compliance:** Internationally sourced equipment must be compliant with Australian regulations and standards (e.g., electrical, gas safety, Workplace Health & Safety).
- **Safety:** Safety precautions are required for the safe handling of syngas[1]. In addition, storing straw can pose a fire hazard, however this can be mitigated by installing sprinkler systems and employing other prevention methods.
- **Feedstock availability variability:** Biomass feedstocks such as straw are subject to seasonal and yearly fluctuations. This can however be overcome by using gasification plants with flexible feedstock input options (e.g., straw and wood chips)[6].

Table 6: Gasification and pyrolysis plant CAPEX /OPEX ranges

Process	CAPEX	OPEX
Gasification – Cogen	$6,000-$9,000 /kWh electricity generated [1,2]	4-6% CAPEX
Pyrolysis	$300-$1,400 /(tonne/year of feedstock)	4-6% CAPEX

Note 1: Based on the range provided by the suppliers (see Appendix-A).

Note 2: The relationship between unit capacity (feedstock input) and capex/opex is inversely proportional. Higher feedstock results in lower costs.

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Gasification and pyrolysis examples

There are a limited number of operational gasification/pyrolysis plants in Australia, however many examples of gasification systems exist globally. Technology developments are underway in Australia which may help improve the commercial feasibility of such systems for Victorian producers.

Commercial uptake overview

There are many gasification and pyrolysis technologies available and in development worldwide. In Australia there are only a limited number of operational gasification/pyrolysis plants[1].

Commercially ready technologies in Australia

- **Rainbow Bee Eater (RBE)** has developed a system called ECHO2 that converts organic residues such as agricultural crop and timber wastes into hydrogen-rich Syngas , Biochar and wood vinegar through a pyrolysis process.The first ECHO2 commercial module provides heat to the Holla-Fresh glasshouse. The first ECHO2 '6 Pack' will provide heat to Katunga Fresh in 2023.
- **Pyrotech Energy** is a technology licensor and provider of equipment, engineering support and service to the waste to energy industries. Their aim is to deliver and deploy mobile pyrolysis plants utilising second generation PyroFlash and PyroGasification reactors for converting waste wood and agriculture residues into biofuels and other high valued bio-chemicals in an environmentally, socially and economically sustainable manner.
- **Earth Systems** has developed CharMaker – Mobile Batch Pyrolysis Plant (MPP 20 and MPP 40) that is a transportable batch pyrolysis technology applicable to any log or stick-sized woody biomass – as well as a new CharMaker Continuous Pyrolysis Plant (CPP), a continuous pyrolysis technology specifically designed to pyrolyse biomass of small size into high-quality biochar and liquid products. Recently, Earth Systems' CharMaker has also been installed and operated at Kadoorie Farm and Botanic Garden (KFBG) in Hong Kong.
- **Pyrocal** is an Australian engineering company whose Continuous Carbonisation Technology (CCT) uses a modified updraft gasifier to optimise biochar yield and quality. The gasifier may be integrated with off-gas combustion and heat recovery as well as emissions control equipment (wet scrubber/electrostatic precipitator).

Emerging technology developments in Australia

- **Wildfire Energy** is developing a Moving Injection Fixed-Bed Gasification technology which takes biomass and waste feedstocks such as agricultural and forestry waste, green waste and municipal solid waste (MSW), and converts this to syngas. The syngas produced can be used for electricity generation via a gas engine, or otherwise for hydrogen production. The technology is intended to intake up to 120 kt/year of biomass. The overall TRL of this technology is around 3-4 although the product gas separation and cleaning process has a higher TRL of 4-5. This indicates the technology is overall at an early stage of development[4].
- **Renergi** have developed an advanced biomass gasification technology which takes biomass feedstocks such as agricultural and forestry waste and converts this to primarily syngas. The syngas produced can be used for electricity generation and heat, as well as being suitable for use in power generation technology such as a gas engine. Renergi have also created a pyrolysis technology which can take a range of feedstock types as well as particle sizes. The overall TRL of Renergi's technology is 6-7, illustrating it has been proven in an industrially relevant setting[4].

Victorian examples of gasification installations

- **Advanced Energy Tech (VIC)** are an EPC business who have a demonstration gasification plant at Pyramid Hill in Victoria[8, 9]. It is understood that the plant is operating on agricultural residues as part of its testing regime to ensure compliance with EPA requirements.

> *"There is growing interest in the utilisation of agriculture biomass and concerns about the rising cost of fuel and fertilisers. However, development of government policies for implementing mature bioenergy technologies that are in wide use overseas are slow"*
>
> **Andrew Lang, Victorian Bioenergy Network**

Case Study: *Meredith Dairy* spans 2,200 hectares, on which cereal and fodder crops are grown and dairy sheep and goats graze.

Meredith Dairy recently installed a biomass gasification-based Combined Heat & Power (CHP) system, with a capacity of 68kW$_e$ and 120kW$_{th}$. The hot water is used for the dairy.

The $600,000 system includes feedstock drying using waste heat from process. Annual operating costs include $80,000 for feedstock collection and storage and an estimated $30,000 for labour.

The CHP system has helped reduce Meredith Dairy's grid electricity reliance by 70%.

Australian examples of gasification/pyrolysis installations

- **Jeffries Composting (SA)** have installed a Pyrocal $3 million 3 MW gasification plant with the support of a government grant. The plant can generate 100 kWe via a syngas burner, steam boiler and then the ORC process. Jeffries use this electricity to operate an on-site compost screening plant and feed any excess electricity to the grid. It also produces hot air, as well as biochar which is used to increase the quality of their compost products. This plant can take up to 2,500 tonnes p.a. of organic matter and wood feedstock[1, 5].
- **Holla-Fresh (SA)** – see case study on page 15

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11. KHL Group, Power from waste project in Australia, 2021. https://www.dieselgasturbine.com/news/power-from-waste-project-in-australia/8016387.article

3. Stakeholder Engagement

Overview of Stakeholder Engagement

The stakeholder engagement was centered around a series of online surveys and in-depth interviews with key stakeholders to understand the current needs of Victorian producers and the ideal financial tool that would be beneficial to them.

Stakeholder engagement purpose, objectives and scope

Stakeholder engagement played a pivotal role in the development of our financial sensitivity tool, aiming to address the challenges faced by the agricultural industry and provide Victorian producers with means to link their operational parameters with their commercial and financial objectives. To ensure the tool effectively catered to the needs of the stakeholders, a comprehensive stakeholder engagement process was conducted.

Arup, in collaboration with Agriculture Victoria, designed survey questions in alignment with the project and engagement objectives. This section outlines the key insights gained from the stakeholder engagement process, highlighting the valuable input received from industry stakeholders and how it shaped the development of the financial sensitivity tool.

The engagement purpose is supported by the following objectives, but not limited to:

- Enhance the financial tool's responsiveness to the current needs of Victorian producers and strengthen its emphasis on connecting operational inputs to successful business outcomes
- Discover opportunities for the tool to prioritise the primary issues, drivers, and challenges faced by producers when adopting new technologies
- Ensure the agricultural producers find the tool engaging, practical, and user-friendly
- Determine the benchmarks necessary for developing the financial tool
- Comprehend the broader challenges, such as regulatory compliance, workplace health and safety, land use planning, and additional skills requirements involved in implementing new technologies.

Engagement principle

The engagement principles for this project, adapted from the IAP2 Core Values and the Victorian Government's Public Engagement Framework 2021-2025, are to be Inclusive, Meaningful and accountable, Transparent and informed and valuable.

Engagement methods and program

The selected engagement methods and the engagement program are provided in Table-7.

Stakeholders' groups and Engagement Results

The stakeholders are categorised into three groups, namely Implementors/End-users, Technology Suppliers, and Industry Organisations. The list and outcomes of the stakeholders who participated in the engagement are provided in Appendix A.

Table 7: Stakeholder Engagement Methods

Engagement methods	
Online survey	Arup designed the survey questions in collaboration with Agriculture Victoria to ensure they match the project and engagement objectives. Survey responses were anonymous (only demographic information about postcode and stakeholder type is retained) unless written approval to retain and report respondent’s identity was received. Refer to Appendix A to see the online survey questions/responses.
In-depth interviews	More specific questions targeted to each stakeholder group were asked during the semi-structured in-depth interviews. The questions were informed from the responses to the targeted survey questionnaires. Arup asked additional questions during the interview to understand the stakeholder responses in more detail. The interview results with technology providers were reviewed and key themes for the development of the tool identified.

Key takeaways from the online survey results

The online survey results presented an informed view of the main drivers and challenges for the commercial feasibility of gasification projects. A user-friendly dashboard and important financial metrics such as revenue & payback period were key to the farmers and producers.

Key Takeaways

Main Drivers

- Survey results indicate that the main factors that drive the commercial feasibility of gasification projects are the **high or volatile energy and gas prices**. The energy costs are predicted to increase by 25% in 2023 (according to the Essential Services Commission (the government energy regulator in Victoria)
- Gasification offers an alternative and potentially more cost-effective energy source, particularly when traditional energy prices are high or unstable.
- Additionally, the survey highlighted the significance of the **lost opportunity for converting agriculture residues into energy**.
- Gasification presents an environmentally sustainable **solution for agriculture residue management**, allowing the efficient conversion of various waste materials into valuable energy products.
- By capitalising on this opportunity, gasification projects can **contribute to both economic and environmental goals**. Understanding these driving factors is crucial for assessing the commercial viability of gasification projects and making informed investment decisions.

Main Challenges

- While there were few challenges identified by the farmers. One of the primary challenges is ensuring a consistent supply of feedstock, which is necessary for the continuous operation of the system.
- The **availability and accessibility of biomass feedstock can vary**, making it essential to establish reliable supply chains or partnerships with biomass suppliers.
- Another significant challenge lies in **securing long-term contracts for biomass procurement**. Long-term contracts provide stability and help mitigate the risk of feedstock scarcity or price fluctuations.
- As the volume and type of feedstock varies for different farmers, we have **customised the financial assessment tool to include feedstock quantity on a monthly basis according to different feedstock types** for an accurate representation of the outputs.

User friendly Dashboard

- The Financial Assessment Tool we have developed will feature an online interactive dashboard interface, designed to provide farmers with a user-friendly experience.
- Through the engagement with farmers, we sought their input on the desired appearance of the dashboard.
- The majority of farmers expressed their preference for a straightforward layout with **simple outputs** that are easy to interpret.
- Recognising the diverse needs of farmers, we also took into account the **importance of customisation options**.
- As a result, the dashboard offers flexibility, allowing users to tailor the tool to their specific requirements if desired. By incorporating farmers' feedback, we created a **Financial Assessment Tool that is intuitive, accessible, and meets the unique needs of individual farmers**.

Financial metrics

- Farmers have indicated the key metrics that are beneficial to them as outcomes of the financial tool. The two main metrics are
  - **Revenue / Savings**
  - **Payback period**
- The payback period is a crucial indicator that helps farmers assess the time it takes for their investment to generate returns and become financially viable.
- By considering this metric, farmers can make informed decisions about resource allocation and project profitability.
- Additionally, revenue and savings metrics enable farmers to track their financial gains and identify areas for improvement.
- We have **incorporated these important metrics into our model**, we aim to provide farmers with a comprehensive and user-friendly tool to effectively manage their finances and optimise their agricultural operations.

Refer to Appendix A to see the online survey questions/responses.

Key takeaways from the in-depth interviews

Following the online survey, we also conducted follow-up in-depth interviews with three technical providers to give us a better understanding of the new emerging technologies and the technical requirements of the plants.

Key Takeaways

Pyrotech Energy

Scheduled interview date: May 24, 2023, with Christos Karantonis, Managing Director of Pyrotech Energy in Australia.

- Pyrotech Energy has a number of projects scheduled for 2024 in Australia and Singapore, in addition to Netherlands and USA. All projects utilise agricultural residue and woody biomass as their feedstock. Pyrotech Energy employs both pyrolysis (Pyroflash) and gasification (Pyro Gasification) technologies, capable of handling various types of feedstocks. While the yields remain consistent, the caloric value of the products may vary slightly based on the composition of the feedstock.
- The recommended feedstock quality for pyrolysis is biomass with a typical size ranging from 2 to 20 mm and a moisture content of 15% for PyroFlash and for PyroGasification with the same typical size ranging and a moisture content of 23%. Straw as the feedstock should be in the form of pellets.
- The Pyrotech Energy facilities can effectively handle biomass feedstocks with ash content up to 6-7%. The estimated annual OPEX for both units range from 30,000 AUD to 50,000 AUD. The water requirement for the operations is approximately 2 litres per day.
- Natural gas is required for startup only, and both technologies will run on their own produced fuel during operation. Pyroflash units are available in two capacity ranges:

Capacity (MTPD feed)	Size Container (ft)	Capital Cost (AUD)
2	20	850,000
10	40	2,100,00

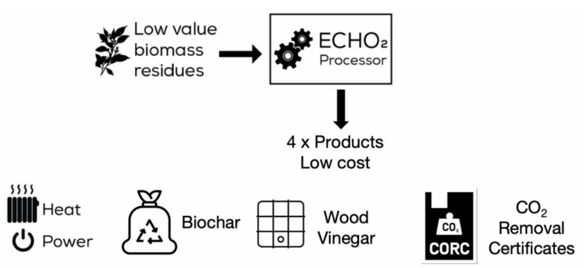
- PyroGasification units are available in four capacity ranges

Capacity (kg/hr feed)	Size Container (ft)	Capital Cost (AUD) Excluding CHP	Capital Cost (AUD) including CHP
100	40	700,000	850,000
200	40	1,000,000	1,300,000
300	40	1,500,000	2,000,000
400	40	1,900,00	2,600,00

RAINBOW BEE EATER

Scheduled interview date: May 25, 2023, with Peter Burgess, RBE' Managing Director, Australia

- ECHO2 , RBE pyrolysis process, was first commercially commissioned at Holla Fresh in 2019, followed by the ECHO2 '6 Pack' at Katunga Fresh in 2023.
- RBE projects have primarily focused on energy consumers, purchasing low-cost biomass from farmers to produce alternative fuel and reduce energy bills. These projects also generate biochar and wood vinegar as by-products for sale in the market. Peter was keen to see the outcomes of this study (tool) since it targets farmers to utilise their own excess residues.
- The required feedstock size ranges from 2 to 15 mm, with a moisture content of less than 25%. No pelletising is necessary when using straw as the feedstock.
- The syngas energy yield is 25%, with a 5% loss, and the remainder is stored in biochar and wood vinegar. They sell the CO$_2$ Removal Certifications (CORCs) on behalf of suppliers and share the profit.



Low value biomass residues

ECHO$_2$ Processor

4 x Products
Low cost

Heat
Power

Biochar

Wood Vinegar

CO$_2$ Removal Certificates

Earth Systems

Scheduled interview date: May 25, 2023, with Andrew Wells, Director, Earth Systems, Australia.

- Earth Systems has developed novel pyrolysis technology which is applied via two systems - Batch and Continuous. They have already built several units globally, including in Sweden (x2), Israel (x1), Hong Kong (x3), New Zealand (x1), Western Australia (x1), and Victoria (x4).
- They have a focus on pyrolysis at low temperature around 500-550 degrees Celsius to produce Biochar, Wood Vinegar, and the option to utilize high-grade excess heat. The Earth Systems pyrolysis process is initiated with a diesel burner and when wood gas reaches sufficient levels automatically stops the burner and becomes a self-sustaining process.
- The Batch system is suitable for whole branches, tree limbs, prunings, vines, etc., and does not require feedstock size reduction.
- The Continuous system is suitable for chipped woody material and finer feedstock types such as chipped branches, limbs, timber and tree prunings, straw, husks, hulls, almond waste, manure, and biosolids . It also allows these feedstocks to be blended/mixed together. No straw pelletising is needed for continuous technology.
- The impact of higher ash content in the feedstock would result in a lower fixed carbon biochar product content.
- The Continuous system capacity has a range of options from 200 kg/hr to 2.0 tonnes per hour of feedstock, with a residence time of 2-25 minutes. Roughly 20-25% of the feedstock is converted to biochar depending on feedstock moisture content and type.
- They have developed two Pre-Dryer Systems to be used with both the Batch System and Continuous System. These systems utilise part of the excess high-grade heat produced in the self-sustaining process to reduce feedstock moisture content before pyrolysis, thereby optimising the pyrolysis plant's throughput.
- The cost of their plant for a continuous System (CPP) with a feedstock capacity of 500 kg/hour, Approx. 100kg biochar/hour. 1--30L wood vinegar/hour. Heat energy approx. 5-600 kw, would be from approximately 900,000 AUD.

4. LCA – Carbon Assessment Model

Methodology
Thermal treatment carbon assessment model

Scope of Study & Process Flow Model

Introduction

For this project, a lifecycle carbon assessment model (LCA) was developed to understand the carbon emissions of the gasification and pyrolysis process. An LCA is a tool that calculates the mass and carbon flows of all inputs and outputs involved in the process and can be a valuable tool to reduce the environmental impact of any process. There are few assumptions and limitations that are implemented within the LCA model, and our approach is set out for reference below.

Calculating Approach and Methodology

The carbon assessment model calculates the mass and carbon flows of all inputs and outputs involved in the process. In carbon assessment terms, this study has been undertaken using an “attributional approach” to modelling. As described in the ISO 14040 standard, an attributional life cycle assessment *“assigns elementary flows and potential environmental impacts to a specific product system typically as an account of the history of the product”*[1]. As part of this attributional approach, this study details the assumptions behind any processes used, using the best current and publicly available data.

The total system carbon emissions are calculated as a sum of the carbon flows at each stage of the process. The carbon emissions from the process are emissions from the release of CO2 to atmosphere, any scope 2 carbon emissions caused by plant parasitic energy requirements (including feedstock pre-treatment) and diesel use from feedstock collection, and stored emissions from the production of biochar and bio-oil. The international standards for Life Cycle Assessment: ISO 14040 and ISO 14044 do not account for scope 1 and 3 emissions. Additionally, scope 3 is only applicable if the biochar and bio-oil were to be burnt. Both these processes are not within the scope and system boundary of this LCA [2].

Scenarios Modelled

In this attributional life cycle assessment 2 scenarios were modelled for comparison with Business As Usual (BAU) processes.

- Scenario 1: Using thermal treatment to maximise syngas production.
- Scenario 2: Using thermal treatment to maximise biochar and pyrolysis liquid creation.
- BAU: burning residues in-situ.

In scenario 1 a gasification process was modelled which resulted in nominal yield values of 80% syngas, 5% bio-oil, 10% biochar and 5% loss. This scenario is intended to maximise the syngas production and subsequent electricity produced by burning the syngas.

In scenario 2 a pyrolysis process was modelled which resulted in nominal yield values of 5% syngas, 67% pyrolysis liquid, 25% biochar and 3% loss. An additional step was included in this scenario to include fractional condensation, to separate wood vinegar from the bio-oil, with assumed yields of 30% and 60% respectively. This scenario is intended to maximise the production of biochar and wood vinegar, usually for the benefit of agricultural use.

Both scenario 1 and 2 included a final stage for the CHP engine process resulting in 30% electricity, 60% heat and 10% losses. Common practices for dealing with crop residues vary from region to region, influenced by varying soil quality, rainfall, crop yields, and established norms. The BAU practice used as a basis for comparison in this assessment, i.e., burning residues in-situ, results in biogenic CO2 emissions to air and no recovery of the energy released during burn-off.

System Boundary

A clear boundary was established for this assessment, within which the carbon footprint calculation was determined. The LCA is project bound and does not include the manufacture of plant and equipment. The system boundary encompasses the collection and transportation of feedstock, the pre-treatment of feedstock, and thermal treatment of the feedstock. It is assumed that all carbon from the previous lifecycle of the feedstock is not included in the boundary of this analysis. Any emissions associated with the storage of biochar are expected to be negligible and have been ignored.

Lubricating oil and water inputs required to run the thermal treatment plant were not included in the system boundary, as it is assumed the carbon outputs would not be significantly affected. Additionally, the heat losses (which is utilised in the CHP engine) from the treatment equipment were ignored.

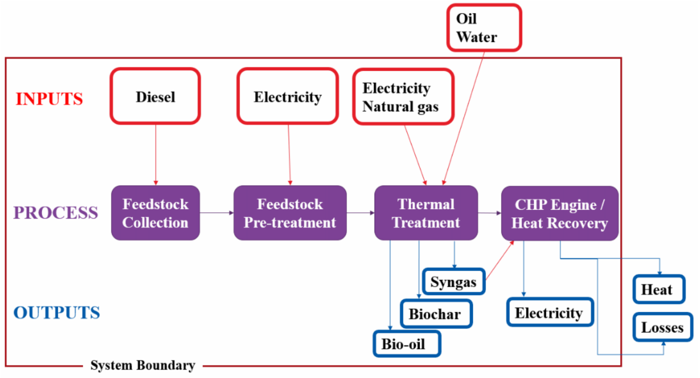


Figure 2a: Scenario 1 – Thermal treatment to optimise syngas production for electricity generation

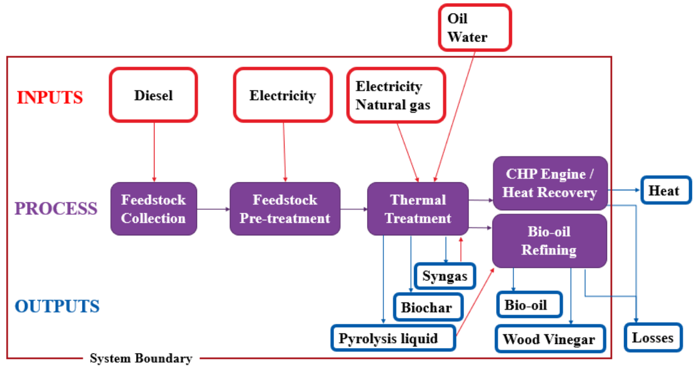


Figure 2b: Scenario 2 – Thermal treatment to optimise for biochar and wood vinegar from pyrolysis liquid

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1. ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework,
2. Environmental Management - International Organization for Standardization (2022). Environmental management - Life cycle assessment - Principles and framework (ISO Standard No. 14040:2006) Retrieved from https://www.iso.org/standard/37456.html

System Boundary
Thermal treatment carbon assessment model

Assumptions & Limitations

There are a number of assumptions and limitations that have been implemented within the carbon assessment model. These have been set out for reference below.

General

The modelling is based on 1 tonne/hour of feedstock material input. Emissions for greater or lesser feedstock throughputs can be scaled accordingly.

Feedstock

The feedstock to the thermal treatment process is straw residues. The carbon content of the feedstock is taken to be 46% (assumed 15% moisture content) [1].

Pre-treatment

Pre-treatment processes include collection of feedstock, drying, screening and sizing the feedstock if required. The pre-treatment of feedstock is included in the model, however drying and screening is not included in the model. It is assumed that drying will be achieved passively either in the field or during stockpiling. Alternatively, parasitic heating load could be used for drying

Biogenic carbon emissions

Biogenic carbon emitted has been sequestered by organic material during its lifecycle and is then released to atmosphere. By this definition, biogenic emissions to atmosphere can be reported as neutral.

The biogenic carbon stored in biochar, bio-oil and wood vinegar has been sequestered by organic material during its lifecycle [2]. By this definition, sequestering the biogenic carbon then storing in the char can be reported as a negative emission. This assumes the carbon in the product is not combusted at any point in the future. It is assumed biochar, bio-oil and wood vinegar is stored at the end of the process before end use.

End uses for biochar can include:

- Soil conditioner
- Additive to concrete and cement
- Additive to road surfacing.

End uses for wood vinegar can include:

- Soil fertiliser
- Water filtration
- Metallurgical applications
- Natural plant pesticide [3].

Electricity input

The energy associated with processing the feedstock for thermal treatment has been included in the boundary of this assessment. It is assumed that all electricity used in the plant is supplied externally from the grid. In scenario 1, grid electricity is only required for start-up.

Syngas clean up

It is assumed oil sludge and particulates from the syngas clean up have not yet been recycled back into the waste input (i.e. assessment is based on the first run). If this was included, the energy content of the input stream would require adjusting.

Diesel

The diesel usage in feedstock collection is included in our calculation, where it is assumed a usage of 6.6 litres/hectare; with assumption that 1.4 tonnes (on average) of feedstock per hectare is collected [4].

Impact categories

For the purposes of this assessment the following impact categories have not been assessed (impacts to these categories are relatively minor for the defined system boundary):

- Acidification potential
- Climate change-GWP100
- Depletion of abiotic resources-fossil fuels
- Eutrophication
- Freshwater aquatic ecotoxicity
- Human toxicity
- Marine aquatic ecotoxicity
- Ozone layer depletion
- Photochemical oxidation
- Terrestrial ecotoxicity
- Particulate matter formation

Emissions

The model focuses solely on accounting for carbon dioxide emissions and does not consider other factors or variables. Its scope is limited to quantifying and analysing the impact of carbon dioxide emissions on two given scenarios. By narrowing the focus to carbon dioxide emissions, the model aims to provide a specific and detailed understanding of the carbon footprint or environmental impact related to carbon dioxide specifically.

It is important to recognise that carbon dioxide is a significant greenhouse gas responsible for climate change, and understanding its emissions is crucial for addressing environmental concerns. However, it is also important to acknowledge that there are other greenhouse gases and environmental factors that contribute to climate change and broader environmental impacts. These may include methane, nitrous oxide, deforestation, land use changes, water consumption, and more.

While the model's focus on carbon dioxide emissions offers valuable insights into a specific aspect of environmental impact, it is necessary to consider additional factors and incorporate a comprehensive analysis to gain a complete understanding of the overall environmental effects of a given system or activity.

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1. Straw for Energy, Teagasc Agriculture and Food Development Authority, 2010, https://www.teagasc.ie/media/website/publications/2010/868_StrawForEnergy-1.pdf
2. Elemental Composition of Biochar Obtained from Agricultural Waste for Soil Amendment and Carbon Sequestration
3. AgriFutures Australia, Short report 4 Bioenergy, 2022
4. Diesel Use in NSW Agriculture and Opportunities to Support Net Zero Emissions. Available at: https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0011/1321796/mov3ment-diesel-use-in-ag.pdf.

Results
Thermal treatment carbon assessment model

Assessment results

Mass & carbon flows

Mass balances at each stage of the process were calculated, enabling the carbon content to be evaluated. The carbon content of the syngas at each stage of the process was calculated from the component mass fraction, molar mass and number of carbon atoms of the component gases.

Parasitic energy

The maximum parasitic electrical load of the process equipment was calculated to be 0.052 tonnes CO2/hr, at 80% utilisation factor. This value includes the use from collection of feed electricity use (or equivalent emissions) associated with diesel stock, feedstock preparation, natural gas and electricity for plant start up.

The average grid carbon intensity was taken to be 0.8 tonnes CO2/MWh [1,2].

Counterfactuals

The carbon assessment model provides a comparison of the carbon emissions associated with the thermal treatment technology to alternative BAU processes.

It is assumed that CO2 makes up 93% of total emissions from burning residues in-situ, with the remaining emissions consisting of CO, CH4, N2O, NH3, SO2, NOx, non-methane volatile organic compounds, PM2.5 and PM10 [3]. For the purposes of the assessment, the CO2 emissions were considered as net zero.

Findings

The key outputs from the carbon assessments are provided in Figure 3 and calculations in Appendix C.

Based on the carbon assessment, the thermal treatment process was found to store biogenic carbon dioxide at 0.317 and 1.465 tonnes per hour (for one tonne per hour of feedstock processed) in Scenarios 1 and 2 respectively, a significant increase on the BAU practice assumed, with no biogenic carbon storage.

Some assumptions were used in the carbon assessment model, which should be understood in the context of this analysis and are outlined in the prior sections. In addition, if the carbon in the bio-oil was to be released to atmosphere at any point in the future (e.g. combusted), the negative emissions could not be counted. Therefore, the emissions have been reported as positive emissions but on a biogenic basis to account for uncertainty around the end state of the products.

Scenario 1

The results of the carbon assessment show that the thermal treatment process is found to release 0.060 tonnes/hour carbon dioxide emissions to atmosphere, of which 0.008 tonnes/hour is biogenic and can be treated as neutral, and 0.052 tonnes/hour is non-biogenic as a result of parasitic energy requirements for operations and plant start-up. The process captures 0.317 tonnes/hour of carbon dioxide in biochar and bio-oil which is biogenic and can therefore be treated as negative.

The process thus results in **net negative 0.272 tonnes/hr** in carbon dioxide emissions.

Scenario 2

The results of the carbon assessment show that the thermal treatment process is found to release 0.053 tonnes/hour carbon dioxide emissions to atmosphere, of which 0.001 tonnes/hour is biogenic and can be treated as neutral, and 0.052 tonnes/hour is non-biogenic as a result of parasitic energy requirements for operations and plant start-up. The process captures 1.465 tonnes/hour of carbon dioxide in biochar, bio-oil and wood vinegar which is biogenic and can therefore be treated as negative.

The process thus results in **net negative 1.414 tonnes/hr** in carbon dioxide emissions.

The two scenarios demonstrate ways that feedstock typically classified as a waste product can be repurposed. Thermal treatment can be used to create electricity, heat, bio-oil, biochar and wood vinegar which can all be re-purposed and can contribute to a circular economy.

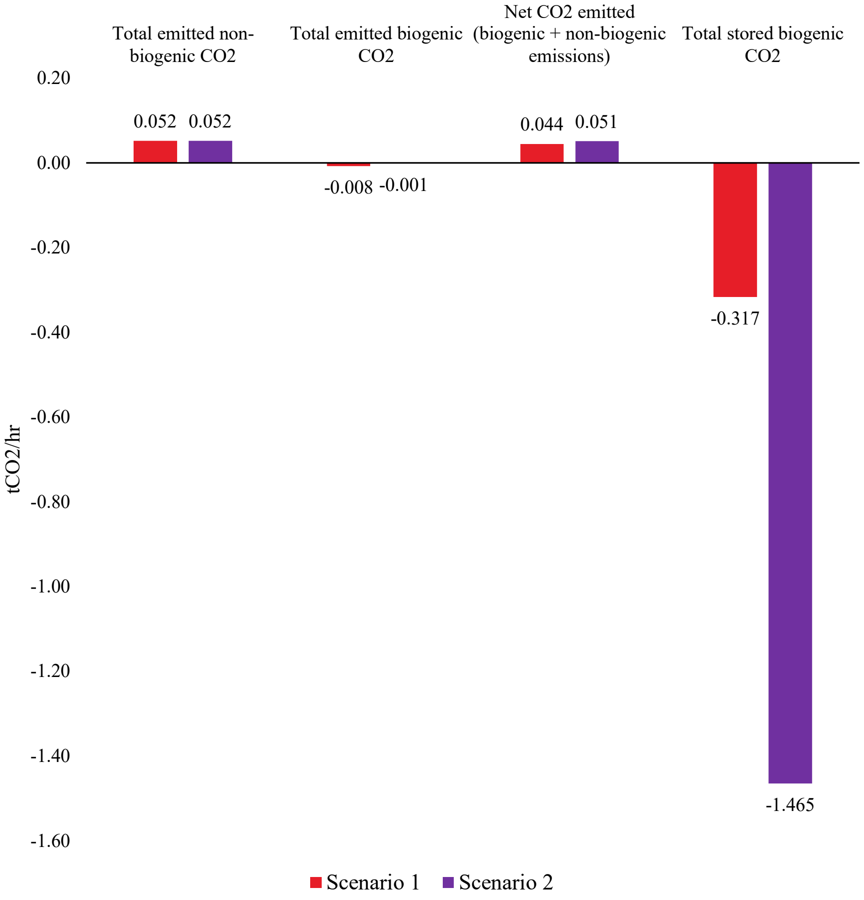

Figure 3: Total emissions (biogenic and non-biogenic) and biogenic CO2 stored per hour (when processing one tonne of feedstock per hour) in scenarios modelled

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1. Vivid Economics, Analysis of electricity consumption, electricity generation emissions intensity and economy-wide emissions, report prepared for the Climate Change Authority, October 2013
2. Australian National Greenhouse Accounts Factors, Australian Government Department of Climate Change, Energy, the Environment and Water 2022.
3. Venkatramanan, Shachi, et al. 2021. Nexus Between Crop Residue Burning, Bioeconomy and Sustainable Development Goals Over North-Western India.

5. Financial Tool

Financial Tool

A financial tool has been developed to allow users to assess the commercial viability of utilising pyrolysis or gasification technology on farms by utilising feedstock as an inputs and calculating the expected equipment size required, costs, potential benefits and commercial returns.

Introduction

A financial tool has been developed to provide farmers with the information needed to assess the economic viability of agricultural residues for energy-on-farm.

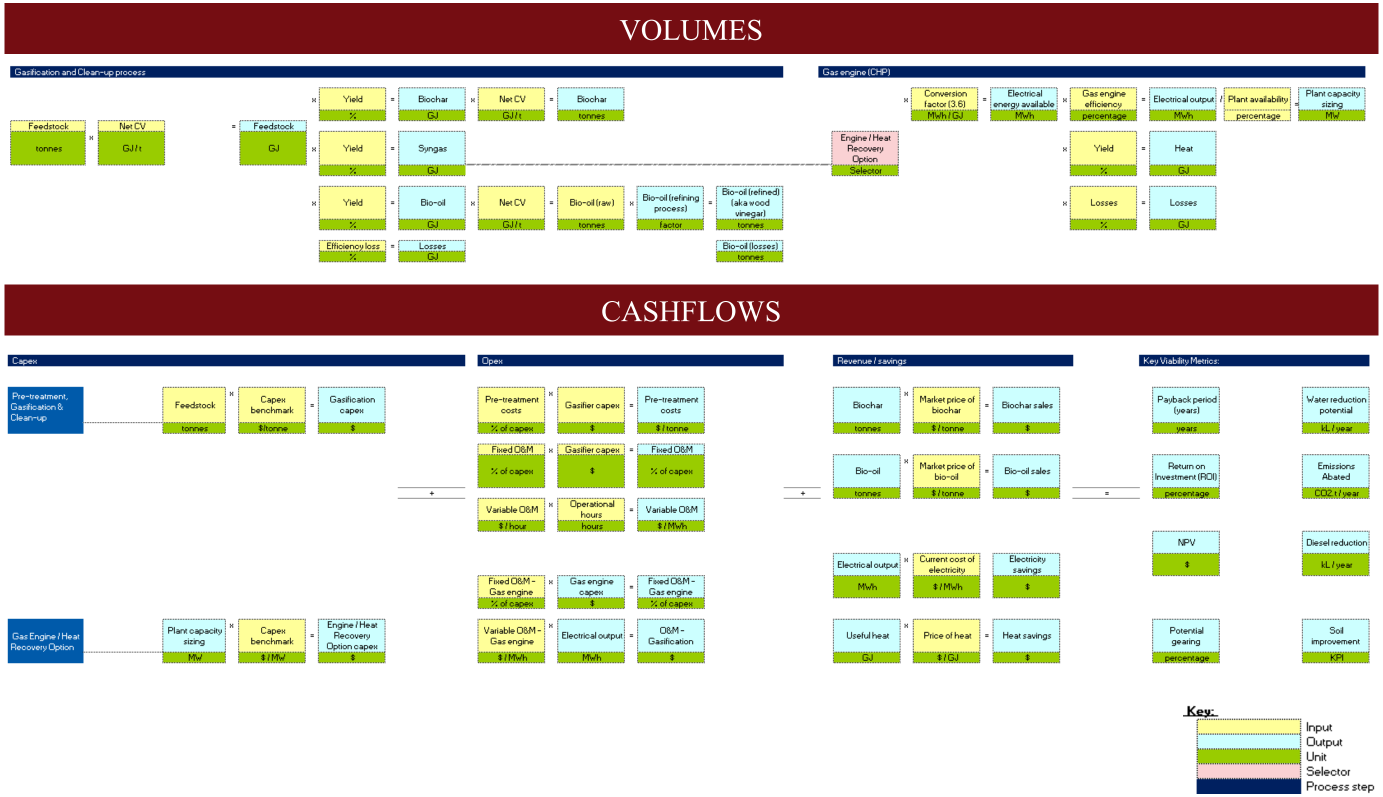
The tool incorporates the market value of energy, value of displacement, nutrient replacement value, operational maintenance costs, CapEx, and all costs and benefits associated with operating a gasification project at a farm and precinct scale. The feasibility assessment tool will enable Agriculture Victoria, service providers of primary producers, and relevant experts to understand the potential opportunity to undertake feasibility assessments for individual farms for onsite gasification and pyrolysis of agricultural residues and / or wood waste.

The tool allows users to input operational parameters which then will produce a scenario-based breakdown of the costs and benefits of advanced thermal treatment operations. The focus of the tool is to assess the commercial viability of pyrolysis or gasification technologies for a farm or a precinct of farms. In order to get the most out of this tool, users should consult with their financial advisor / accountant to fully understand the implications for farm operations.

Tool Overview

The tool has several key features, including a section for users to input project specific parameters, calculation tabs that profile out expected cashflows and benefits over the project life, as well as a dashboard that acts as the main user interface, presents key outputs and allows users to change key inputs to better understand the key drivers of a processed project.

The tool also includes a Process Flow so the user may understand how the tool has been built up, what the drivers are and what key outputs can be expected. The process flow is highlighted in the adjacent figure, which illustrates how the volume of available feedstock drives the volume of heat, electricity and products, and allows the sizing of equipment. This in-turn drives the cashflows in terms of capex, opex, lifecycle costs and revenues. The cashflows are used to highlight key viability metrics such as payback period, rate of return and emissions abated.



Overview of the Financial Tool Process Flow

Financial Tool

A User Guide is included in the financial tool to ensure it is as user friendly as possible. The guide goes through the step-by-step process users should undergo in order to input data, run scenario and interpret the results. The minimum data required from users is the expected feedstock tonnages.

“The User Guide”

A model guide has been produced to ensure that the tool is as user friendly as possible. It includes a step by step approach for how users should utilise the tool including:

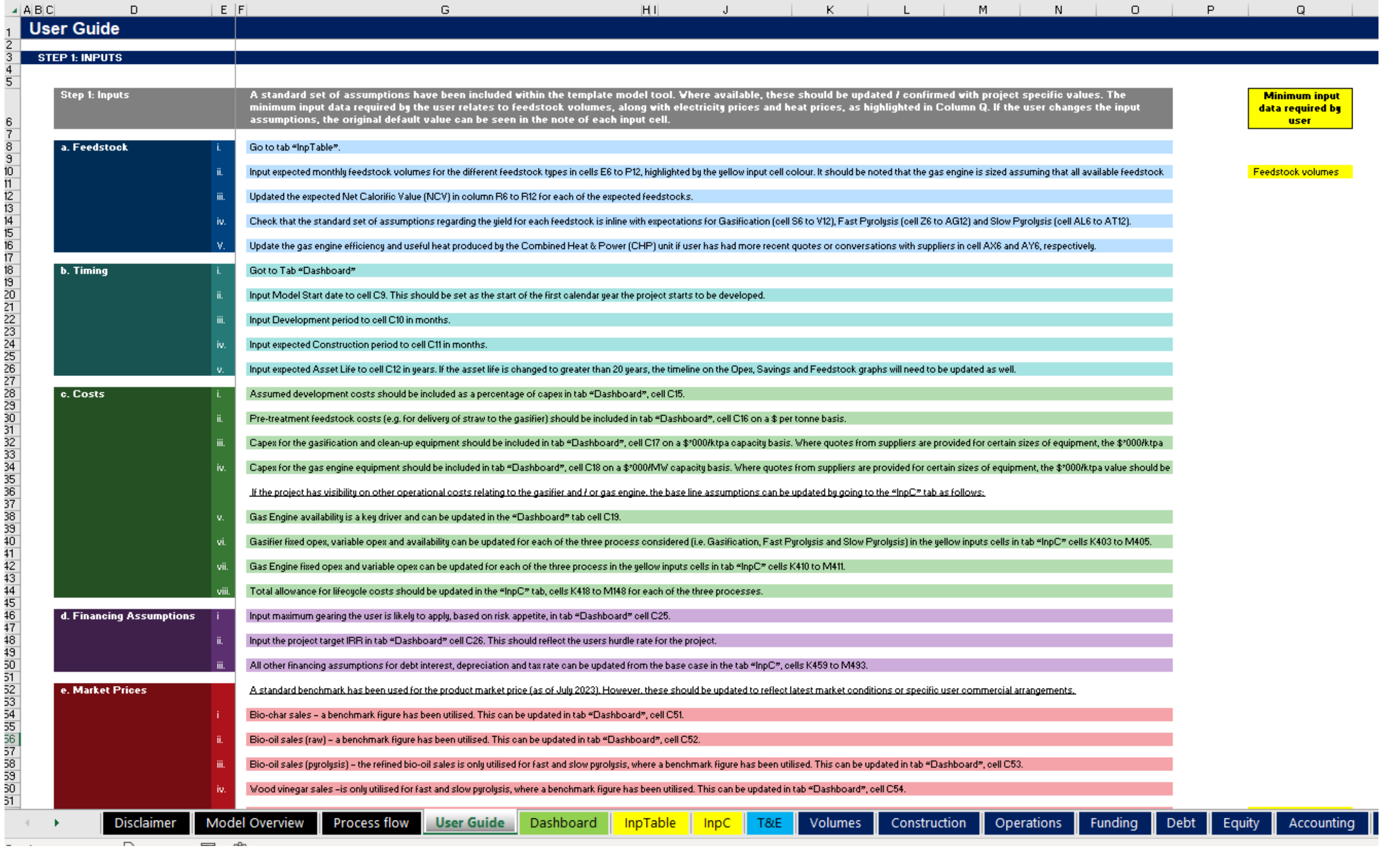
- How to input key data
- How to run different scenario’s
- How to interpret the results

The adjacent image shows an extract from the user guide in the financial tool where there is a clear separation on what users should do when considering each of the key model drivers including feedstock, timing, costs, financing assumptions and market prices of project outputs.

It goes on to describe how the different scenarios can be run, where they can be viewed and other precautions taken to ensure the integrity of the model is maintained.

The tool includes a standard set of assumptions based on a literature review and benchmarked figures. These can either be utilised by users or replaced with project specific values if required. A conservative approach to the base case figures has been taken so that the potential benefits are not too overstated.

The minimum data required from users is the expected feedstock volumes each month, with all other inputs having at least a base case assumption within the model.



User Guide

STEP 1: INPUTS

Step 1: Inputs		**A standard set of assumptions have been included within the template model tool. Where available, these should be updated / confirmed with project specific values. The minimum input data required by the user relates to feedstock volumes, along with electricity prices and heat prices, as highlighted in Column Q. If the user changes the input assumptions, the original default value can be seen in the note of each input cell.**	**Minimum input data required by user**
a. Feedstock	i.	Go to tab “InpTable”.	
	ii.	Input expected monthly feedstock volumes for the different feedstock types in cells E6 to P12, highlighted by the yellow input cell colour. It should be noted that the gas engine is sized assuming that all available feedstock	Feedstock volumes
	iii.	Updated the expected Net Calorific Value (NCV) in column R6 to R12 for each of the expected feedstocks.	
	iv.	Check that the standard set of assumptions regarding the yield for each feedstock is inline with expectations for Gasification (cell S6 to V12), Fast Pyrolysis (cell Z6 to AG12) and Slow Pyrolysis (cell AL6 to AT12).	
	v.	Update the gas engine efficiency and useful heat produced by the Combined Heat & Power (CHP) unit if user has had more recent quotes or conversations with suppliers in cell AX6 and AY6, respectively.	
b. Timing	i.	Got to Tab “Dashboard”	
	ii.	Input Model Start date to cell C9. This should be set as the start of the first calendar year the project starts to be developed.	
	iii.	Input Development period to cell C10 in months.	
	iv.	Input expected Construction period to cell C11 in months.	
	v.	Input expected Asset Life to cell C12 in years. If the asset life is changed to greater than 20 years, the timeline on the Opex, Savings and Feedstock graphs will need to be updated as well.	
c. Costs	i.	Assumed development costs should be included as a percentage of capex in tab “Dashboard”, cell C15.	
	ii.	Pre-treatment feedstock costs (e.g. for delivery of straw to the gasifier) should be included in tab “Dashboard”. cell C16 on a $ per tonne basis.	
	iii.	Capex for the gasification and clean-up equipment should be included in tab “Dashboard”, cell C17 on a $’000/ktpa capacity basis. Where quotes from suppliers are provided for certain sizes of equipment, the $’000/ktpa	
	iv.	Capex for the gas engine equipment should be included in tab “Dashboard”, cell C18 on a $’000/MW capacity basis. Where quotes from suppliers are provided for certain sizes of equipment, the $’000/ktpa value should be	
		<u>If the project has visibility on other operational costs relating to the gasifier and / or gas engine, the base line assumptions can be updated by going to the “InpC” tab as follows:</u>	
	v.	Gas Engine availability is a key driver and can be updated in the “Dashboard” tab cell C19.	
	vi.	Gasifier fixed opex, variable opex and availability can be updated for each of the three process considered (i.e. Gasification, Fast Pyrolysis and Slow Pyrolysis) in the yellow inputs cells in tab “InpC” cells K403 to M405.	
	vii.	Gas Engine fixed opex and variable opex can be updated for each of the three process in the yellow inputs cells in tab “InpC” cells K410 to M411.	
	viii.	Total allowance for lifecycle costs should be updated in the “InpC” tab, cells K418 to M148 for each of the three processes.	
d. Financing Assumptions	i	Input maximum gearing the user is likely to apply, based on risk appetite, in tab “Dashboard” cell C25.	
	ii.	Input the project target IRR in tab “Dashboard” cell C26. This should reflect the users hurdle rate for the project.	
	iii.	All other financing assumptions for debt interest, depreciation and tax rate can be updated from the base case in the tab “InpC”, cells K459 to M493.	
e. Market Prices		<u>A standard benchmark has been used for the product market price (as of July 2023). However, these should be updated to reflect latest market conditions or specific user commercial arrangements.</u>	
	i	Bio-char sales – a benchmark figure has been utilised. This can be updated in tab “Dashboard”, cell C51.	
	ii.	Bio-oil sales (raw) – a benchmark figure has been utilised. This can be updated in tab “Dashboard”, cell C52.	
	iii.	Bio-oil sales (pyrolysis) – the refined bio-oil sales is only utilised for fast and slow pyrolysis, where a benchmark figure has been utilised. This can be updated in tab “Dashboard”, cell C53.	
	iv.	Wood vinegar sales –is only utilised for fast and slow pyrolysis, where a benchmark figure has been utilised. This can be updated in tab “Dashboard”, cell C54.	

Financial Tool

The Dashboard in the financial tool is the main interface with the user. This is where the majority of inputs can be inserted by users and is where the key outputs are presented. The intention is for users to utilise these outputs to help inform decision making on the commercial viability of a project.

The Dashboard

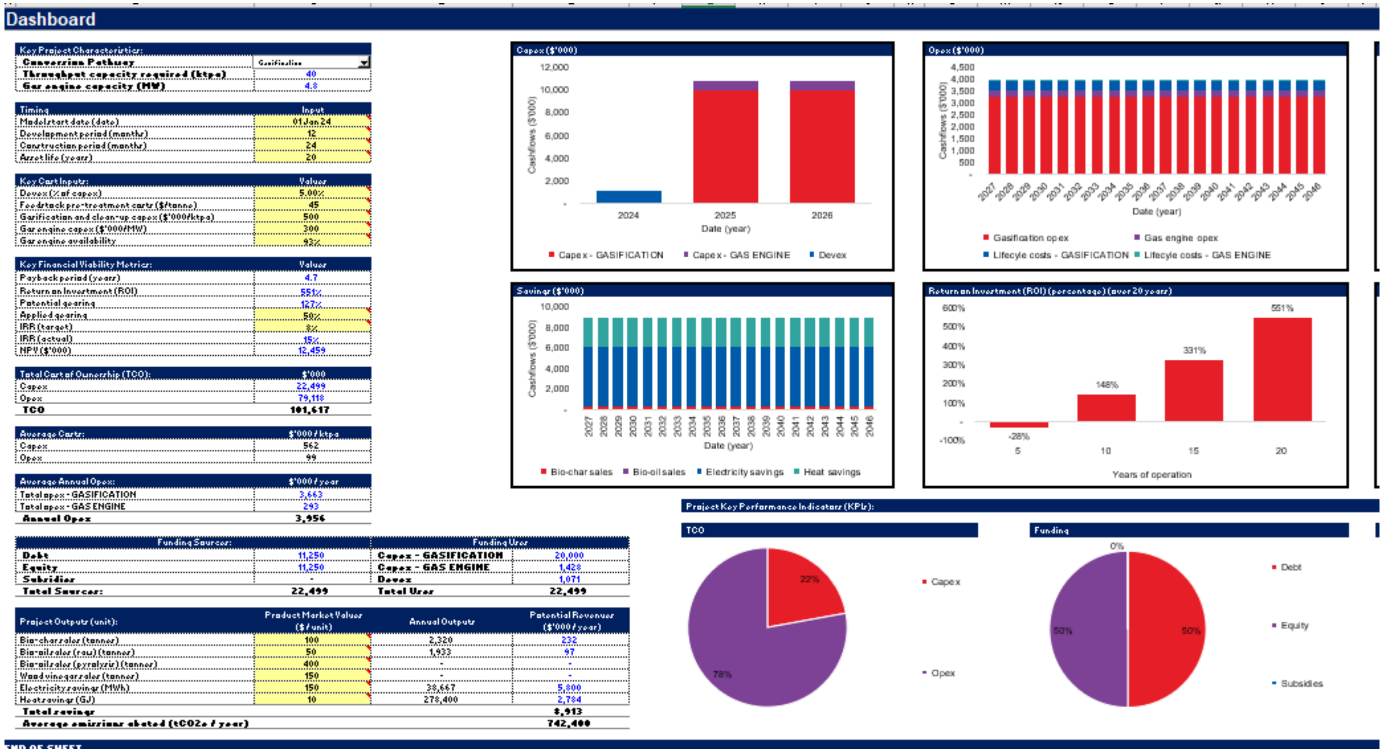
The Dashboard in the financial tool is the main interface with the user. This is where the majority of inputs can be inserted by users and is where the key outputs are presented.

An extract of the Dashboard is presented in the adjacent figure. The yellow cells represent the key inputs driving the model, with the graphs profiling out the cash flows and indicating the potential returns.

The tables are broken down into key categories including project characteristics (where the technology type can be selected via drop down menu), timing assumptions, key cost inputs, financial viability metrics, total cost of ownership in terms of capex and opex, sources and uses of funding (which can be a combination of either debt and equity) and the various revenues from product outputs based on a market value.

The intention is for users to utilise these outputs to help inform decision making on the commercial viability of a project and form part of a larger assessment process into the benefits and risks of a proposed project.

It is expected that a wide range of users will utilise the model with various different backgrounds. Therefore, it would be sensible for users to ensure the proper advice is sought so that the results are not misinterpreted and that the tool can provide the right information to the right people.



Dashboard

Key Project Characteristics:	
Conversion Pathway	Gasification
Throughput capacity required (ktpa)	40
Gas engine capacity (MW)	4.8

Timing	Input
Model start date (date)	01 Jan 24
Development period (months)	12
Construction period (months)	24
Asset life (years)	20

Key Cost Inputs:	Values
Devex (% of capex)	5.00%
Feedstock pre-treatment costs ($/tonne)	45
Gasification and clean-up capex ($'000/ktpa)	500
Gas engine capex ($'000/MW)	300
Gas engine availability	93%

Key Financial Viability Metrics:	Values
Payback period (years)	4.7
Return on Investment (ROI)	551%
Potential gearing	127%
Applied gearing	50%
IRR (target)	8%
IRR (actual)	15%
NPV ($'000)	12,459

Total Cost of Ownership (TCO):	$'000
Capex	22,499
Opex	79,118
TCO	**101,617**

Average Costs:	$'000 / ktpa
Capex	562
Opex	99

Average Annual Opex:	$'000 / year
Total opex - GASIFICATION	3,663
Total opex - GAS ENGINE	293
Annual Opex	**3,956**

Funding Sources:		Funding Uses	
Debt	11,250	**Capex - GASIFICATION**	20,000
Equity	11,250	**Capex - GAS ENGINE**	1,428
Subsidies	-	**Devex**	1,071
Total Sources:	**22,499**	**Total Uses**	**22,499**

Project Outputs (unit):	Product Market Values ($ / unit)	Annual Outputs	Potential Revenues ($'000 / year)
Bio-char sales (tonnes)	100	2,320	232
Bio-oil sales (raw) (tonnes)	50	1,933	97
Bio-oil sales (pyrolysis) (tonnes)	400	-	-
Wood vinegar sales (tonnes)	150	-	-
Electricity savings (MWh)	150	38,667	5,800
Heat savings (GJ)	10	278,400	2,784
Total savings			**8,913**
Average emissions abated (tCO2e / year)			**742,400**

END OF SHEET

Extract from the Financial Tool showing part of the Dashboard

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Appendix A: Stakeholder Responses

Stakeholders Engagement Feedback and Results

Table A1 - Prospective End-Users (1/2)

Respondent Description	**Grain Producer (Western Central Victoria)**	**Grain Producer (Western Central Victoria)**	**Grain Producer (Western Central Victoria)**	**Grain Producer (Western Central Victoria)**	**Grain Producer (Western Central Victoria)**
Do you currently use gasification and/or pyrolysis of biomass residues?	No	No	No	No	No
Are you interested in using gasification and/or pyrolysis of biomass residues?	Yes	Yes	Yes	Yes	Yes
Which energy products or co-products of gasification/pyrolysis of biomass residues are of interest to you?	Electricity + heating + cooling	Electricity (e.g., gasifier + gas engine genset), Biochar, Biofuel (e.g., renewable diesel)	Electricity (e.g., gasifier + gas engine genset), Biochar, Biofuel (e.g., renewable diesel)	Electricity (e.g., gasifier + gas engine genset), Biochar, Biofuel (e.g., renewable diesel)	Electricity + heating, Biochar, Biofuel (e.g., renewable diesel)
If you selected Other, please specify:					
What type of biomass residues would you consider using for gasification and/or pyrolysis?	Agricultural residues (wheat straw, rice straw, husks, wheat bagasse, etc.), Woody biomass (wood chips, tree prunings, etc.)	Agricultural residues (wheat straw, rice straw, husks, wheat bagasse, etc.)	Agricultural residues (wheat straw, rice straw, husks, wheat bagasse, etc.)	Agricultural residues (wheat straw, rice straw, husks, wheat bagasse, etc.)	Agricultural residues (wheat straw, rice straw, husks, wheat bagasse, etc.), Other
If you selected Other, please specify:					Manures
How many tonnes of biomass residue do you currently have access to and/or produce per year?	Between 5,000 tonnes and 10,000 tonnes	Greater than 10,000 tonnes	Between 1,000 tonnes and 5,000 tonnes	Between 5,000 tonnes and 10,000 tonnes	Between 1,000 tonnes and 5,000 tonnes
If you selected Other, please specify:					
What are the main outcomes you would seek from gasification and/or pyrolysis of biomass residues?	Energy security, Source of income / additional revenue	Waste reduction (better biomass management), Source of income / additional revenue	Waste reduction (better biomass management), Energy security, Improve soil health (using biochar), Source of income / additional revenue	Waste reduction (better biomass management), Improve soil health (using biochar), Lowering GHG / emissions, Source of income / additional revenue	Waste reduction (better biomass management), Energy security, Cost savings, Improve soil health (using biochar), Lowering GHG / emissions, Source of income / additional revenue
How do you normally manage your agricultural residues or excess biomass (that may be used for gasification and/or pyrolysis)?	Burning	Retaining crop stubble in the soil	Retaining crop stubble in the soil, Burning	Burning	Retaining crop stubble in the soil, Other
If you selected Other, please specify:					Bail as well to chicken farm and returns to farm as fertiliser
How much does it currently cost ($ per tonne) to manage these residues? Please ignore collection costs.	$5-10/tonne	0	$150	2.5	0
What are your current energy uses and requirements, broken down by source?	Electricity,Other	Electricity,Water		Electricity	Electricity,Gas,Other
If you selected Other, please specify:	transport fuels for tractors and other farm equipment				Diesel

Stakeholders Engagement Feedback and Results

Table A1 - Prospective End-Users (2/2)

Respondent Description	Grain Producer (Western Central Victoria)	Grain Producer (Western Central Victoria)	Grain Producer (Western Central Victoria)	Grain Producer (Western Central Victoria)	Grain Producer (Western Central Victoria)
What are the key metrics that are most important to you that would demonstrate financial success? Please select all that apply.	Revenue (total amount of money generated from sale of products),\ Payback period / Return on Investment, Operating expenses	All of the above	Revenue (total amount of money generated from sale of products), Payback period / Return on Investment, Operating expenses, Construction period and lead time, IRR (Internal rate of return), NPV (Net present Value), Cash flow metrics, All of the above	Revenue (total amount of money generated from sale of products), Payback period / Return on Investment	Payback period / Return on Investment, Construction period and lead time,IRR (Internal rate of return), Cash flow metrics
The Financial Assessment Tool will be an online interactive dashboard interface. When accessing the Financial Assessment Tool dashboard, please select the input and output features that would be most beneficial to you and your business.	Highly customisable number of inputs, Simple output (e.g. payback, total savings)	Limited number of inputs, Simple output (e.g. payback, total savings), Complex financial / investment performance metrics (e.g., EBITDA, depreciation, internal rate of return (IRR), Net Present Value (NPV), return on investment)	Limited number of inputs, Highly customisable number of inputs, Simple output (e.g. payback, total savings), Complex financial / investment performance metrics (e.g., EBITDA, depreciation, internal rate of return (IRR), Net Present Value (NPV), return on investment)	Simple output (e.g. payback, total savings)	Highly customisable number of inputs, Simple output (e.g. payback, total savings)

Stakeholders Engagement Feedback and Results

Table A2 - Implementors

Respondent Details	**Advanced Energy Tech - Adam Riley**	**Meredith Dairy - Dominic Murphy**
What was the total cost ($AUD) to install your gasification and/or pyrolysis system?	$1,120,000	$600,000
What is the rated capacity? Please answer in either tonnes/hour or kW capacity.	300 kg/hr and 1 MWth	CHP - 68kWe, 120kWth
How significant were these costs to your farm business at the time of installation, on a scale of 1 to 5 where 1 is "not at all significant" and 5 is "very significant"?	4	4
What was the main cost for achieving regulatory compliance for your gasification and/or pyrolysis system on your farm?	EPA	Other
If you selected Other, please specify:		Minimal regulatory hurdles due to scale.
Based on your answer above, what was the total cost [$AUD] of the regulatory compliance?	250000	Nil
Which energy products or co-products do you produce from your biomass residues using gasification and/or pyrolysis?	Other	Electricity + heating
If you selected Other, please specify:	Thermal energy - high grade	
How much does it cost annually to operate your gasification and/or pyrolysis system, including operation, maintenance, electricity, labour, etc.?	Will get back to us on this	Estimate of $30,000 maintenance labour
How much does it cost to collect (including storage and transport, if necessary) your biomass feedstock (e.g., $/tonne or $/year)?	Best case scenario: $0 $0/tonne for olive pit and can make this viable	$80,000/year
If you pre-treat your biomass residues (such as drying, chipping, screening) how much does it cost (e.g., $/tonne or $/year)?	Not required of this biomass type	Drying in equipment which is part of the whole system using waste heat from process
What are the main challenges of operating your gasification and/or pyrolysis system?	Biomass availability,Other	Biomass consistency (incl. pre-treatment size reduction),Reliability / maintenance,Other
If you selected Other, please specify:	Technology is only getting better, getting locked in a long-term supply of biomass is the big challenge.	Expertise and parts availability

Stakeholders Engagement Feedback and Results

Table A3 - Technology Suppliers (1/3)

Respondent Details	**Rainbow Bee Eater** **Peter Burgess (Managing Director)**	**Earth Systems** **Andrew Wells (Managing Director)**	**Inoplex** **Brendan Mason**
How many gasification or pyrolysis projects has your company been a part of in Australia (or elsewhere)?	2	12	12
Please provide a list of reference projects and a brief description of the technology implemented.	Holla-Fresh Tantanoola SA 2019 Katunga Fresh Katunga Vic under construction 2023	Earth Systems is an Environmental Sciences and Engineering business. It has developed a novel pyrolysis technology and has commercialised this via two Systems - Batch and Continuous. This allows a vast array of biomass feedstock types and forms to be converted to various biochars. Built and Commissioned plants in Sweden (x2), Israel (x1), Hong Kong (x3), New Zealand (x1), Western Australia (x1), Victoria (x4).	We design and build screw-fed gasifiers for 10 to 500 KW applications
What type(s) of gasification and/or pyrolysis technology do you provide for agricultural residues (biomass)? Please specify if you provide multiple technologies (e.g., gasification and pyrolysis).	Australian designed, owned and manufactured ECHO2 pyrolysis systems	Earth Systems has a focus on pyrolysis, with biochar, wood vinegar and potential high grade heat use/conversion to power.	Biomass is fed through our gasifiers with steam reformers
What is the scale or input/ouput capacity of your gasification and/or pyrolysis technology (e.g., feedstock tonne/hour input, electrical output or nameplate capacity)? Please specify if you provide multiple technologies or system capacities.	ECHO2 '6 pack' per Katunga Fresh project 4MW of clean dry syngas, 2 tonnes an hour of high carbon biochar and 5 tonnes an hour of CO2 removal certificates from 5 tonnes an hour of straw of dry wood residues.	Batch System (FPP) - 10mT woody feedstock/6-7 hour batch. 2m3 biochar/batch. 1000L wood vinegar/batch. Heat energy approx. 1.5Mw peak. Continuous System (CPP) - 500kg feedstock/hour. Approx. 100kg biochar/hour. 1-100L wood vinegar/hour. Heat energy approx. 5-600 kw.	10 to 500 kg per hour
Which energy products or co-products do your PYROLYSIS systems produce from biomass residues?	Purified and cooled syngas, Biochar, Other	Biochar, Bio-oil, Electricity + heating	Syngas, Biochar, Electricity (e.g., syngas), Electricity + heating, Electricity + heating + cooling
If you selected Other, please specify:	CORCs (carbon removal certificates) and Wood Vinegar		
Which energy products or co-products do your GASIFICATION systems produce from biomass residues?	Purified and cooled syngas, Biochar, Other	Not applicable	Syngas, Biochar, Electricity (e.g., gasifier + gas engine genset), Electricity + heating, Electricity + heating + cooling
If you selected Other, please specify:	CORCs (carbon removal certificates) and Wood Vinegar		
What is the total cost for supply, installation, and commissioning of your gasification /pyrolysis systems on a kW or tonnes/per annum basis?	AUD20M for 4MW clean dry syngas	Our plants start from USD$750,000 ex-works, ex-taxes & duties, + installation & commissioning + travel and accomodation costs and servicing.+ per diems.	0
How much does it cost annually to operate your gasification/pyrolysis system, including, maintenance, electricity, labour, etc.?	Circa $1.5M/year	1-2 FTE's + 3-5% Purchase price	0
What are the main challenges of operating your PYROLYSIS system?	Biomass storage (incl. pre-treatment drying etc), Biomass consistency (incl. pre-treatment size reduction)	Start-up / shut-down issues, Not applicable	Biomass storage (incl. pre-treatment drying etc)
If you selected Other, please specify:		Batch and Continuous plants have slightly different characteristics. Both are robust systems, but are designed to run constantly - so less cooling right down and then heating right back up again the better.	

Stakeholders Engagement Feedback and Results

Table A3 - Technology Suppliers (2/3)

Respondent Details	**Rainbow Bee Eater** **Peter Burgess (Managing Director)**	**Earth Systems** **Andrew Wells (Managing Director)**	**Inoplex** **Brendan Mason**
What are the main challenges of operating your GASIFICATION system?	Biomass storage (incl. pre-treatment drying etc), Biomass consistency (incl. pre-treatment size reduction)	Not applicable	Biomass storage (incl. pre-treatment drying etc)
If you selected Other, please specify:		We don't focus directly on gasification.	
What types of agricultural residues can your technology accept?	Wheat straw, Rice straw, Wood chips, Tree pruning, Husks, Other	Wheat straw, Rice straw, Wood chips, Tree pruning, Husks, Other	Wheat straw, Rice straw, Wood chips, Tree pruning, Husks, Other
If you selected Other, please specify:	Bagasse, cotton trash - as best we understand - anything that is mixed size particles circa 90% between 2 & 15mm (not sludge) and < 25% moisture	Many, many others - we have a CPP taking stable waste (saw dust, shredded paper/carboard, horse manure), we have one taking compost, we have done work on incontinence waste and also biosolids, we've looked at spent meal, cotton gin waste and packaging materials. Other non-ag materials.	coffee grinds
For your gasification/pyrolysis technologies to function optimally, is there a necessary feedstock specification such as particle size, moisture content, volatile content, ash content, density, chemical composition, etc.? If so, please explain.	Mixed particle size circa 90% between 2 & 15mm. < 25% moisture. Wood residues with minor contamination with non-F & Cl plastics will be OK. Not CCA.	The two key variables are biomass energy content and moisture content. We provide both a Batch System and Continuous System to cater for the differing types and forms of biomass feedstock. Blending of different feedstocks allows processing of a broader range of biomass types and this is a key feature of CPP.	No, non-optimal materials can be processed, the yields are lower
What pre-treatment, if any, is required?	Size. Moisture <25%.	Earth Systems has developed two complimentary Pre-Dryer Systems to couple with both the Batch System and Continuous System. This takes the excess high-grade heat we produce in our self-sustaining process and helps reduce feedstock moisture content prior to pyrolysis and therefore optimises CharMaker (name we give to our pyrolysis plants) throughput.	drying
Can a single gasifier or pyrolysis unit accept different types of residues, with or without blending (i.e., fuel flexibility)?	No		
If the answer above was YES, please detail the different types of residues the unit can accept.		Depends on the System: Batch - whole branches, tree limbs, prunings, vines, sleepers, untreated fence posts, pallets etc. Continuous - chipped: branches, limbs, tree prunings, chipped pallet waste, straw, husks, hulls, olive pips, almond waste, manures, packaging materials, cotton gin waste, shredded material/textile, biosolids and literally many more	

Stakeholders Engagement Feedback and Results

Table A3 - Technology Suppliers (3/3)

Respondent Details	**Rainbow Bee Eater** **Peter Burgess (Managing Director)**	**Earth Systems** **Andrew Wells (Managing Director)**	**Inoplex** **Brendan Mason**
What would be the conversion factor or efficiency of each stage of your gasification/pyrolysis system, e.g., for each kJ in feedstock how many kJ is in the purified syngas?	Circa 25% with wood and straw	Pyrolysis' rule of thumb, is roughly 20-25% of feedstock is converted to biochar	0
Please outline how the feedstock characteristics would affect them.	High ash feedstocks will have lower % gasification	Biomass high in cello-lignin produces high grade biochar with low ash. Agricultural straws have lower lignin and much higher ash content, so less biochar. But we learning all the time, they all have a fit , place or use.	0
What are the main factors that drive commercial feasibility of gasification or pyrolysis projects? Please select all that apply.	Electricity and gas prices, Environmental benefits	Feedstock availability and cost,Government policies and incentives,Environmental benefits,Social perception,Other	Feedstock availability and cost
What are the key drivers of operational feasibility for gasification or pyrolysis projects? Please select all that apply.	Environmental benefits, Energy security or reliability, Other	Available feedstock(s), Energy savings, Environmental benefits, Social license, Soil benefits from biochar, Other	Available feedstock(s)
If you selected Other, please specify:	Establishing first and second mover projects requires energy project owner champion. Biochar & Wood Vinegar Markets still emerging.	Reduction of Landfill, Animal Health benefits,	
For your gasification and pyrolysis units, what are the key parameters that affect capital and operating costs? Please select all that apply.	Capacity and size of the bioenergy technology, Feedstock characteristics, Energy output and utilisation, Feedstock transportation and logistics	Feedstock characteristics, Energy output and utilisation, Feedstock transportation and logistics, Regulatory compliance	Capacity and size of the bioenergy technology, Feedstock characteristics
If you selected Other, please specify:			
Would you be interested in participating in a more detailed interview in the future?	Yes	Yes	Yes

Stakeholders Engagement Feedback and Results

Table A4 – Industry Associations and Representatives

Respondent Description	**Victorian Bioenergy Network** **Daryl Scherger**	**Australasian Agriculture Equities** **Ber Draper**	**Agriculture Victoria**
What are the key trends that you are observing in the agriculture and energy sectors?	• Concern about rising cost of fuel and fertiliser, Increasing interest in utilisation of agricultural biomass (but from a very low base) slowness in developing government policies for implementing mature bioenergy technologies that are in wide use overseas • Increasing interest amongst farmers in addressing climate change and utilizing their wastes. Higher energy costs are also driving interest in on farm energy production.	Sustainability Regeneration	• Energy price volatility and increases are making investment in sustainable energy all the more appealing. • With ever increasing utility costs and the cost of doing business, farmers are continually looking at ways to become more efficient and at ways to better manage these costs.
What are the key focus areas that project developers/facilitators/implementors of this technology need to demonstrate to access government funding for projects? Please select all that apply.	• Sustainability (carbon emissions savings), • Economic viability, • Technical expertise, • Feedstock availability, • Community engagement (community benefits), • Other	• Sustainability (carbon emissions savings), • Economic viability, • Technical expertise, • Community engagement (community benefits)	• Sustainability (carbon emissions savings), • Economic viability, • Technical expertise, • Feedstock availability, • Community engagement (community benefits)
If you selected Other, please specify:	• Availability of reliable authoritative up to date information for all sectors • Potential jobs created.		How it aligns with broader government objectives
In your opinion, what are the top three challenges for agricultural producers implementing gasification or pyrolysis on their sites?	• Cost, • Permits and regulatory compliance, • Technical expertise (new skills required to maintain the bioenergy units)	Cost, Permits and regulatory compliance, Feedstock availability	• Cost • Technical expertise (new skills required to maintain the bioenergy units), • Feedstock availability • Market demand

Appendix B: Syngas Purification Processes

Advanced thermal treatment processes
Process overview

Table B1: Syngas contaminants and relevant cleaning technologies

Contaminant	Technique employed	Process	Principle	T (°C)	Removal efficiency (%)	Comments
Tar	Hot Gas Cleaning Technique (HGC)	Thermal Cracking	Employing high T to crack tar	1100-1300	~80%	Expensive, results in low process efficiency
		Catalytic cracking	Employing catalyst to crack tar at comparatively low T	Vary	Varies	Operational challenges due to coking, sintering and poisoning
		Non-thermal plasma	Decomposition of tar by plasma	~400 (pulsed corona plasma)	Varies	Complex, high-energy demand
	Cold gas cleaning technique (CGC)	Wet scrubbing	Absorption of tar components in H2O	<100	Varies	Waste H_2O needs treatment prior to discharge
Particulates	Hot Gas Cleaning Technique (HGC)	Cyclones	Inertial separation	> 1000	90%	e.g., conventional and enhanced cyclones
		Filtration	Diffusion ,inertial impaction, gravitational settling	~ 250 (fabric) ~600 (panel bed) ~1000 (metal barrier)	~99%	e.g., fabric filter, panel bed filter, metal barrier filter &rigid filter
		Electro-static separations	Difference in dielectric properties under electric field	~400	Not available	e.g., parallel plate precipitator, tube type
	Cold gas cleaning technique (CGC)	Wet scrubbing	(i) Separation by inertial force (ii) electrostatic force (iii) T gradient (iv) liquid vapour pressure	< 100	~95% (PM5) ~70% (sub-micron) (dynamic scrubber)	e.g., spray (scrubber, wet dynamic scrubber, cyclonic scrubber, impact wet scrubber)

Advanced thermal treatment processes

Process overview

Table B2: Syngas Purification Processes

Process	Description
Thermal Cracking and catalytic reforming	The traditional chemical methods for tar removal are thermal cracking and catalytic reforming; thermal cracking converts tar into syngas and coke at high temperature ($T > 800$ °C) in the absence of a catalyst; catalytic reforming takes place in the presence of a catalyst, usually Ni, and tar is converted mainly into syngas. These two methods suffer from low conversion efficiency and rapid catalyst deactivation.
Cyclones, filtration and wet scrubbing	To comply with environmental regulations and protect downstream processes, syngas must undergo cleaning to eliminate various contaminants such as fine particulates, sulfur, ammonia, chlorides, mercury, and trace heavy metals. Depending on the specific application, conditioning of the syngas may be necessary to adjust the hydrogen-to-carbon monoxide (H2-to-CO) ratio according to downstream process requirements. Typical processes for clean-up and conditioning include cyclones and filters for bulk particulate removal, wet scrubbing for fine particulate, ammonia, and chloride removal, solid absorbents for mercury and trace heavy metal removal, water gas shift (WGS) for H2-to-CO ratio adjustment. Regarding fine particulate removal, raw syngas is typically cooled and scrubbed with water in a trayed column to eliminate fine char and ash particles before recycling to the slurry-fed gasifiers. In dry feed gasification, cyclones and candle filters are employed to recover most of the fine particulates for recycling to the gasifiers, followed by final clean-up using water quenching and scrubbing. The scrubbing process also removes fine particulates, chlorides, ammonia, some H2S, and other trace contaminants from the syngas. The spent water from the scrubber column is directed to the sour water treatment system. Solid-concentrated underflows from the settler bottom are filtered to recover the fine particulates as a filter cake, which can either be discarded or recycled to the gasifier based on its carbon content. The settler water is recycled for gasification purposes, with any excess sent to the wastewater treatment system for disposal [1].
Plasma cracking	Plasma cracking of tars is a method that uses plasma to decompose tars into less harmful substances. Plasma, consisting of free radicals, ions, and excited molecules, creates a highly reactive environment that initiates tar decomposition reactions. There are two types of plasma cracking: thermal and non-thermal, based on the plasma temperatures. Thermal plasma is mainly used as a heat source in single-stage or two-stage systems, while non-thermal plasma systems utilize various types of plasma sources. Non-thermal plasma has been successful in removing tar model compounds, such as naphthalene, with high conversion rates. However, the real-life application of plasma cracking is limited due to disadvantages like the limited lifetime of pulsed power devices, high costs, and high energy demand. Nevertheless, plasma cracking remains relatively effective for tar removal from syngas [2].
Electrostatic precipitator (ESP)	An electrostatic precipitator (ESP) is a device that removes dust or other fine particles from gases. It comprises two electrodes between which electrical charges circulate. The discharge electrode is supplied with high voltage (negative or positive) and charges the particles present in the gas to be cleaned. Then the charged particles drift toward the earthed electrode where they are neutralised. The particles collected are recovered in the lower part of the ESP by a rapping system of the collecting electrode [3].

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1. National Energy Technology Laboratory, 6.2 SYNGAS CONTAMINANT REMOVAL AND CONDITIONING. https://netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/cleanup
2. Lotfi S, Ma W, Tunney J and Du N. (2021). Technologies for Tar Removal from Biomass-Derived Syngas. Petroleum & Petrochemical Engineering Journal. 5. 1-35. 10.23880/ppej-16000271.
3. Villot, A., Gonthier, Y., Gonze, E., Bernis, A., Ravel, S., Grateau, M., and Guillaudeau, J. (2012). Separation of particles from syngas at high-temperatures with an electrostatic precipitator. https://doi.org/10.1016/j.seppur.2011.04.028.

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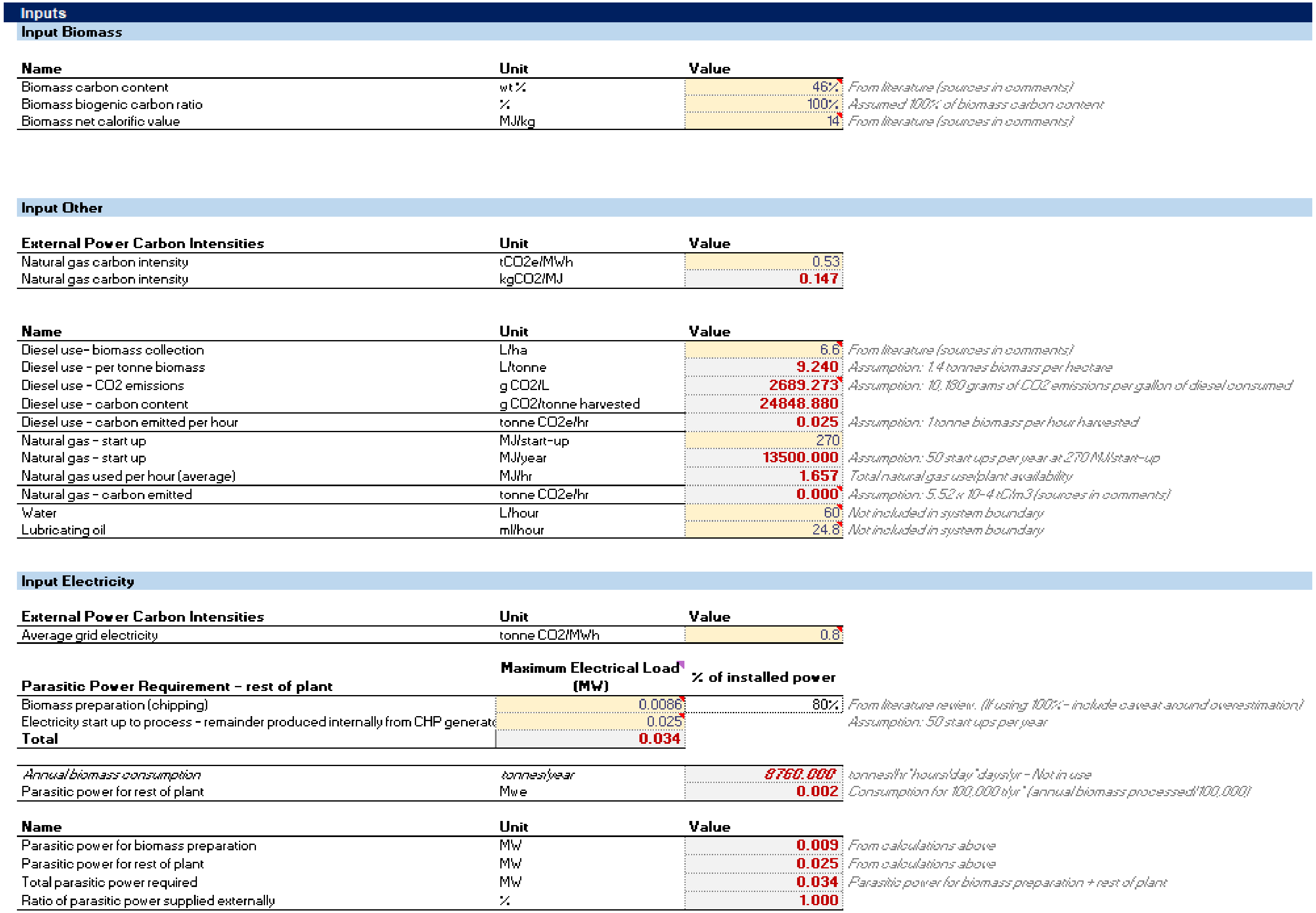
Appendix C: Carbon Assessment Model Details

Carbon assessment model
Model overview



Inputs

Input Biomass

Name	Unit	Value	
Biomass carbon content	wt %	46%	*From literature (sources in comments)*
Biomass biogenic carbon ratio	%	100%	*Assumed 100% of biomass carbon content*
Biomass net calorific value	MJ/kg	14	*From literature (sources in comments)*

Input Other

External Power Carbon Intensities	Unit	Value
Natural gas carbon intensity	tCO2e/MWh	0.53
Natural gas carbon intensity	kgCO2/MJ	**0.147**

Name	Unit	Value	
Diesel use- biomass collection	L/ha	6.6	*From literature (sources in comments)*
Diesel use - per tonne biomass	L/tonne	**9.240**	*Assumption: 1.4 tonnes biomass per hectare*
Diesel use - CO2 emissions	g CO2/L	**2689.273**	*Assumption: 10,180 grams of CO2 emissions per gallon of diesel consumed*
Diesel use - carbon content	g CO2/tonne harvested	**24848.880**	
Diesel use - carbon emitted per hour	tonne CO2e/hr	**0.025**	*Assumption: 1 tonne biomass per hour harvested*
Natural gas - start up	MJ/start-up	270	
Natural gas - start up	MJ/year	**13500.000**	*Assumption: 50 start ups per year at 270 MJ/start-up*
Natural gas used per hour (average)	MJ/hr	**1.657**	*Total natural gas use/plant availability*
Natural gas - carbon emitted	tonne CO2e/hr	**0.000**	*Assumption: 5.52 x 10-4 tC/m3 (sources in comments)*
Water	L/hour	60	*Not included in system boundary*
Lubricating oil	ml/hour	24.8	*Not included in system boundary*

Input Electricity

External Power Carbon Intensities	Unit	Value
Average grid electricity	tonne CO2/MWh	0.8

Parasitic Power Requirement - rest of plant	Maximum Electrical Load (MW)	% of installed power	
Biomass preparation (chipping)	0.0086	80%	*From literature review. (If using 100% - include caveat around overestimation)*
Electricity start up to process - remainder produced internally from CHP generat	0.025		*Assumption: 50 start ups per year*
Total	**0.034**		

Annual biomass consumption	*tonnes/year*	***8760.000***	*tonnes/hr *hours/day *days/yr - Not in use*
Parasitic power for rest of plant	Mwe	**0.002**	*Consumption for 100,000 t/yr * (annual biomass processed/100,000)*

Name	Unit	Value	
Parasitic power for biomass preparation	MW	**0.009**	*From calculations above*
Parasitic power for rest of plant	MW	**0.025**	*From calculations above*
Total parasitic power required	MW	**0.034**	*Parasitic power for biomass preparation + rest of plant*
Ratio of parasitic power supplied externally	%	**1.000**	

1. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references
2. https://www.sciencedirect.com/science/article/pii/S2667056922000700
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17. https://onlinelibrary.wiley.com/doi/10.1002/jpln.202100239
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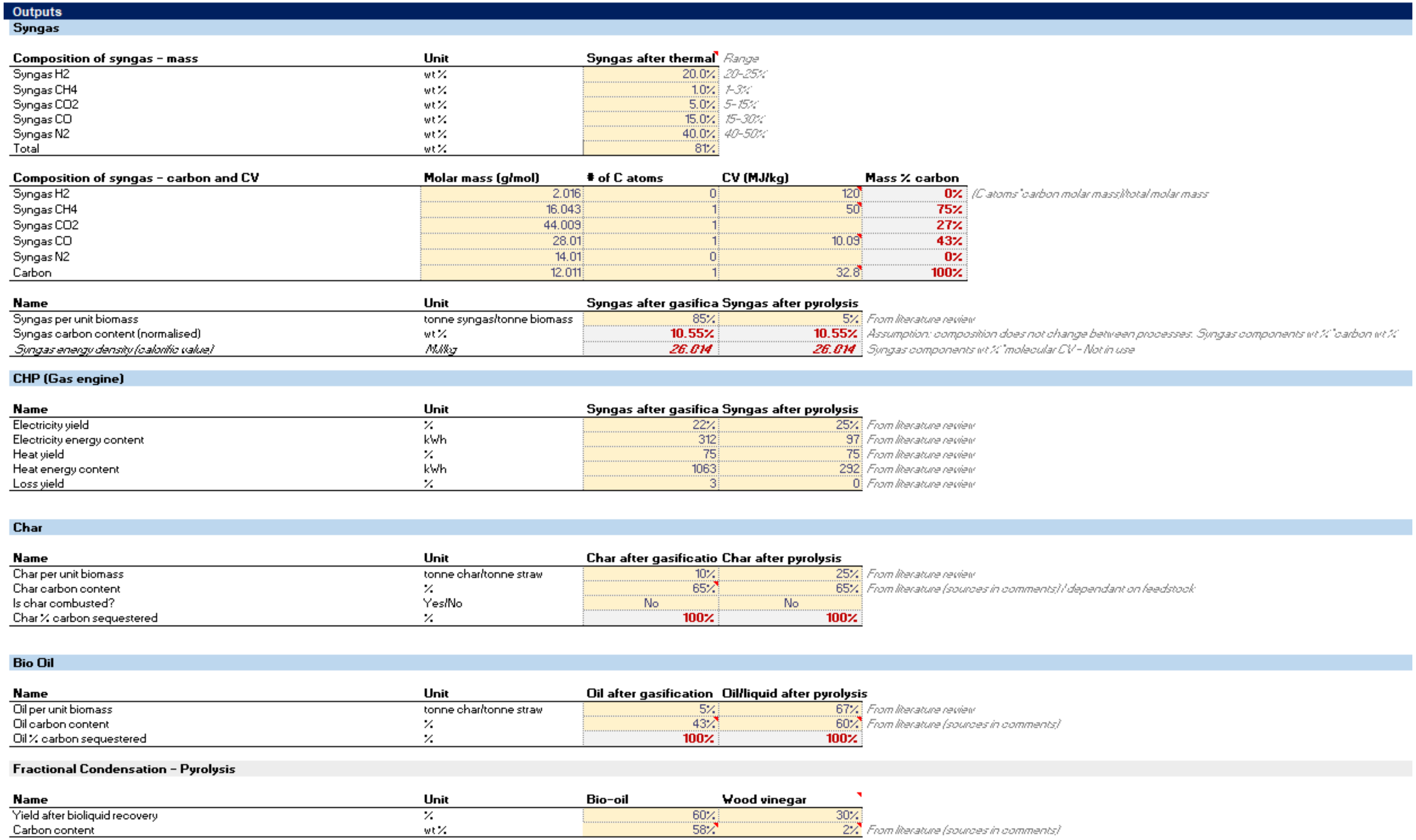
Carbon assessment model
Model overview



Outputs

Syngas

Composition of syngas - mass	Unit	Syngas after thermal	Range
Syngas H_2	wt %	20.0%	20-25%
Syngas CH_4	wt %	1.0%	1-3%
Syngas CO_2	wt %	5.0%	5-15%
Syngas CO	wt %	15.0%	15-30%
Syngas N_2	wt %	40.0%	40-50%
Total	wt %	81%	

Composition of syngas - carbon and CV	Molar mass (g/mol)	# of C atoms	CV (MJ/kg)	Mass % carbon	
Syngas H_2	2.016	0	120	0%	(C atoms*carbon molar mass)/total molar mass
Syngas CH_4	16.043	1	50	75%	
Syngas CO_2	44.009	1		27%	
Syngas CO	28.01	1	10.09	43%	
Syngas N_2	14.01	0		0%	
Carbon	12.011	1	32.8	100%	

Name	Unit	Syngas after gasifica	Syngas after pyrolysis	
Syngas per unit biomass	tonne syngas/tonne biomass	85%	5%	From literature review
Syngas carbon content (normalised)	wt %	10.55%	10.55%	Assumption: composition does not change between processes. Syngas components wt % *carbon wt %
Syngas energy density (calorific value)	*MJ/kg*	*26.014*	*26.014*	Syngas components wt % *molecular CV - Not in use

CHP (Gas engine)

Name	Unit	Syngas after gasifica	Syngas after pyrolysis	
Electricity yield	%	22%	25%	From literature review
Electricity energy content	kWh	312	97	From literature review
Heat yield	%	75	75	From literature review
Heat energy content	kWh	1063	292	From literature review
Loss yield	%	3	0	From literature review

Char

Name	Unit	Char after gasificatio	Char after pyrolysis	
Char per unit biomass	tonne char/tonne straw	10%	25%	From literature review
Char carbon content	%	65%	65%	From literature (sources in comments) / dependant on feedstock
Is char combusted?	Yes/No	No	No	
Char % carbon sequestered	%	100%	100%	

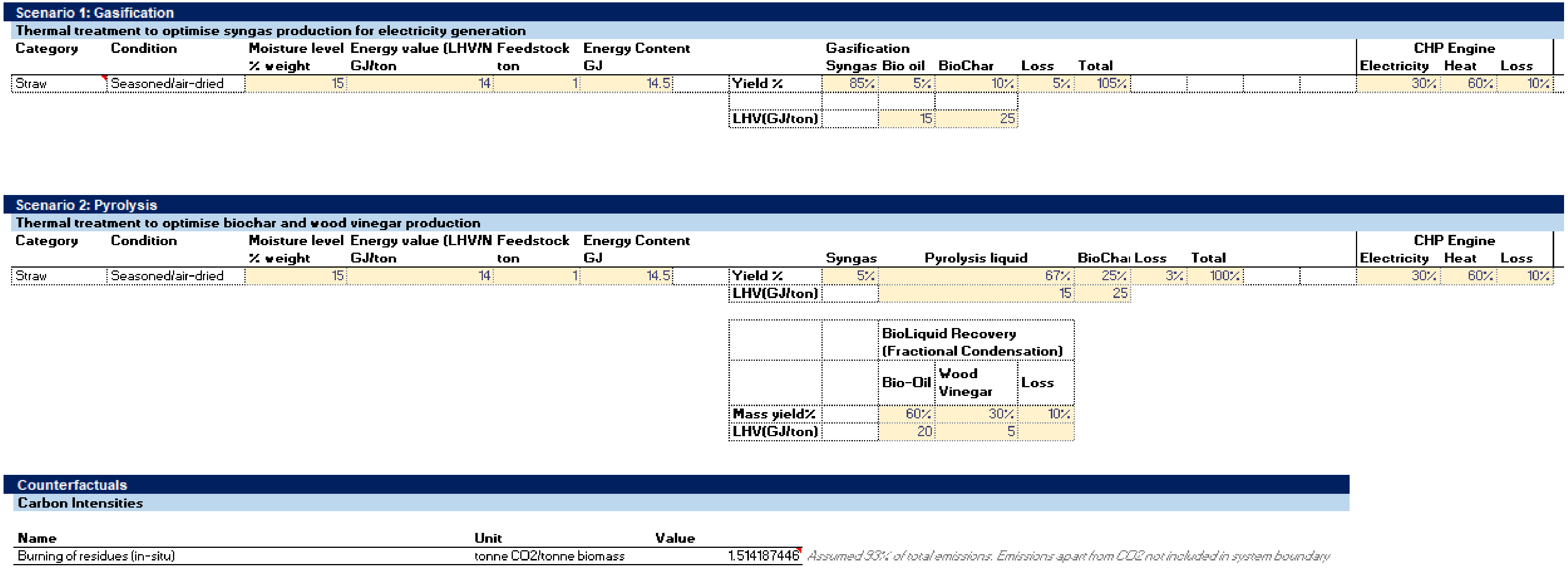
Bio Oil

Name	Unit	Oil after gasification	Oil/liquid after pyrolysis	
Oil per unit biomass	tonne char/tonne straw	5%	67%	From literature review
Oil carbon content	%	43%	60%	From literature (sources in comments)
Oil % carbon sequestered	%	100%	100%	

Fractional Condensation - Pyrolysis

Name	Unit	Bio-oil	Wood vinegar	
Yield after bioliquid recovery	%	60%	30%	
Carbon content	wt %	58%	2%	From literature (sources in comments)

Carbon assessment model
Model overview



Scenario 1: Gasification

Thermal treatment to optimise syngas production for electricity generation

Category	Condition	Moisture level % weight	Energy value (LHV/N GJ/ton	Feedstock ton	Energy Content GJ
Straw	Seasoned/air-dried	15	14	1	14.5

	Gasification Syngas	Bio oil	BioChar	Loss	Total
Yield %	85%	5%	10%	5%	105%
LHV(GJ/ton)		15	25		

CHP Engine Electricity	Heat	Loss
30%	60%	10%

Scenario 2: Pyrolysis

Thermal treatment to optimise biochar and wood vinegar production

Category	Condition	Moisture level % weight	Energy value (LHV/N GJ/ton	Feedstock ton	Energy Content GJ
Straw	Seasoned/air-dried	15	14	1	14.5

	Syngas	Pyrolysis liquid	BioChai	Loss	Total
Yield %	5%	67%	25%	3%	100%
LHV(GJ/ton)		15	25		

CHP Engine Electricity	Heat	Loss
30%	60%	10%

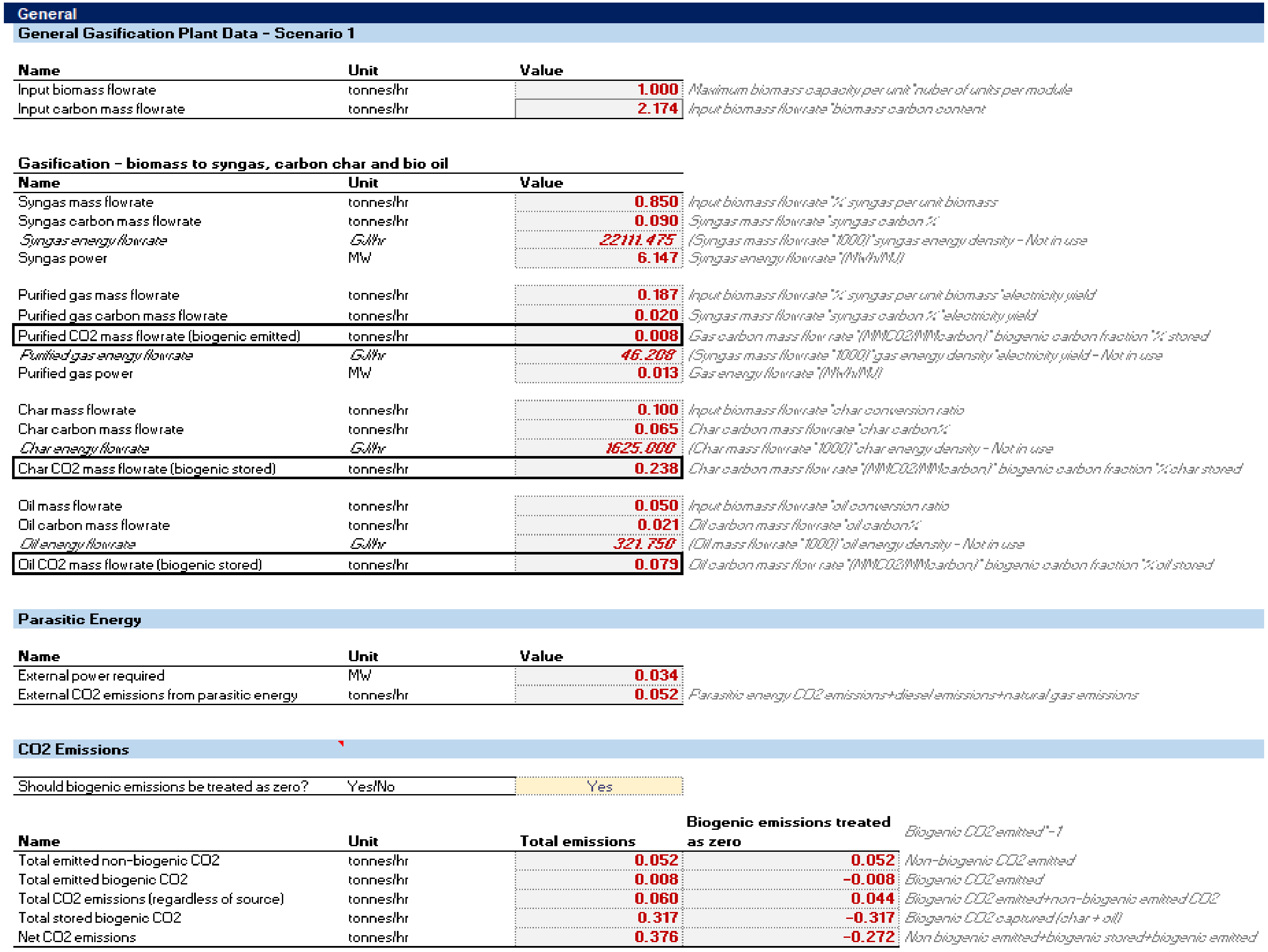
		BioLiquid Recovery (Fractional Condensation)		
		Bio-Oil	**Wood Vinegar**	**Loss**
Mass yield%		60%	30%	10%
LHV(GJ/ton)		20	5	

Counterfactuals

Carbon Intensities

Name	Unit	Value	
Burning of residues (in-situ)	tonne CO2/tonne biomass	1.514187446	*Assumed 93% of total emissions. Emissions apart from CO2 not included in system boundary*

Carbon assessment model
Model overview



General

General Gasification Plant Data - Scenario 1

Name	Unit	Value	
Input biomass flowrate	tonnes/hr	1.000	Maximum biomass capacity per unit *nuber of units per module
Input carbon mass flowrate	tonnes/hr	2.174	Input biomass flowrate *biomass carbon content

Gasification - biomass to syngas, carbon char and bio oil

Name	Unit	Value	
Syngas mass flowrate	tonnes/hr	0.850	Input biomass flowrate *% syngas per unit biomass
Syngas carbon mass flowrate	tonnes/hr	0.090	Syngas mass flowrate *syngas carbon %
Syngas energy flowrate	*GJ/hr*	*22111.475*	(Syngas mass flowrate *1000)*syngas energy density - Not in use
Syngas power	MW	6.147	Syngas energy flowrate *(MWh/MJ)
Purified gas mass flowrate	tonnes/hr	0.187	Input biomass flowrate *% syngas per unit biomass *electricity yield
Purified gas carbon mass flowrate	tonnes/hr	0.020	Syngas mass flowrate *syngas carbon % *electricity yield
Purified CO2 mass flowrate (biogenic emitted)	tonnes/hr	0.008	Gas carbon mass flow rate *(MMCO2/MMcarbon) * biogenic carbon fraction *% stored
Purified gas energy flowrate	*GJ/hr*	*46.208*	(Syngas mass flowrate *1000)*gas energy density *electricity yield - Not in use
Purified gas power	MW	0.013	Gas energy flowrate *(MWh/MJ)
Char mass flowrate	tonnes/hr	0.100	Input biomass flowrate *char conversion ratio
Char carbon mass flowrate	tonnes/hr	0.065	Char carbon mass flowrate *char carbon%
Char energy flowrate	*GJ/hr*	*1625.000*	(Char mass flowrate *1000)*char energy density - Not in use
Char CO2 mass flowrate (biogenic stored)	tonnes/hr	0.238	Char carbon mass flow rate *(MMCO2/MMcarbon) * biogenic carbon fraction *% char stored
Oil mass flowrate	tonnes/hr	0.050	Input biomass flowrate *oil conversion ratio
Oil carbon mass flowrate	tonnes/hr	0.021	Oil carbon mass flowrate *oil carbon%
Oil energy flowrate	*GJ/hr*	*321.750*	(Oil mass flowrate *1000)*oil energy density - Not in use
Oil CO2 mass flowrate (biogenic stored)	tonnes/hr	0.079	Oil carbon mass flow rate *(MMCO2/MMcarbon) * biogenic carbon fraction *% oil stored

Parasitic Energy

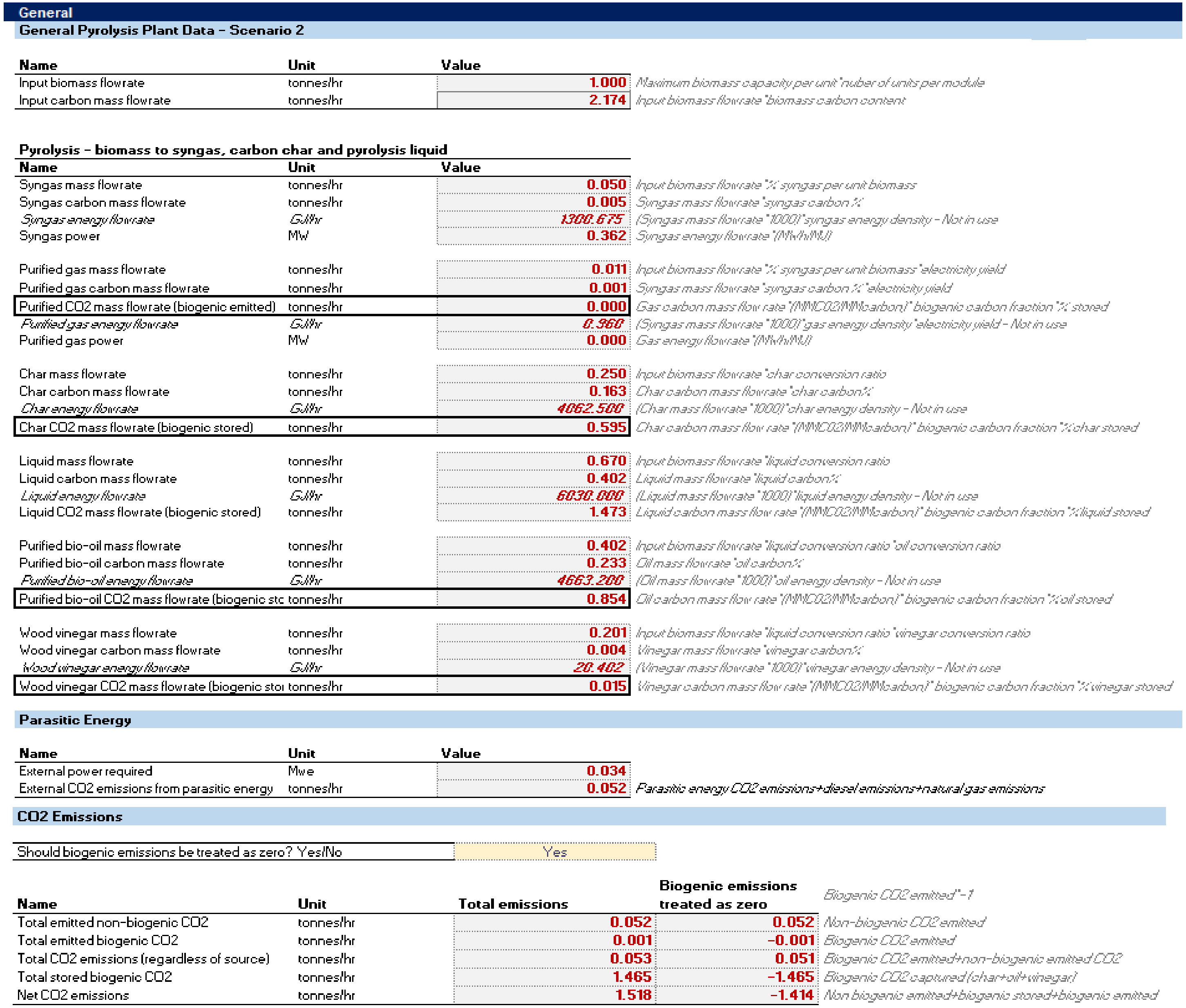
Name	Unit	Value	
External power required	MW	0.034	
External CO2 emissions from parasitic energy	tonnes/hr	0.052	Parasitic energy CO2 emissions+diesel emissions+natural gas emissions

CO2 Emissions

Should biogenic emissions be treated as zero?	Yes/No	Yes

Name	Unit	Total emissions	Biogenic emissions treated as zero	Biogenic CO2 emitted*-1
Total emitted non-biogenic CO2	tonnes/hr	0.052	0.052	Non-biogenic CO2 emitted
Total emitted biogenic CO2	tonnes/hr	0.008	-0.008	Biogenic CO2 emitted
Total CO2 emissions (regardless of source)	tonnes/hr	0.060	0.044	Biogenic CO2 emitted+non-biogenic emitted CO2
Total stored biogenic CO2	tonnes/hr	0.317	-0.317	Biogenic CO2 captured (char + oil)
Net CO2 emissions	tonnes/hr	0.376	-0.272	Non biogenic emitted+biogenic stored+biogenic emitted

Carbon assessment model
Model overview



General

General Pyrolysis Plant Data - Scenario 2

Name	Unit	Value	
Input biomass flowrate	tonnes/hr	1.000	*Maximum biomass capacity per unit *nuber of units per module*
Input carbon mass flowrate	tonnes/hr	2.174	*Input biomass flowrate *biomass carbon content*

Pyrolysis - biomass to syngas, carbon char and pyrolysis liquid

Name	Unit	Value	
Syngas mass flowrate	tonnes/hr	0.050	*Input biomass flowrate *% syngas per unit biomass*
Syngas carbon mass flowrate	tonnes/hr	0.005	*Syngas mass flowrate *syngas carbon %*
Syngas energy flowrate	*GJ/hr*	*1300.675*	*(Syngas mass flowrate *1000)*syngas energy density - Not in use*
Syngas power	MW	0.362	*Syngas energy flowrate *(MWh/MJ)*
Purified gas mass flowrate	tonnes/hr	0.011	*Input biomass flowrate *% syngas per unit biomass *electricity yield*
Purified gas carbon mass flowrate	tonnes/hr	0.001	*Syngas mass flowrate *syngas carbon % *electricity yield*
Purified CO2 mass flowrate (biogenic emitted)	tonnes/hr	0.000	*Gas carbon mass flow rate *(MMCO2/MMcarbon) * biogenic carbon fraction *% stored*
Purified gas energy flowrate	*GJ/hr*	*0.960*	*(Syngas mass flowrate *1000)*gas energy density *electricity yield - Not in use*
Purified gas power	MW	0.000	*Gas energy flowrate *(MWh/MJ)*
Char mass flowrate	tonnes/hr	0.250	*Input biomass flowrate *char conversion ratio*
Char carbon mass flowrate	tonnes/hr	0.163	*Char carbon mass flowrate *char carbon%*
Char energy flowrate	*GJ/hr*	*4062.500*	*(Char mass flowrate *1000)*char energy density - Not in use*
Char CO2 mass flowrate (biogenic stored)	tonnes/hr	0.595	*Char carbon mass flow rate *(MMCO2/MMcarbon) * biogenic carbon fraction *%char stored*
Liquid mass flowrate	tonnes/hr	0.670	*Input biomass flowrate *liquid conversion ratio*
Liquid carbon mass flowrate	tonnes/hr	0.402	*Liquid mass flowrate *liquid carbon%*
Liquid energy flowrate	*GJ/hr*	*6030.000*	*(Liquid mass flowrate *1000)*liquid energy density - Not in use*
Liquid CO2 mass flowrate (biogenic stored)	tonnes/hr	1.473	*Liquid carbon mass flow rate *(MMCO2/MMcarbon) * biogenic carbon fraction *%liquid stored*
Purified bio-oil mass flowrate	tonnes/hr	0.402	*Input biomass flowrate *liquid conversion ratio *oil conversion ratio*
Purified bio-oil carbon mass flowrate	tonnes/hr	0.233	*Oil mass flowrate *oil carbon%*
Purified bio-oil energy flowrate	*GJ/hr*	*4663.200*	*(Oil mass flowrate *1000)*oil energy density - Not in use*
Purified bio-oil CO2 mass flowrate (biogenic stc	tonnes/hr	0.854	*Oil carbon mass flow rate *(MMCO2/MMcarbon) * biogenic carbon fraction *%oil stored*
Wood vinegar mass flowrate	tonnes/hr	0.201	*Input biomass flowrate *liquid conversion ratio *vinegar conversion ratio*
Wood vinegar carbon mass flowrate	tonnes/hr	0.004	*Vinegar mass flowrate *vinegar carbon%*
Wood vinegar energy flowrate	*GJ/hr*	*20.402*	*(Vinegar mass flowrate *1000)*vinegar energy density - Not in use*
Wood vinegar CO2 mass flowrate (biogenic stoi	tonnes/hr	0.015	*Vinegar carbon mass flow rate *(MMCO2/MMcarbon) * biogenic carbon fraction *% vinegar stored*

Parasitic Energy

Name	Unit	Value	
External power required	Mwe	0.034	
External CO2 emissions from parasitic energy	tonnes/hr	0.052	*Parasitic energy CO2 emissions+diesel emissions+natural gas emissions*

CO2 Emissions

Should biogenic emissions be treated as zero? Yes/No	Yes

Name	Unit	Total emissions	Biogenic emissions treated as zero	*Biogenic CO2 emitted*-1*
Total emitted non-biogenic CO2	tonnes/hr	0.052	0.052	*Non-biogenic CO2 emitted*
Total emitted biogenic CO2	tonnes/hr	0.001	-0.001	*Biogenic CO2 emitted*
Total CO2 emissions (regardless of source)	tonnes/hr	0.053	0.051	*Biogenic CO2 emitted+non-biogenic emitted CO2*
Total stored biogenic CO2	tonnes/hr	1.465	-1.465	*Biogenic CO2 captured (char+oil+vinegar)*
Net CO2 emissions	tonnes/hr	1.518	-1.414	*Non biogenic emitted+biogenic stored+biogenic emitted*

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