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Feasibility Study Report: Pyrolysis as A Carbon Abatement Mechanism

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1 EXECUTIVE SUMMARY

This report outlines the feasibility of using pyrolysis technology to sequester 10% of Australia's total carbon dioxide emissions. The investigation found that it is possible to use Elephant Grass as a feedstock to achieve this. A total land area of 5443 square kilometres of Elephant Grass is required to sequester 10% of Australia's carbon dioxide emissions, which totals 50.2MT of carbon dioxide. The three main products of pyrolysis are biochar, bio-oil and syngas. Fast pyrolysis is intended to produce more significant amounts of bio-oil from the elephant grass feedstock to optimise revenue. The laws and regulations relevant to a pyrolysis plant on this scale have also been outlined regarding workers' rights, environmental protections, biodiversity, noise and machinery. The total number of pyrolysis units needed to process all this feedstock mass was 41, with an estimated cost of around $49.2 billion. The optimal area to grow the elephant grass after considering the ideal growing conditions, availability of train transport and the land cost was Central Western Australia, specifically the Greater Geraldton area. The feasibility of using alternative feedstock for pyrolysis is also outlined. However, no alternative sources were available in large amounts of dry biomass weight and hence is negligible to the intended crop of choice: Elephant Grass. After considering three different scenarios, the most optimal scenario yielded a net yearly revenue of $8.3 billion, with an initial investment of $67.5 billion, resulting in an ROI of 8.61% and a break-even point of just over eight years.

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2 INTRODUCTION

The following document outlines the recommended plant species which can sustain the pyrolysis plant most cost-effectively compared to other plant-type candidates. It also explores the possibility of using alternative feedstock instead of fixed farmland biomass. Based on these suggestions, pyrolysis technology suitable for the project will be highlighted. The information will produce three scenarios to discover the best business plan for pyrolysis as a carbon abatement method in Australia (2022). This will ultimately examine the likelihood of the project's feasibility at the current state.

2.1 PURPOSE

Australia releases over 500 MT of carbon dioxide into the atmosphere per year from electricity, transport and industry usage of fossil fuels [1] [2]. Whilst emissions and climate policies are focused on the net-zero target, there is no focus on removing carbon dioxide from the atmosphere. Siphoning carbon out of the atmosphere will help reverse many adverse impacts caused by climate change, e.g. lower the global temperature back down to pre-industrial levels [3] levels. This project discusses a method that can achieve this goal in two stages.

- The growth of plants to photosynthesise carbon dioxide out of the atmosphere.
- The pyrolysis of their biomass to prevent the carbon dioxide from releasing back into the atmosphere via aerobic decomposition [4].

In conjunction with other policies and strategies employed to reach net-zero emissions, pyrolysis will theoretically allow Australia's yearly emissions to get negative values. Large-scale global implementation of such technology could completely revert global warming's temperature effects [5].

2.2 BACKGROUND

Greenhouse gas emissions due to fossil fuel usage have become a severe environmental concern due to the negative impacts on the climate across the planet. Currently, over 180 countries are committed to limiting the global temperature rise to below 2°C above preindustrial levels, and the recent 2021 UN Climate Change Conference (COP26) saw many of these countries agree to reach net-zero emissions by 2050 [6]. It has become increasingly clear that a substantial reduction in the energy generated through fossil fuels must be made. Several renewable energy sources such as wind, solar, thermal, hydro, and biomass-generated power have much potential to reduce this reliance [7] [8]. Currently, 29% of the world's electricity generation is produced from renewable sources [9], as shown in Figure 1.

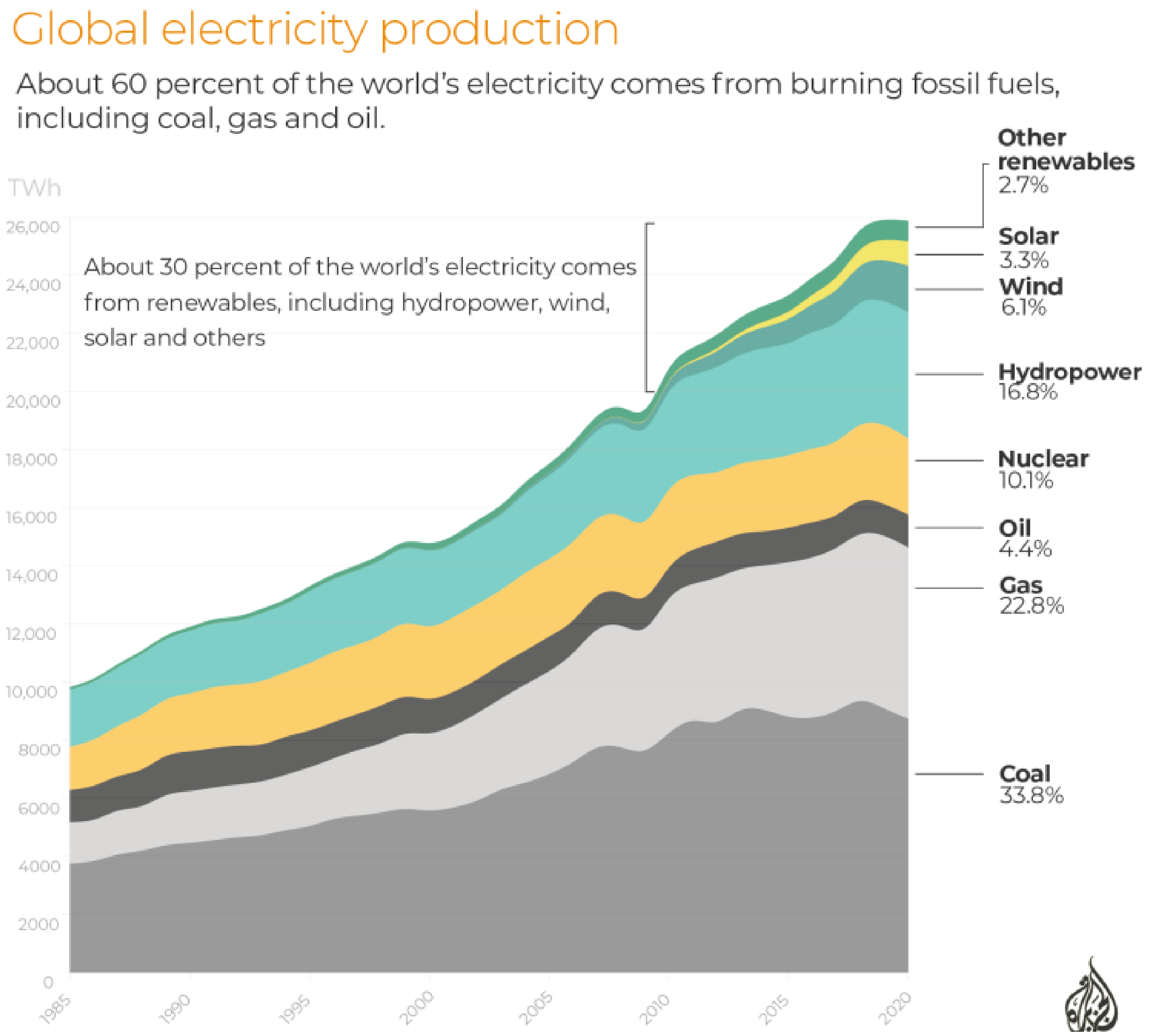


Figure 1: Renewable energy produced compared with global energy consumption [9] [10]

Among this selection, biomass is the the major renewable energy source that produces carbon and can be refined into liquid fuel [11] [12] [13]. Biomass examples are oil seeds, grasses, woods, crops, municipal solid waste, algae, aquatic plants and animal waste. These can be further broken down into various biomass classifications as shown in Table 1 [14].

Table 1: Summary of Biomass Classifications [14]

Terrestrial	First Generation	Corn, Barley, Maize, Cassava, Sweet Potato, Sugar cane
	Second Generation	Forestry byproducts, Agricultural residues, switch grass, common reed, eucalyptus, biodegradable municipal solid wastes, shrubs, elephant grass
Aquatic		Microbaterium, Microalgae, seaweeds

Pyrolysis is a possible carbon abatement method which produces liquid fuel which can be used in vehicles and machinery. Pyrolysis is the process of heating organic material, generally biomass, in the absence of oxygen. As no oxygen is present, combustion does not occur during pyrolysis[15]. Instead, the biomass is thermally decomposed into combustible gases, liquids and biochar. The quantity of each product produced is dependent on various conditions such as the temperature, heating rate, particle size, pressure and the content of the biomass used. Pyrolysis could be a technology used to decrease carbon content in the atmosphere, reducing greenhouse gas emissions[16] [17].

2.3 APPROACH

This report is based on scholarly literature, including conferences, theses, articles, government reports and published business data. The literature was found using databases such as ABI Inform, SciFinder and Google Scholar. Other sources are directly from the Government or specific business reports and proposals. No date restrictions were placed on the data collected. However, where possible, an effort was made to include the most recent literature to review the current state of pyrolysis technology and the processes outlined in this report. Resources were used based on their relevance to which they described and explained the areas which have been investigated. Many assumptions have also been made to produce this report and are outlined where relevant.

3 PROBLEM STATEMENT

Australia's climate has warmed by 1.4 $\pm$ 0.24 °C since national records started in 1910 [18]. This has had many impacts on human health, ecosystems and infrastructure [19]. Carbon dioxide has been the largest contributor to global warming and has increased in concentration within the atmosphere by 48% since pre-industrial times (before 1750). This has been caused by burning fossil fuels, cutting down forests, increasing livestock farming and fertilizers containing nitrogen. Both countering climate change and adapting to the warming world are top priorities for countries around the world [20]. Greenhouse gas emissions can be minimized by utilizing renewable energy sources. A significant energy source is biomass, the major renewable energy source which produces liquid fuels [21]. Many conversion technologies convert resources into fuels while off-setting greenhouse gases, such as gasification, esterification, anaerobic digestion and pyrolysis. Of these, pyrolysis is most commonly used in the treatment of organic material. This process converts organic matter into solid residues containing ash and biochar, liquids that can be separated into fuels, hydrocarbons and gases that can be used for energy generation. Using pyrolysis to produce fuels could hence offset a large portion of the greenhouse gases produced by Australia.

This report outlines the feasibility of implementing pyrolysis technology as a carbon abatement method to remove 10% of Australia's annual emissions from the atmosphere. The report additionally aims to quantify the potential of growing trees or other organic material for use with pyrolysis technologies to abate greenhouse gas emissions.

3.1 OBJECTIVES

1. To determine the scale of forest or other plantations required to sequester 10% of Australia's annual emissions
2. To determine a suitable plant species to sequester carbon dioxide from the atmosphere
3. To select the most appropriate pyrolysis technology for the given problem
4. To appropriately scale and determine the requirements to pyrolyse timber/organic matter
5. To produce a flow chart design of the system to be used
6. To determine the mechanisms to create fertiliser from biochar
7. To determine how pyrolysis gases can be used for energy generation
8. To conduct a cost-benefit analysis

9. To develop a business case including revenue costs, profitability, the requirement for ACCU generation and at which ACCU value is this project profitable

3.2 OUT OF SCOPE

Due to time constraints and the relevance of some topics to justifying the results of this feasibility study, several areas of interest are considered to be outside this project's scope. These include:

- The detailed specifics of harvesting wet feedstock. This includes but is not limited to the machinery, staff, transport, energy, fuel and utilities that are required for harvesting
- The refining of products from bio-oil, systems used and equipment for refining bio-oil into further developed products and fuels
- Land required to accommodate pyrolysis plants
- What type of pyrolysis setup would be required to process alternative fuels
- Market analysis for expected price changes of bio-oil and biochar with a large influx of these products to the market

4 LAWS AND REGULATIONS

A large scale project as described above is very rarely done, and would be required to meet a large amount of legal regulations, including both environmental and construction policies. If one were to want to commence this project, a separate study into the environmental and economic effects of this project would have to be undertaken, and legal requirements would have to be researched. In this section, we have provided a list of different government laws and regulations that this project will have to abide by, which may be a useful start for further research. These are shown in Tables 2 and 3.

Table 2: Farm facilities, fuel and equipment regulations

Legislation	Topics Covered
The Competition and Consumer Act 2010	• product safety and labelling • unfair market practices • price monitoring • industry codes • industry regulation – airports, electricity, gas, telecommunications • mergers and acquisitions
Australian Consumer Law (ACL)	The ACCC has provided information about consumer rights, refunds, and what to do in the event of travel and other event cancellations as a result of the COVID-19 pandemic.
Environment Protection and Biodiversity Conservation Act 1999	Framework to protect and manage nationally and internationally important flora, fauna, ecological communities and heritage places.
Noise Legislation (EPA 2017)	Created to balance the need for industrial activity with the community's desire to minimise intrusive sounds. It sets assessment noise levels, consistent methods, and best practice measures to manage industrial noise, and is based on the latest scientific research regarding noise's health effects [22].

Table 3: Farm facilities, fuel and equipment regulations

Legislation	Topics Covered
Farmers and the national environment law	Some agricultural activities may need federal government approval. Those most relevant to farmers are: • nationally threatened and migratory species • nationally threatened ecological communities • wetlands of international importance • world and national heritage properties, and • the Great Barrier Reef.
Heritage protection	The EPBC Act protects certain nationally significant (protected) animals, plants, habitats or places.
Migratory species protection	The EPBC Act protects certain nationally significant (protected) animals, plants, habitats or places.
Threatened species protection and ecological communities	To ensure the protection of native Australian species. [23]
Wetlands protection	To protect wetlands across New South Wales.
Work Health and Safety Regulations 2011	Protects the safety of workers, improves safety outcomes, reduces compliance costs for business' and improves efficiency for health and safety regulators [24].
Environmental Protection Act	Prevents and minimises the risks of harm to human health and the environment from pollution and waste.
National Greenhouse and Energy Report Act 200	A national framework for reporting and disseminating company information about greenhouse gas emissions, energy production, energy consumption and other information specified under NGER legislation [25].
Effect on soil structure	To control are soil erosion, soil salinity, soil acidity, soil contamination, nutrient loss and soil structure decline. [26]
Recycling and Waste Reduction Act 2020	To reduce the environmental and other impacts of products and waste material, and for related purposes [27].

5 REVIEW OF PYROLYSIS TECHNOLOGIES

Pyrolysis is the thermal decomposition of organic matter, such as biomass, in the absence of oxygen, resulting in three main products, which are biochar, bio-oil, and gas, in varying proportions. However, the process could be tailored to enhance the production of any of the three by changing the pyrolysis conditions. The subsequent sections will review and describe the type of pyrolysis, reactors, and condensers used for this project and the variance in the compositions of their respective outputs.

5.1 EXISTING PYROLYSIS FACILITIES

In order to estimate how feasible it is to develop and run a large-scale pyrolysis plant, it is crucial to consider Australia's adoption of this technology - with particular attention to how states differ in their uptake and acceptance of this technology. Table 4 shows pyrolysis plants within Australia and the sclae at which they process the feedstock each is designed for

Table 4: Existing and Proposed Pyrolysis Facilities Within Australia

Name of Company	Location	Type of Feedstock	Tonnage	Price	Completed
Pacific Pyrolysis [28]	Sommersby NSW	Organic Wastes	N/A	N/A	Yes
Renergi [29] [30]	Collie WA	Biomass and Garbage	12000t/year	9.8 million	No
Pyrotech [31] [32]	Mobile Unit	Organic Waste	10t/day	1.5 million	Yes
Aenergy [33]	Mobile Unit	Biomass	3t/h	N/A	Yes
AgBioEn [34]	Victoria	Biomass	750,000t/year	1.2 billion	No
Brightmark [35]	Parkes NSW	Plastics	200,000t/year	260 million	No
Carnarvon Energy and Frontier Impact Group [36]	Narrogin WA	Biomass	N/A	2 million	No
Jeffries Biochar Operations [37]	South Australia	Biomass	150,000t/year	N/A	Yes

5.2 TYPES OF PYROLYSIS

Pyrolysis technology can be categorised as slow, intermediate, and fast pyrolysis. However, slow and fast pyrolysis are most commonly used in large-scale industries. The yield and proportion of the produced components, which are bio-gas, bio-oil, and biochar, greatly depend on the pyrolysis conditions and feedstock type [38].

Fast pyrolysis has a rapid heating rate, short residence time, and high temperature, producing bio-oil as the main product. In contrast, slow pyrolysis occurs at a low heating rate and moderate temperature with a long residence time. Slow pyrolysis also produces biochar as the main product [39]. Table 5 summarises the pyrolysis parameters and product yields for different types of pyrolysis technology.

Table 5: Overview of Pyrolysis Parameters and Product Yields for Different Types of Pyrolysis Technology [39]

Process	Reaction temp °	Heating rate	Residence time	Feedstock size	Product yield %		
					Bio-oil	Bio-char	Gas
Slow pyrolysis	300-550	<50°C/min (0.1-0.8°C/s)	5-30 min; 25-35 hr	Briquette/ whole	20-50	25-35	20-50
Intermediate pyrolysis	300-450	200-300°C/min (3-5°C/s)	≈10 min	Coarse/ chopped /finely ground	35-50	25-40	20-30
Fast/flash pyrolysis	300-1000	10 to 1000°C/s	<2 s	Finely ground	60-75	10-25	10-30

The produced biochar characteristics depend on the feedstock used and initial thermal treatment. Biochar produced at higher temperatures has a high pH value, higher fixed carbon content. In contrast, biochar produced at lower temperatures has a higher cation exchange capacity, higher yield, lower fixed carbon contents, and extra functional groups [38].

Slow pyrolysis provides more significant environmental benefits as it produces biochar as the main product, which can be used to sequester the carbon and can be applied to soil to improve its quality. During the initial feasibility study of this project, it was decided to use the slow pyrolysis technology since the main objective of this project was to sequester 10% of Australia's annual emissions. Thus, it was planned to use the biochar produced from the slow pyrolysis process to sequester the carbon. However, after analysing and calculating the area of the land and biomass required to sequester 10% of Australia's annual emissions, it was discovered that there is a large amount of excess biochar. Thus, it was decided to change the type of pyrolysis used in this project to fast pyrolysis. The main reason is that fast pyrolysis has a better economic return since it produces bio-oil as the main product. Bio-oil has a higher value and profit than producing more significant amounts of biochar through slow pyrolysis [39]. The bio-oil produced will be used as one of the sources of this project's revenue.

5.3 TYPES OF REACTORS

Various types of pyrolysis reactors have been developed to convert the biomass into three main products, which are liquid (bio-oil), solid (biochar), and gas (syngas). The yields of individual products depend on not only the types of pyrolysis but also the reactor operating conditions and configuration. The concepts such as heat supply, heat transfer, and volatile residence time are vital to maximising the product yields and compositions and allowing the control for the hot zone classification of pyrolysis processes as slow, intermediate, or fast modes [40]. Numerous reactors for the fast pyrolysis process have been investigated to exceed the temperature of 400 °C in a few seconds to heat the biomass. Suitable reactors for fast pyrolysis include auger reactors, rotating cone reactors, bubbling fluidised beds, circulating fluidised beds, ablative reactors, and entrained flow reactors. Table 6 shows the summary of the key features for each reactor [41].

Table 6: Comparison of Key Features for Different Types of Reactors

Reactor type	Maximum yield (wt%)	Complexity	Feed size specification	Scale-up
Auger	60	Medium	Medium	Medium
Rotating Cone	70	High	High	Easy
Bubbling Fluidized Beds	75	Medium	High	Easy
Circulating Fluidized Beds	70	High	High	Easy
Ablative	75	High	Low	Difficult
Entrained Flow	60	Medium	High	Easy

Fluidized bed reactors have garnered the most attention for the fast pyrolysis process owing to their simplicity of operation, uniform heat, excellent heat and mass transfer characteristics, reasonable control of the reaction parameters, and relative ease of scale-up. It has been reported that the yields of 60-75 % of bio-oil can be achieved through this type of reactor for the fast pyrolysis process [41].

Fluidization is a process where the fine solids are transformed into a fluid-like state through contact with a liquid or gas. The main force responsible for the fluidization process is the gas's upward fluid drag on the solid particles. The fluid drag will continue to rise if the gas flow rate through the fixed bed increases, resulting in a pressure drop. This occurrence will continue until the gas velocity maintains a critical value known as the minimum fluidization velocity. When the fluid drag is equal to the particle weight, the fixed bed will transform into the fluidized bed reactor at this stage.

Figure 2 shows the typical bubbling fluidized-bed reactor [42]. A bubbling fluidized-bed reactor is a well-established approach for fast pyrolysis where the fluidization of the solids is relatively stationary and low velocities gas is used. Due to the gas input rate being in surplus of what can pass through the interstices with a frictional resistance less than the bed weight, bubbles will form at the reactor entrance where the fluidizing gas enters the bed. Therefore, the layers of solids above the holes are pushed until they make a void through the porous surface that the gas can enter at the incipient fluidization velocity [43].

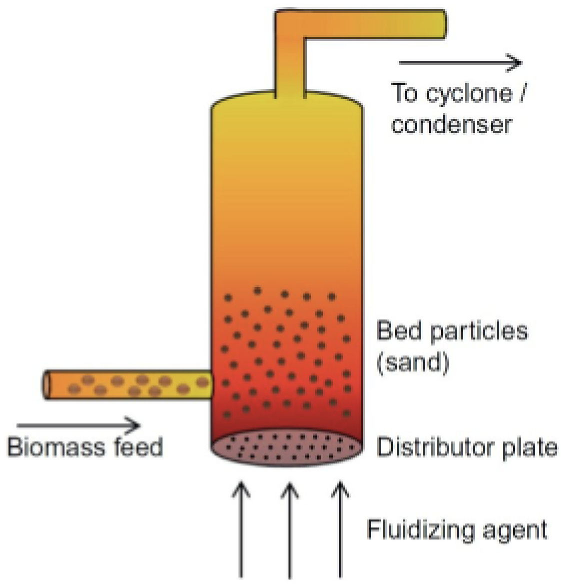


Figure 2: Bubbling fluidized-bed reactor.

Among various fluidized-bed reactors, **bubbling fluidized-bed reactors** have been extensively used in fast pyrolysis processes from the lab-scale to large-scale industrial use. This is due to its excellent advantages, including uniform temperature distribution, uniform mixing, and the ability to operate continuously. This type of reactor also has an extreme movement of the particles that promotes uniform conditions and smart inter-mixture throughout the bed, which results in highly economical heat transfer [42]. For these reasons, a bubbling fluidized bed is intended to be used.

Achieving efficient pyrolysis operation requires an optimal feed particle size. With large particle sizes, it becomes difficult to produce bio-oil and char from the reactor. If fine biomass particles are fed into the reactor, the biomass may get entrained out of the reactor without fully undergoing the pyrolysis process [44]. After considering the key features and advantages of different reactor types, this project has determined to choose the bubbling fluidized-beds reactors to be used in the pyrolysis process.

5.4 TYPES OF CONDENSER

While the reactor conditions are responsible for the oil yield and quality, the condenser system affects the bio-oil quality. The volatile vapours exiting the pyrolysis reactor are passed through the char separator and then fed into the condenser, where the condensable and non-condensable vapours are separated. Currently, the typical condensers used in the biomass pyrolysis systems, can be classified into two types which are direct and indirect condensing systems representing the direct or indirect contact between hot volatiles and the cooling liquid [45].

The most common condensers used for the direct condensing system are spray columns or towers, while the indirect condensing system is the shell and tube condensers. The spray towers or columns have the same design. However, there are various types of shell and tube condensers, including Graham, coil, Alihn, and spiral condensers, where each type has its respective configuration, and design [46].

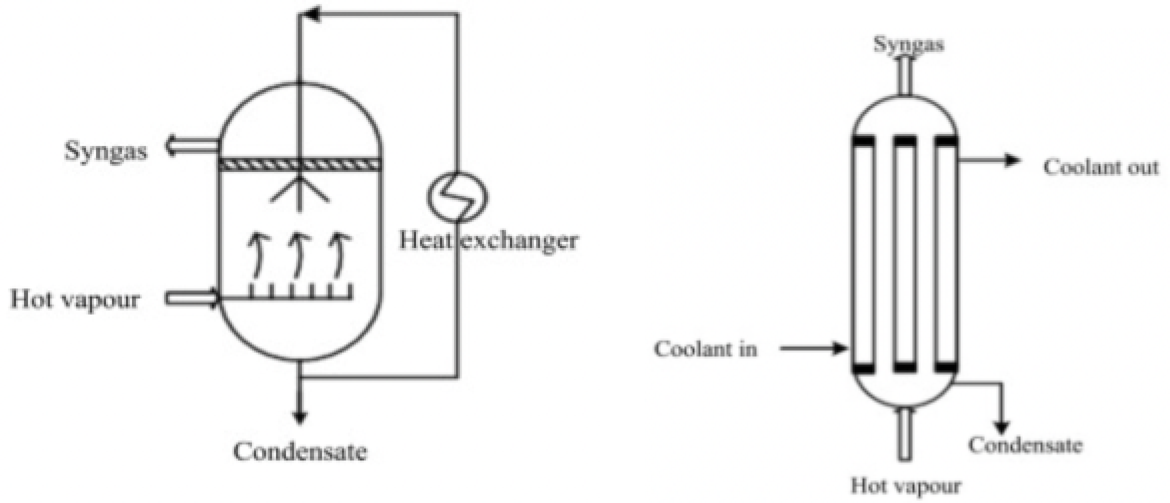


Figure 3: Spray column condenser (left) and shell and tube condenser (right)

Figure 3 above shows the schematics of a direct and indirect condenser that have been extensively used in the pyrolysis process. A spray column also referred to as a spray tower quench system, utilizes a re-circulated spray of coolant in a counter-current manner to cool and collect all of the liquid at once. The coolant can be smoke condensate, water, or other solvents. Spray columns are usually operated in large-scale units. Shell and tube condensers use a cold surface to cool the gases and condense hot volatiles, allowing the system to use a serial condenser train instead of a single condenser. This creates the chance of separating the oil into different fractions depending on the dew point of the oil components. However, the mass transfer resistance of the gases forces the conventional indirect contact heat exchangers to larger sizes [46].

Due to several advantages of direct condensing systems over indirect ones, a **direct condensing system** will be used. The benefits include low capital and maintenance costs, simple design, high specific heat transfer areas, and high heat transfer rates. The spray columns condensers are also typically used in the large-scale units, while the shell and tube condensers usually are used in pilot and lab-scale units [46].

5.5 PROCESS DIAGRAM

Figure 4 shows the general process that the biomass used for fast pyrolysis will undergo.

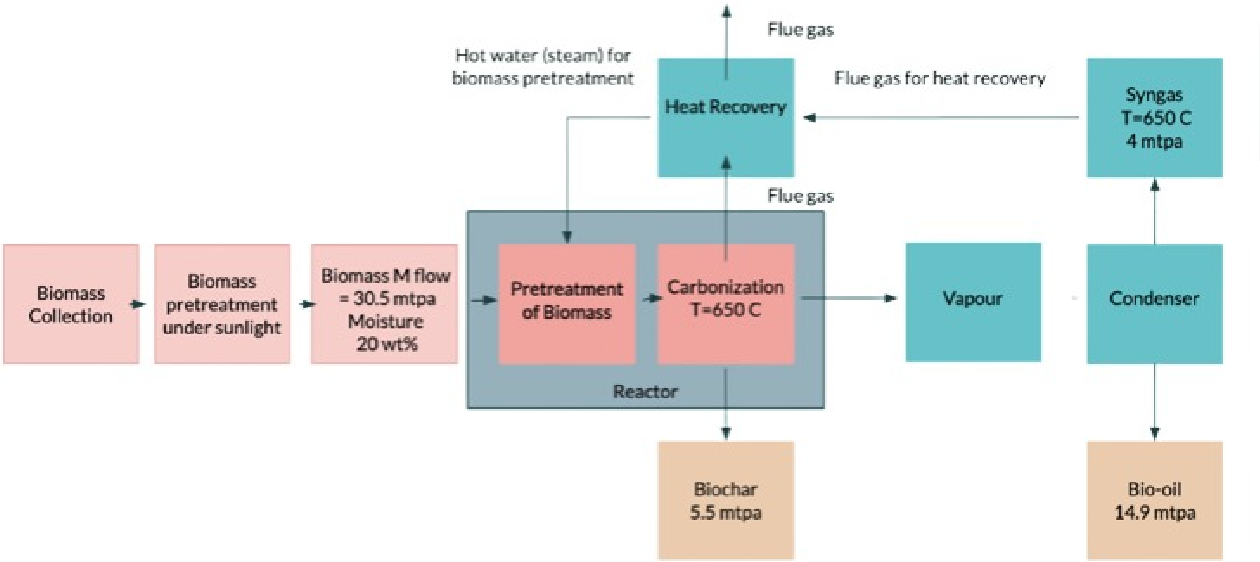


Figure 4: Process flow diagram of proposed fast pyrolysis method

After collecting the biomass, the biomass will be dried under the sunlight. It is a feedstock requirement to have a low moisture content of $<$10% for fast pyrolysis; therefore, the drying process is a critical pre-treatment process. The moisture content of the elephant grass can be reduced from 50% to 20% after drying under sunlight in fields for three days. This biomass will be further dried in an oven at temperatures from 40° to 120°. Following this, the elephant grass will be fed into the pyrolysis reactor, which will undergo further pre-treatment and carbonisation processes. The pre-treatment processes can be categorised into physical, chemical, and thermal. The main objective for these pre-treatments is to modify the characteristics of biomass for its better accessibility toward the final process and enhanced output.

Physical treatment to the elephant grass includes grinding, extrusion and exposure to high pressures. These processes cause changes in the structure of lignocellulosic biomass. Chemical treatment is usually used for the fractionation of lignocellulosic biomass. Thermal treatment is carried out to reduce the moisture content as this must be reduced to $\approx$ 10% in order for fast pyrolysis to work [39]. Therman treatment also lower the biomass's viscosity (the fluids measure of resistance to deformation), and eliminate pathogens in biological processes [10].

After the pyrolysis process, biochar, vapour and flue gas are produced. The flue gas is intended to be used for heat recovery. The vapour products will be quenched in the condenser, and the bio-oil will be separated from the gases to be sold. The non-condensable gases (syngas) will be recycled and used for heat recovery and to power the pyrolysis process. An external energy source will be required to initiate this process before the syngas can be used to power the pyrolysis machine. Following this, the pyrolysis machine will be powered by bio-oil and syngas. The details outlined in the mass and energy balance are provided in Appendix C and D to quantify the amount of energy consumed in the process.

6 FEASIBILITY STUDY OUTCOMES

This feasibility study will mainly focus on the possibility of the pyrolysis mechanism as a carbon abatement process for sequestering 10% of Australia's annual emissions. It explores different plant types which satisfy the requirements for the project and the recommended plant which can deliver outcomes that can be sustained and maintained compared to other candidates. It also discusses alternative feedstock for situations when only a low biomass yield is obtained from the proposed farmland. Using the recommended plant types along with the most suitable pyrolysis technology will be discussed based on the current Australian pyrolysis technology available in 2022. These data will be split into three possible outcomes to provide detailed economic and geographical information on possible pyrolysis sites. The three scenarios will be used to evaluate and provide a final statement on the feasibility of the large carbon pyrolysis project as a carbon abatement process for reducing the net carbon emission in Australia.

6.1 FEEDSTOCK FEASIBILITY ANALYSIS

The first step in determining the most suitable feedstock for this pyrolysis project was to specify a list of plants with high carbon absorbing potential. Through Google research into online science magazine articles and research through academic databases such as Web of Science and ScienceDirect, we determined the following list of plants to explore further deeply:

1. Elephant Grass
2. 'Beema' Bamboo
3. Eucalyptus
4. Live Oak
5. East Palatka Holly
6. Mahogany
7. Slash Pine

These plants were selected based on the amount of carbon dioxide they sequestered, how quickly they grew and what type of plant they were. Several trees were selected to vary between softwoods and hardwoods, fast-growing and slow-growing trees, bamboos and grasses. By selecting various plants known for sequestering significant amounts of carbon dioxide, it is possible to determine the most suitable plant for this investigation.

One primary assumption made is that trees immediately reach maximum carbon sequestration potential. This is erroneous as trees take many years to reach maturity, and young trees sequester less carbon dioxide than older trees due to the fewer leaves undergoing photosynthesis. Thus, the estimates for the tree species sequestration rates are relatively high, and more realistic values for their carbon sequestration values would be lower. This is to take the best possible scenario for trees as a comparison with other investigated biomass such as bamboo and Elephant Grass. The investigation used the best-case scenario as trees were found to perform worse than bamboos and grasses generally.

The efficiency of the species' carbon dioxide sequestration was the first metric to compare the plants to determine the most suitable species. This was calculated by sourcing papers with prior studies into the carbon sequestration of the plants above. These papers provided values in one of two units:

1. A value of the biomass in **tonnes/ha/year**. This value was provided for bamboo, grass and eucalyptus.
2. A value of pounds of **CO2/tree/year**. This value was provided for all the remaining trees.

A universal unit of tonnes of CO2 sequestered per square kilometre per year was used to compare the different units provided. This provided a standard of comparison that does not depend on the type of biomass, the area of biomass required, or the time taken to sequester carbon.

To convert the first type of unit provided, tonnes/ha/year, to our standard unit of tonnes of CO2/sqkm/year, the method outlined in a paper from the University of New Mexico [47] was used. One MegaGram (Mg) is equal to one metric tonne. First, the value must be multiplied by 100 to convert from tonnes of biomass/ha/year to tonnes of biomass/sqkm/year. Second, the value must be multiplied by 45% to obtain a value of tonnes of carbon/sqkm/year. This is because the carbon content in all biomatter ranges from 45-50% [48], and we decided to use a lower estimate of 45%. Finally, to convert from tonnes of carbon/sqkm/year to tonnes of carbon dioxide sequestered/sqkm/year, the value must be multiplied by the ratio between a mass of a carbon dioxide molecule and a carbon atom. The atomic mass of a carbon dioxide molecule is 44.01 amu [49], whilst the mass of a carbon molecule is 12.01 amu [50], hence the ratio is equal to $\frac{44.01}{12.01} \approx 3.66$. Thus, the initial value in tonnes/ha/year can be multiplied by 164.7 to obtain an equivalent value in the units required.

To convert the second type of unit provided, pounds of CO2/tree/year, to the standard unit of tonnes of CO2/sqkm/year, first, the planting density of the specific species of each plant must be researched. This value can calculate the number of plants per square kilometre. Multiplying the initial value of pounds of CO2/tree/year by the number of plants/sqkm, a value for the pounds of CO_2/sqkm/year is determined. Finally, the unit of pounds must be converted to tonnes, and this can be done by dividing the value by 2205 [51], to give an equivalent value in the units required for comparison.

The values researched are shown in Table 7

Table 7: Total Mass for Various Plant Species

Species of Plant	Researched CO2 Value	Planting Density	Converted CO2 Value
Eucalyptus [52]	30.9 tonnes of biomass/ha/year	N/A	5090 tonnes of CO2/sqkm/year
Elephant Grass [53]	45-57 tonnes of biomass/ha/year	N/A	9224 tonnes of CO2/sqkm/year
'Beema' Bamboo [54]	69-80 tonnes of CO2/ha/year	N/A	7450 tonnes of CO2/sqkm/year
Live Oak [55] [56]	487 pounds of CO2 / tree / year	545 trees/acre	29744 tonnes of CO2/sqkm/year
East Palatka Holly [57] [56]	769 pounds of CO2/tree/year	Spacing of 12.5 feet = 68890 trees/sqkm	24026 tonnes of CO2/sqkm/year
Mahogany [58] [56]	623 pounds of CO2/tree/year	833-1100 trees/hectare	27308 tonnes of CO2/sqkm/year
Slash Pine [56]	539 pounds of CO2/tree/year	Spacing of 2.4m = 173612 trees/sqkm	42439 tonnes of CO2/sqkm/year

The converted carbon sequestration values were calculated using one of the methods described above. From this data Figure 5 was produced.

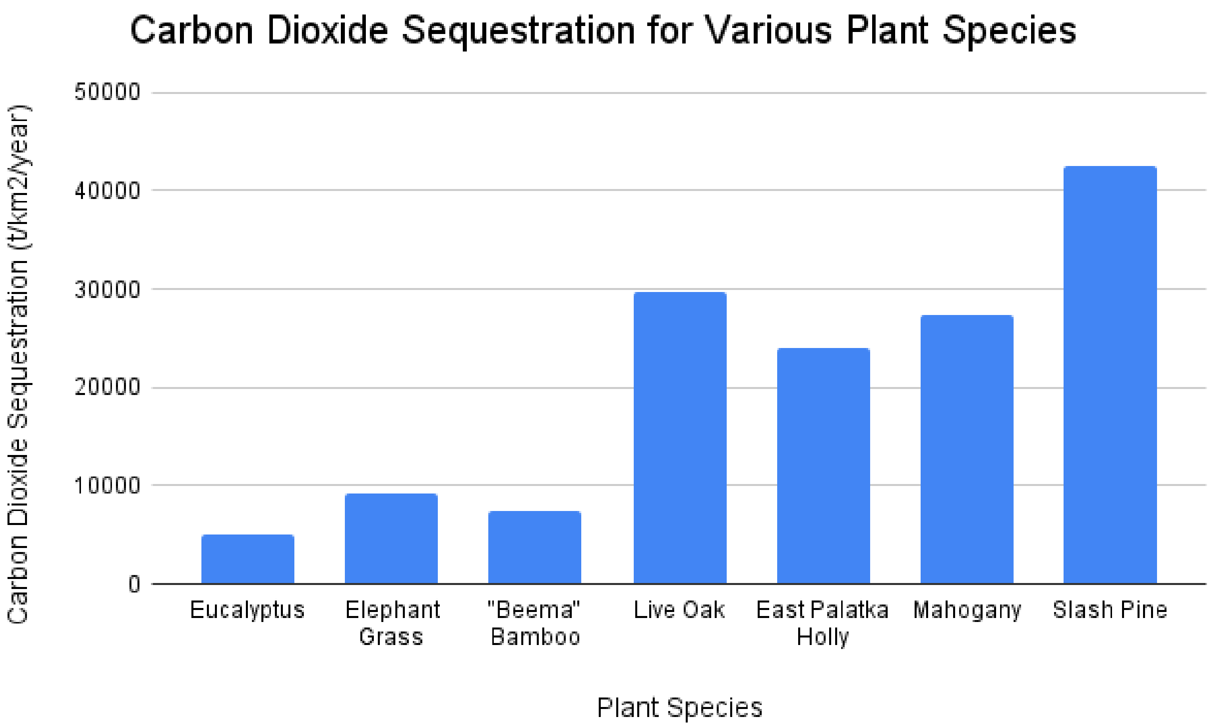


Figure 5: Carbon Dioxide Sequestration per square kilometre per year for various plant species

Apart from Eucalyptus, the trees are three to five times more efficient than the grasses. Slash Pine (the most efficient plant), sequesters 42,438 tonnes of CO_2/sqkm/year, as opposed to Elephant Grass, the most efficient grass, which sequesters 9,224 tonnes of CO_2/sqkm/year.

6.1.1 AREA OF LAND REQUIRED

From the values of carbon dioxide sequestration previously calculated, the total plantation land area required to sequester 10% of Australia's yearly emissions for each species can be calculated. This can be done by dividing the value of 10% of Australia's annual emissions (50.2 million tonnes of CO_2) by the carbon dioxide sequestration values in tonnes of CO_2/sqkm/year to give a land area value in sqkm. A graph showing these values is shown below:

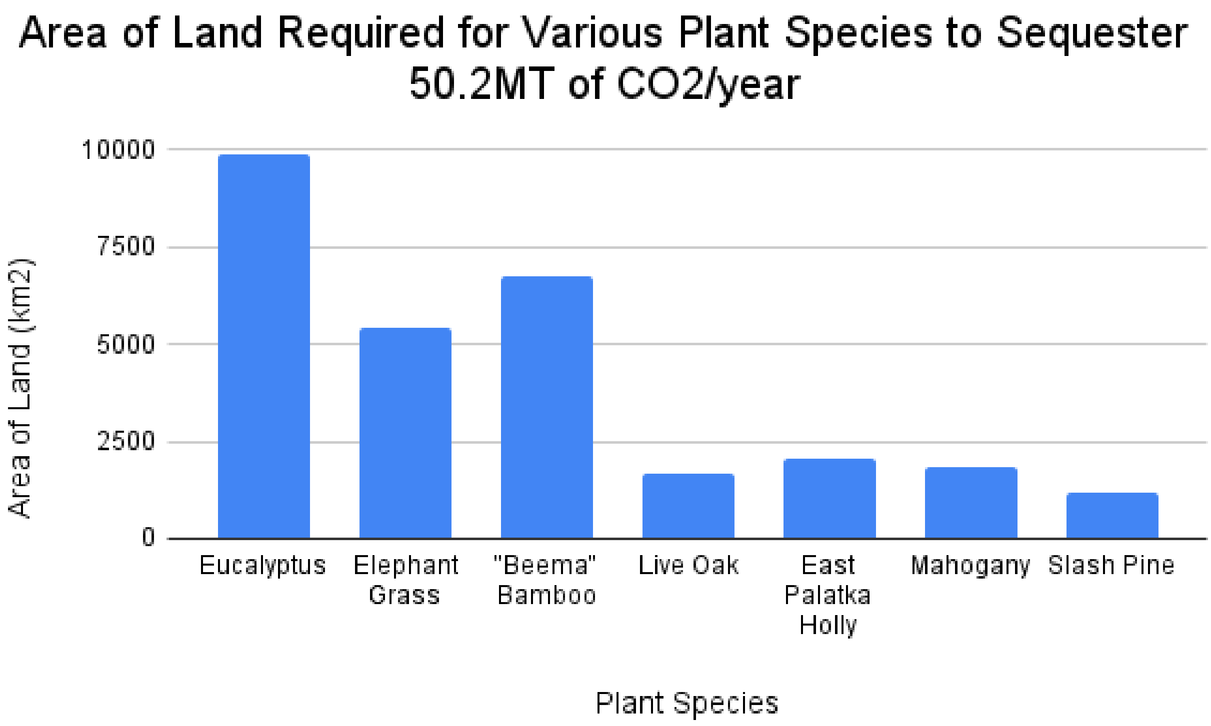


Figure 6: Area of plantation land required for various plant species.

As expected, the plant species with greater carbon sequestration efficiency require a smaller area of plantation land. Slash Pine, the most efficient of the plants in question, requires a plantation land area of 1,183 sqkm, as opposed to Elephant Grass, the most efficient grass, which requires a plantation land area of 5,443 sqkm, around five times that of Slash Pine. To visualise the scale of these areas, we compared them to the land size of Greater Sydney. A map of Greater Sydney is shown in Figure 7.

Figure 7: Map of Greater Western Sydney [59] [60]

The total area of Greater Western Sydney is 9,000 sqkm [61]. Thus, for a plantation of Slash Pine, a plantation area of about 13.1% the size of Greater Western Sydney would be required, and for a plantation of Elephant Grass, a plantation area of about 60.4% the size of Greater Sydney. The required plantation area of 5,443 sqkm is equivalent to the land areas of the Hawkesbury, Blue Mountains, Penrith, Blacktown, The Hills, and Liverpool LGAs (5550 sqkms) [60].

6.1.2 TOTAL DRY BIOMASS WEIGHT

The dry biomass weight is an important metric to consider for the functionality and feasibility of the pyrolysis project. This is due to pyrolysis plants having a maximum limit on the number of tonnes of dry matter they can process per hour. If the total number of dry matter tonnes of feedstock is far greater than this limit, and the time is taken to process it is too long, then that plant would be an infeasible biomatter alternative.

Before calculating the dry biomass, some assumptions must be made. The first assumption is that all plant species have a water content of 50% [48]. This assumption was made as water content can vary even amongst the same plant. As the values for all plants ranged up to 50% as a maximum, the report will assume the worst-case scenario where all plants have 50% water content.

The second assumption is used where an accurate value for the weight of a tree was unable to be sourced. It must be estimated using the density of the species' wood and typical tree height and trunk diameter.

There were three main methods used to calculate the total dry biomass and the final collated data is summarised in Table 8.

1. Converting a value of Dry Biomass in Mg/ha to total tonnes of biomass. First, convert hectares to square kilometres by multiplying by 100, then multiply by the total plantation area in square kilometres to find a total dry biomass value in tonnes. A Dry Biomass in Mg/ha value was given for bamboo and Elephant Grass.
2. Converting a value of Wet Biomass in Mg/ha to total tonnes of biomass. First, convert hectares to square kilometres by multiplying by 100, then multiply by the plantation area in square kilometres. Finally, multiply by 50% to convert from wet to dry biomass, assuming the water content is 50%. A Wet Biomass in Mg/ha value was given for Eucalyptus.
3. Having no prior information on the biomass/hectare or tree mass. For this scenario, we had to estimate the mass of a single tree by using values for its wood density, average height, and average trunk diameter. Finally, we multiplied the total number of trees required using the planting density values already researched in the Feed Stock Feasibility Analysis section. This method was used for the large trees, Live Oak, East Palatka Holly, Mahogany and Slash Pine, due to the scarcity of biomass information on these trees.

Table 8: Carbon Sequestration Values for Various Plant Species

Species of Plant	Mass per tree	Wet Biomass (tonnes/ha)	Dry Biomass (tonnes/ha)	Total Dry Biomass (tonnes)	References
Eucalyptus	N/A	40-85	20-42.5	3.08e7	[62] [63] [64]
Elephant Grass	N/A	N/A	56.04	3.05e7	[53]
'Beema' Bamboo	N/A	N/A	112.48	7.58e7	[65] [66] [54] [67]
Live Oak	5.47	7370.34	3685.17	6.22e8	[68]
East Palatka Holly	0.63	431.6	215.8	4.51e7	[69]
Mahogany	15.75	15219.75	7609.875	1.40e9	[70]
Slash Pine	2373	4119.528	2059.764	2.44e8	[71] [72] [73] [74] [75]

A graph containing the final calculated values for total wet biomass is shown in Figure 8.

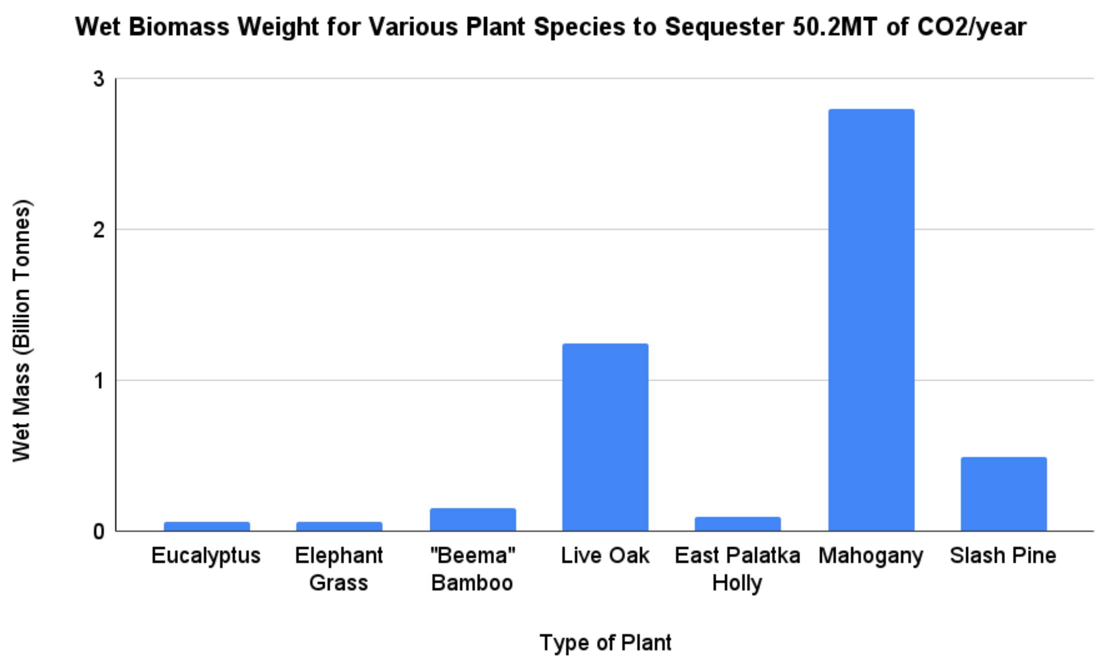


Figure 8: Total wet biomass weight for various plant species

The wet biomass will have to dry to 10% moisture content; hence, after removing the weight of each plant that accounts for the moisture, the dry biomass weight can be obtained. This is shown in Figure 9.

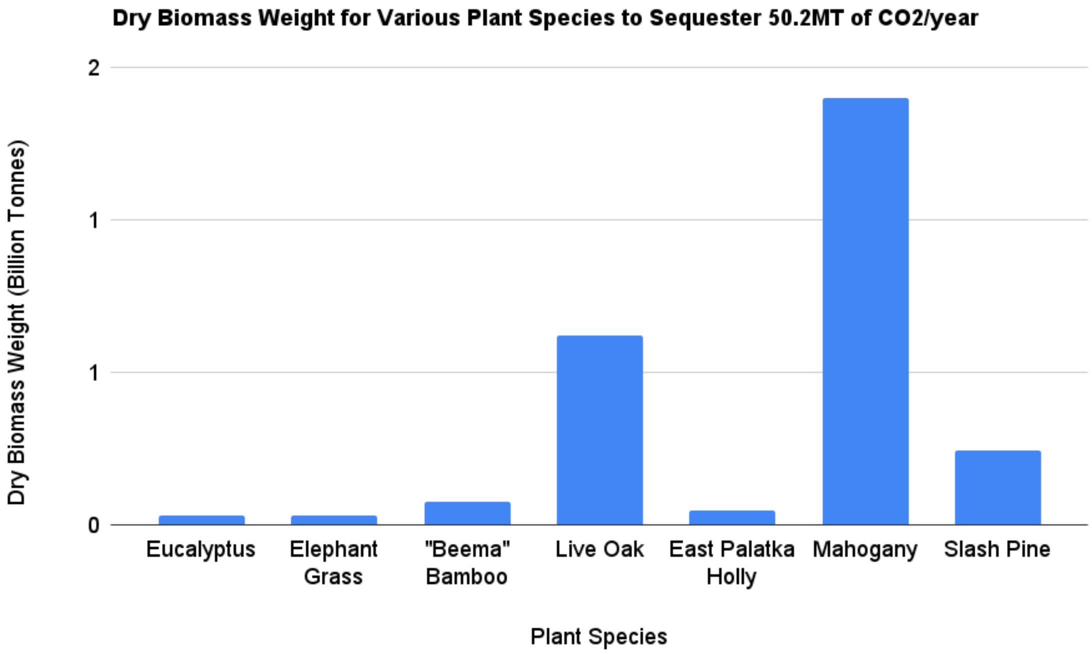


Figure 9: Total dry biomass weight for various plant species

Figure 9 shows that the total dry biomass of three of the four large trees is 1-2 orders of magnitude higher than the grasses. Eucalyptus and East Palatka Holly have comparable total biomass within the same order of magnitude. One thing to note is that the estimation method used for the four large trees neglects the weight of any offshoot branches and leaves. For large trees with wide canopies, such as Live Oak, these branches and leaves make up a significant portion of the total weight. Hence, the weight estimates for the four large trees should be considered as absolute minimum estimates, as the 'true' weight would be higher, possibly even an extra order of magnitude in some cases. This favours trees in the analysis.

6.1.3 TOTAL NUMBER OF PYROLYSIS UNITS REQUIRED

The number of pyrolysis units required can be calculated once a unit's maximum feedstock per hour value is known. AgBioEn, an Australian renewable energy company based in Victoria, which started development of a pyrolysis plant in 2021 for 2 billion Australian dollars. This facility is currently under construction. Their investment in the machinery and site preparation is **1.2 billion dollars** for a single plant, with plans to process up to **750,000 tonnes** of agricultural waste per annum [76]. The article never specifies whether this value of 750,000t is wet or dry mass, however, due to reasons as mentioned in Section 5.5, fast pyrolysis requires dry matter feedstock (< 10% water content), and even other pyrolysis methods requires the wet matter to be dried before being used as feedstock. A Sweedish report on Pyrolysis states that ”in general, fresh sources of biomass needs to be dried before being used in a combustion or pyrolysis process” [77]. Thus, an assumption we made was that the figure of 750,000t refers to the dry feedstock mass, although it was not directly specified. Like the pyrolysis project discussed in this report, the AgBioEn project will use biomass waste, such as corn husks and stalks, as feedstock in the machines. It will output renewable diesel, bio-jet fuel, LPG, heat (for on-farm glasshouses), food-grade liquified CO2 and a soil nutrient that can be ploughed back to grow more crops [76]. Using this value of 750,000 tonnes per pyrolysis plant, we can calculate the number of units required to process the biomass in 1 year by simply dividing the total dry biomass estimated in the previous section by this number. The following graph summarises the results:

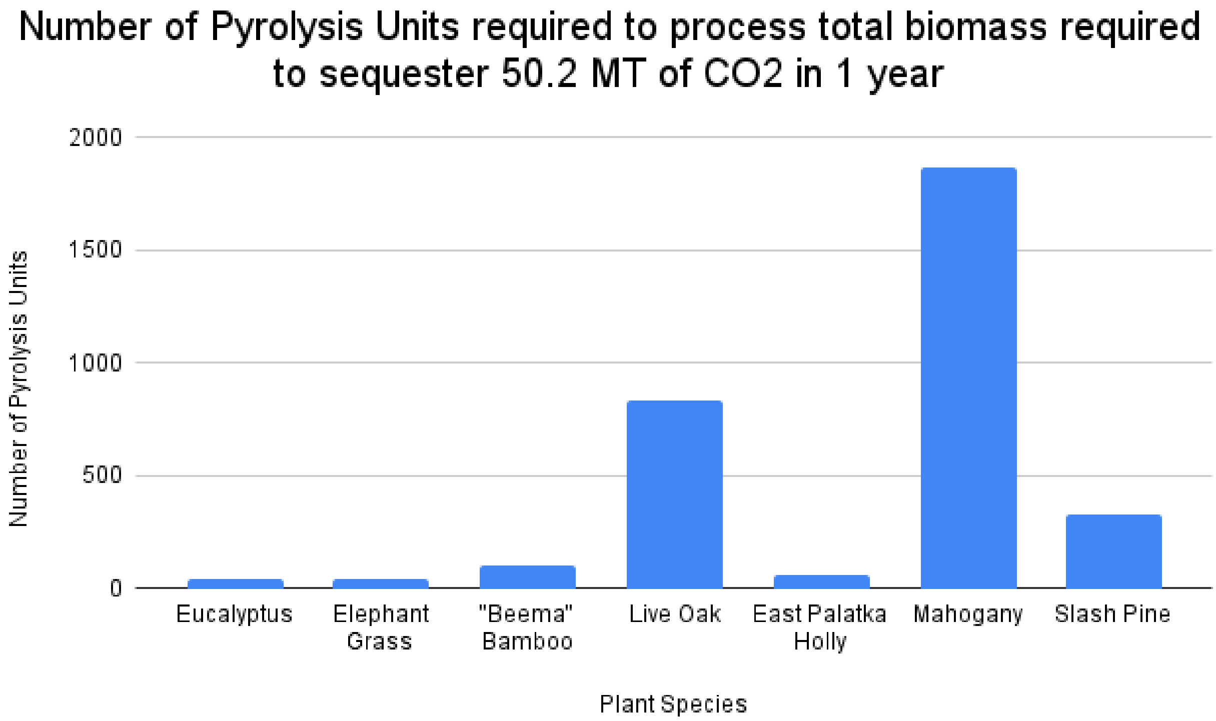


Figure 10: Number of pyrolysis units required to process total biomass needed to sequester 50.2 MT of CO2 in one year

As seen in the above graph, the plants with higher total dry biomass require a more significant number of pyrolysis units to process their biomass in 1 year. The species with the lowest unit requirement is Elephant Grass, only requiring 41 units, as opposed to some of the higher carbon sequestering trees like Live Oak and Slash Pine, which need 830 and 325 units, respectively, an entire order of magnitude higher. It is important to note that several assumptions made throughout this analysis favoured trees. However, the Elephant Grass requires fewer pyrolysis plants to offset the 10% of Australia’s emissions needed for this analysis.

6.1.4 COMPONENTS OF LIGNOCELLULOSIC BIOMASS

Pyrolysis is a process that produces biochar, bio-oil and gases based on the lignocellulosic composition of the biomass. The three main types of the lignocellulosic composition of biomasses are cellulose, hemicellulose and lignin. Depending on their composition, they have been found to produce different percentages of biochar bio-oil and non-condensable gases after pyrolysis — a pie chart of this breakdown is shown in Figure 11.

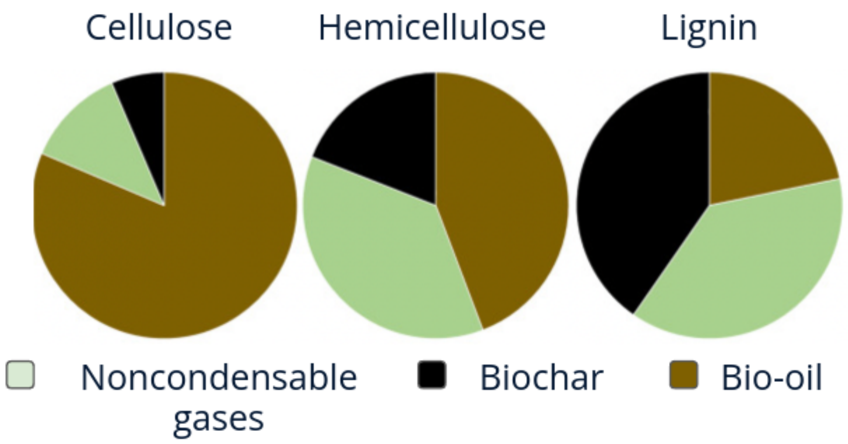


Figure 11: Breakdown of products produced from cellulose, hemicellulose and lignin [78] [44]

The biomass used as a feedstock in the pyrolysis process plant will be composed of cellulose, hemicellulose and lignin, which is dependent on the chosen plant selection. Figure 12 shows a ternary plot of cellulose, hemicellulose and lignin.

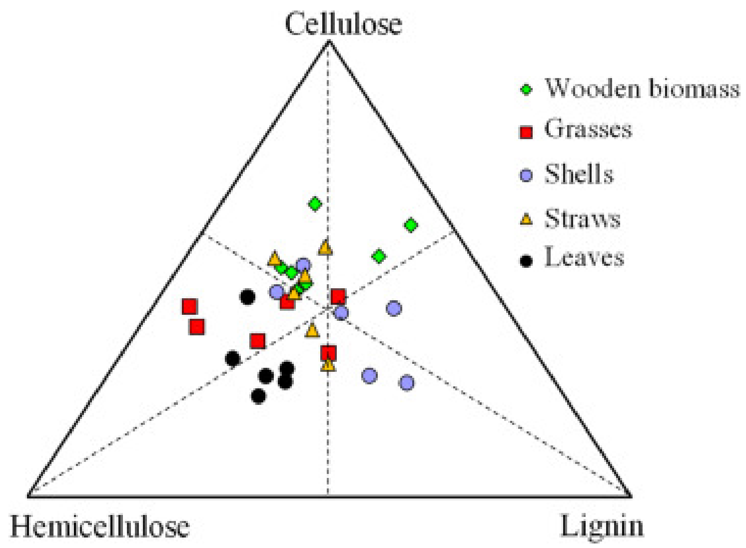


Figure 12: The lignocellulosic composition of different biomass sources. [44]

From Figure 12, it can be seen that more hemicellulose and lignin will produce more biochar. Grasses, straws and leaves are better than trees and wooden biomass in producing biochar, while wooden biomass is generally better at producing bio-oil as it is high in cellulose.

6.1.5 PREPARATION OF BIOMASS

In order to process the plants which are being compared, it is crucial to consider what preparation needs to be undertaken to process each plant in a pyrolysis machine. As the pyrolysis machine discussed in Section 5.3 is a fast pyrolysis machine and hence the biomass used must be ground down to a size of $<$2mm lengths. The process for trees and grasses is further explained below.

6.1.5.1 Trees

Firstly trees must be debarked, chipped and screened [79]. They also need to be dried out as they generally contain anywhere from 30% to 50% moisture [80] and must be reduced to 10% in order for fast pyrolysis to take place [81] [82]. This can be done in a high temperature (200°C) oven for a few hours [83], but generally, this is a much longer process. It takes chipped wood 2-3 days to get to 25-30% moisture content but can take several weeks to get below 20% [84] [85]. Alternatively, a fan could be used to dry freshly chipped wood to 10% in 68-139 hours [84]. Split logs just left to dry can take 18-24 months to dry when stored in a wood shed and take 9-12 months to dry outside (15% moisture) [85] [86]. A milling machine is also required to be used to split the dried wood down to the $<$2mm length required for fast pyrolysis [79] [87].

6.1.5.2 Grasses

Grasses as much leaner and can be cut into smaller pieces when initially harvested. Grasses also need to be dried as they can contain 14-50% moisture [88]. In order to dry elephant grass to 20% moisture, the grass can be left in the fields for three days (although this is dependent on clear weather) [89] [90]. It is also possible to heat the grass at 40-120°C for up to 5 hours to dry the grass to 10% moisture [91]. From here, the grass needs to be grounded with a milling machine to reach the appropriate $<$2mm size chips for use in fast pyrolysis [87].

6.1.6 FINAL SELECTED PLANT

The final selected plant was Elephant Grass for several reasons. Firstly the total dry biomass of Elephant Grass is the lowest out of all the plants that have been investigated at a total weight of 3.05 $\times 10^7$ tonnes. This total dry weight is the equivalent amount of Elephant Grass required to sequester 10% of Australia's annual Co2 emissions. Elephant Grass requires the least amount of pyrolysis plant units (41) due to the lower biomass. Grasses are also have a good hemicellulose and lignin composition, which produce a reasonable amount of biochar, bio-oil and non-condensable gases, although it is worse than trees at producing bio-oil. Elephant Grass is also easier to dry as it can be dried in the field for three days or dried with an oven to remove the remaining moisture or heated at 40-120°C for up to 5 hours if the weather does not permit drying in the fields [91]. Trees also need to be debarked and chipped before drying [86] [85]. This makes the harvesting easier for grasses compared to trees, further justifying the use of Elephant Grass. Trees also take longer to grow and can only be cut down after a certain number of years (anywhere from 10 to 40 years) [92]. Trees need to be grown this long as they take time to reach their peak carbon sequestering potential [92] [93]. This means that trees would only produce biochar after a certain number of years and would need to be intermittently planted to allow for the constant pyrolysis process.

6.2 ALTERNATIVE FEEDSTOCK

There exist many alternative plants which can be used as feedstock for pyrolysis. Waste from farmers, weed removal and landfill could provide alternative feedstock and are considered in this section.

6.2.1 AGRICULTURAL WASTE

According to the Department of Primary Industries and Regional Development, Western Australia produces 10 million tonnes of biomass per year [94]. These statistics indicate plenty of alternative feedstock if the Elephant grass farmland does not meet its expected yield production.

Table 9: Average Agricultural Biomass Amounts for Western Australia

Biomass Type	Tonnes Per Year
Cereal Straw	**6,930,000**
Dairy Effluent (wet weight)	2,313,000
Hardwood Residues	1,186,000
Softwood Residues	371,000
Horticulture	76,000
Grape Marc	20,200
Cattle Feedlots	19,500
Broiler Litter(wet weight)	19,300

As indicated from Table 9, Western Australia is well known for being Australia's wheat belt. Cereal straw or wheat straw biomass waste of almost 7 million tonnes is produced annually. The research conducted by Dr Niaz Muhammad states that 3% (w/w) of cereal straw is converted into biochar if it is processed by pyrolysis at 300-500 degrees °C [95]. For hardwood and softwood, the carbon content is 79.0 and 85.3 wt%, which produces higher amounts of biochar per mass than the elephant grass and cereal straw [96].

6.2.2 FOREIGN AND INVASIVE PLANT SPECIES

Several plants throughout Australia are classified as foreign, invasive or weed plants. These are often actively removed by governments in order to protect local fauna and biodiversity of plants. These could possibly be used as an alternative feedstock for pyrolysis in order to produce more biochar and bio-oil for revenue. The major categories of these plants are considered in this section as an alternative fuel source.

6.2.2.1 Aquatic Weeds

Widespread aquatic weeds such as Leafy Elodea, Hydrocotyle, and Parrot's feather can be found over extensive water storage facilities or natural water systems around Australia [97]. Although having a large mass of green plants may seem beneficial to the environment, it causes more damage than good. These aquatic weeds can cause oxygen depletion when it covers the water's surface. This leads to decreasing wildlife population and reduces biodiversity. If the growth rate of the aquatic reaches extreme, it can cause significant blockage of the water system. In order to manage these aquatic weeds, the state department uses methods such as manual removal and chemical removal. The standard selection of chemicals certified by the government includes Diquat and Copper Cupricide [98].

6.2.2.2 Land Weeds

The African Boxthorn, Alligator Weed, Asparagus, and Parkinsonia are examples of common land weeds in Australia [99]. These weeds tend to have a higher growth rate than native species, which leads to these plants taking over the native species' habits and reducing biodiversity. Similar methods are used to control land weeds. One of the chemicals used for the management is Logan, which is sprayed at the site to kill the target plant. Although the government annually removes these weeds, they are not suitable for the project as an alternative source because they are an unreliable feedstock source. This is mainly because it depends on manual labour to remove, and they are considered minor and significantly smaller quantities than wheat straw mentioned before. However for Parkinsonia, this woody weed is spread throughout the Northern parts of Australia as shown by the density map given in Figure 13. It is estimated that 2904 MT of Parkinsonia biomass is available, with the calculation given in Appendix A.

6.2.2.3 Tyres

Although this is not strictly biomass, tyres can be used as an alternative feedstock for pyrolysis. Tyres will not contribute directly to the carbon abatement mechanism, but producing fuels derived from tyres, will still reduce carbon emissions than when left in a landfill. According to the Tyre Stewardship 2019 - 2020 report, 92,000 T of used and disposed tyres were reused, and 187,000T were processed to Tyre Derived Products (TDP). However, 127,000 T were dumped or buried in a landfill. This portion of dumped tyres has the potential to be alternative feedstock. A breakdown of how tyres are generally recycled or dumped is shown in Figure 14.

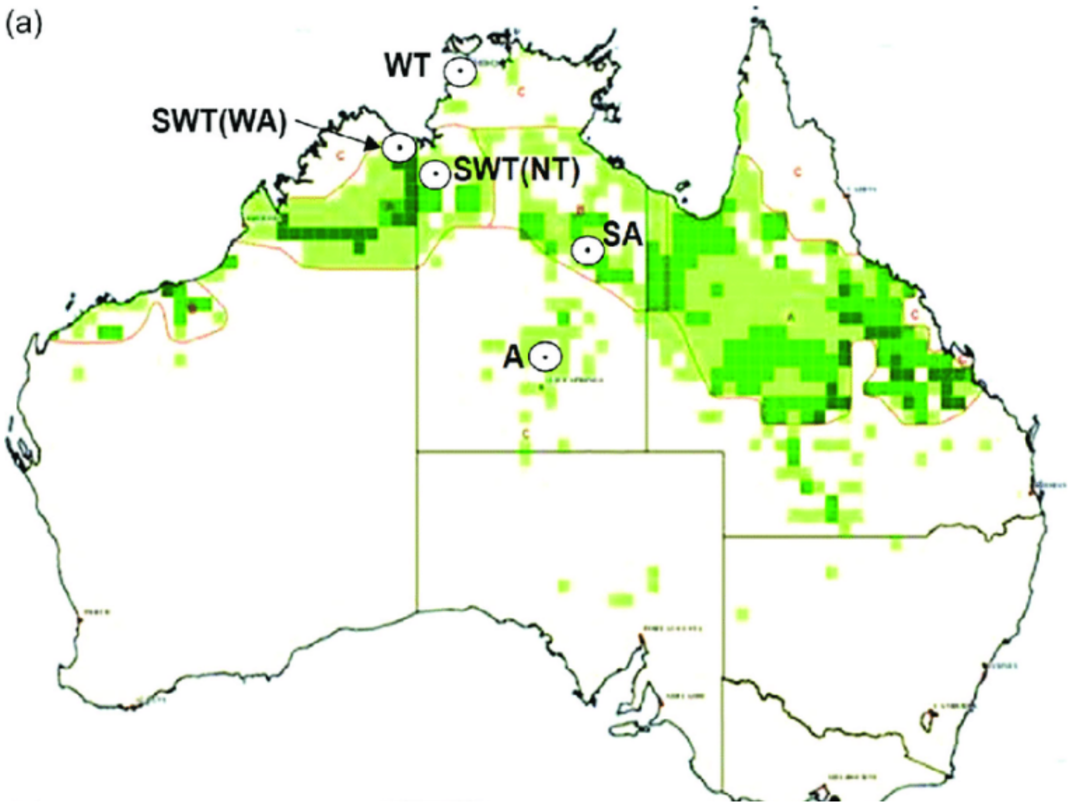
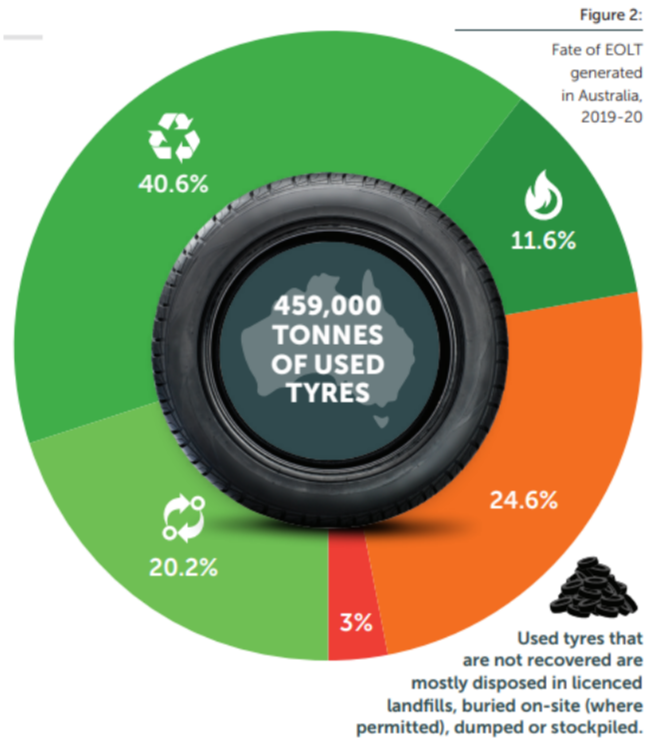
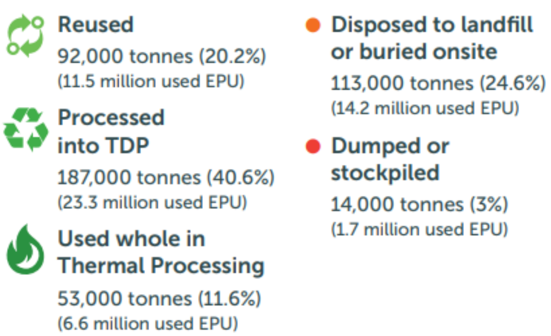


Figure 13: Distribution of Parkinsonia across Australia



(a) Pie Chart of Used Tyres in Australia 2019-2020 [100]



(b) legend

Figure 14: Used Tyres in Australia 2019-2020 [100]

6.3 LOCATION AND CLIMATE

Several options for suitable locations within Australia were determined and analysed to compare where Elephant Grass Grows best. In this analysis, the main factors analysed were environmental stability and suitability of the land for growing Elephant Grass.

6.3.1 CLIMATE COMPARISON

Elephant Grass is a hardy plant that is tolerant of many harsh weather conditions, such as drought. However, some minimum weather conditions need to be met in order to obtain an optimal yield. Firstly, Elephant Grass ideally grows in temperatures from 25-40 degrees Celsius and will stop growing in temperatures less than 15 degrees Celsius. Elephant Grass grows in areas with rainfall ranging from 200-4000mm per annum. However, ideally prefers rainfall of above 1500mm per annum. Elephant Grass requires well-drained soil and is very intolerant to flooding. Elephant Grass also prefers total sunlight exposure. However, it can still thrive in partial sunlight. It cannot grow in full shade. Lastly, Elephant Grass is a nutrient-hungry species and gives optimal yield when adequately fertilised. [101].

Taking into account these requirements, three main areas in Australia come to mind as ideal locations for an Elephant Grass plantation:

1. **Queensland**
2. **Northern Western Australia**
3. **Southern Western Australia**

According to the Bureau of Meteorology, Brisbane's average temperature ranges from an annual mean minimum temperature of 15.8 degrees Celsius to a yearly mean maximum temperature of 25.4 degrees Celsius[102]. Perth's average temperature varies from an annual mean minimum temperature of 12.9 degrees Celsius to a yearly mean maximum temperature of 24.8 degrees Celsius [103]. Clearly, in general, Brisbane (southern QLD) is more often in the temperature range required by Elephant Grass as opposed to Perth (southern WA).

Figure 15 shows data from The Bureau of Meteorology's Australian Water Availability Project that has been plotted by the Queensland Government Department of Environment and Science [104].

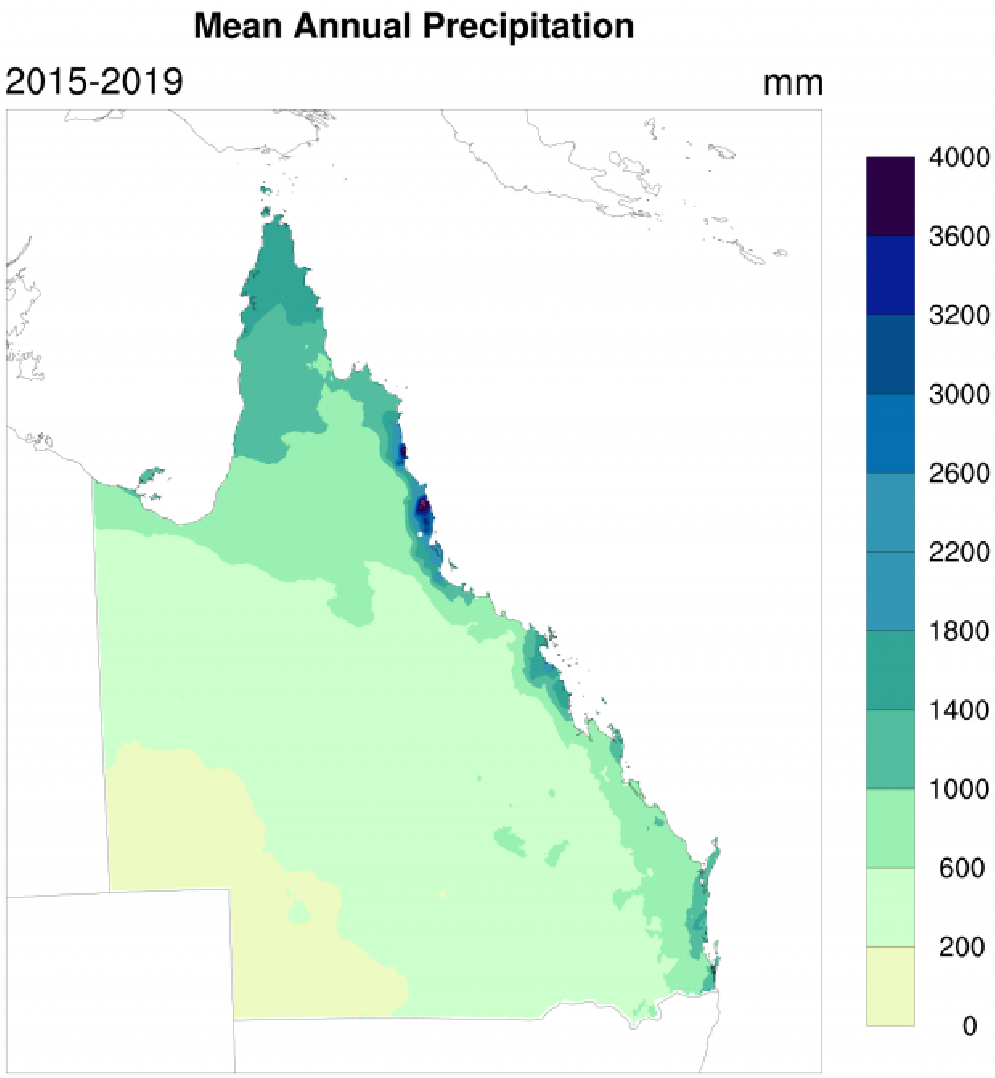


Figure 15: Mean annual precipitation in Queensland from 2015-2019 [104] [105]

As seen in Figure 15, most of Central and Southern Queensland meets the minimum annual required rainfall standard of 200mm. However, the more ideal (higher) rainfall amounts are closer to the coast of Northern Queensland, where the average yearly rainfall ranges from 600-1800mm. However, in this same study, it was also discovered that the rates of precipitation in the large majority of Queensland were declining [104] [105]. This can be seen in Figure 16.

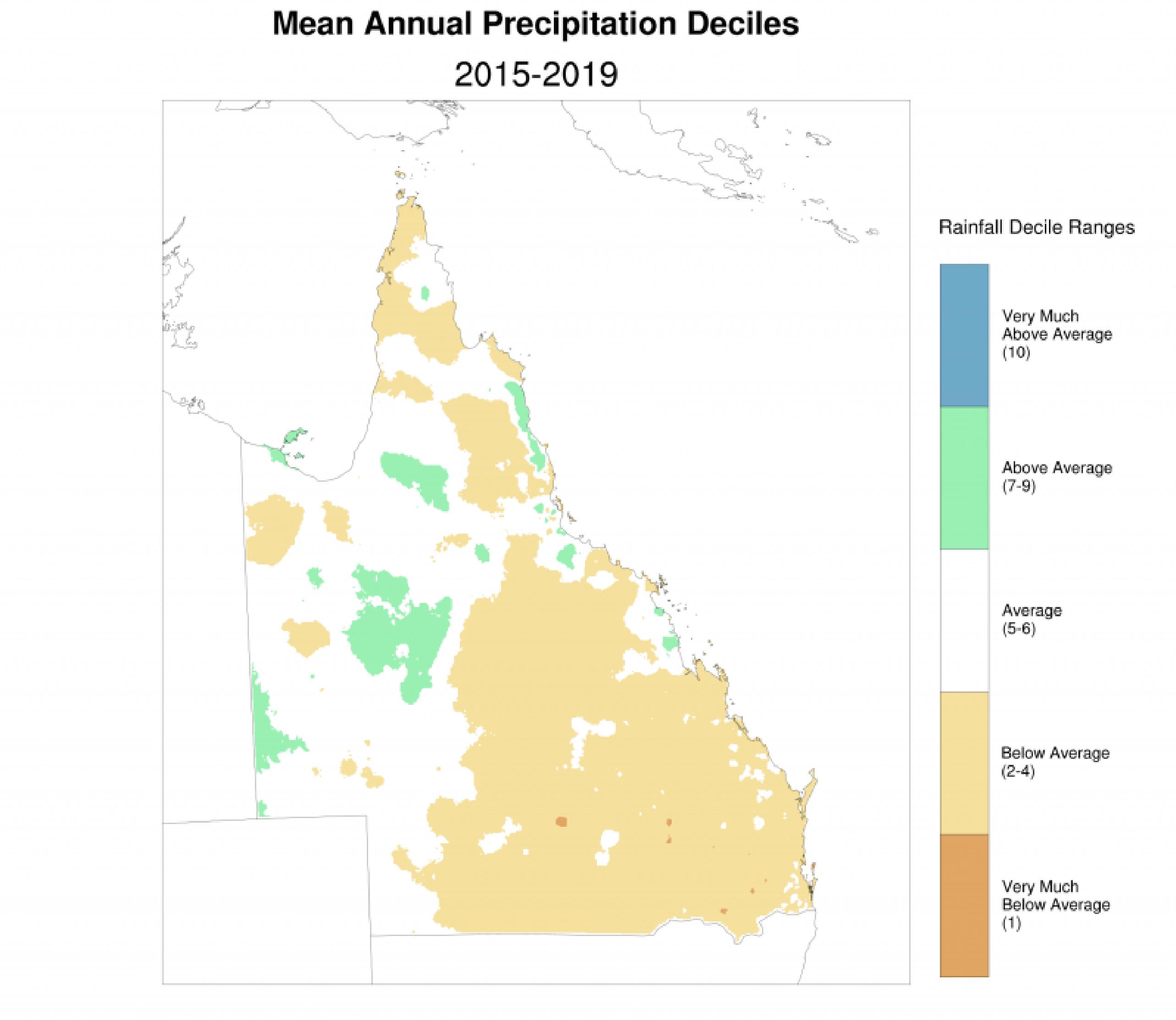


Figure 16: Mean annual precipitation decline in Queensland from 2015-2019 [104] [105]

Queensland received below-average rainfall in many areas with ideal rain for Elephant Grass growth. With this trend possibly continuing, Queensland may be a less ideal location than initially expected.

The Bureau of Meteorology's 30-year climatology study also contains an image depicting the average annual rainfall in Western Australia from 1981-2010 [106]. This is shown in Figure 17.

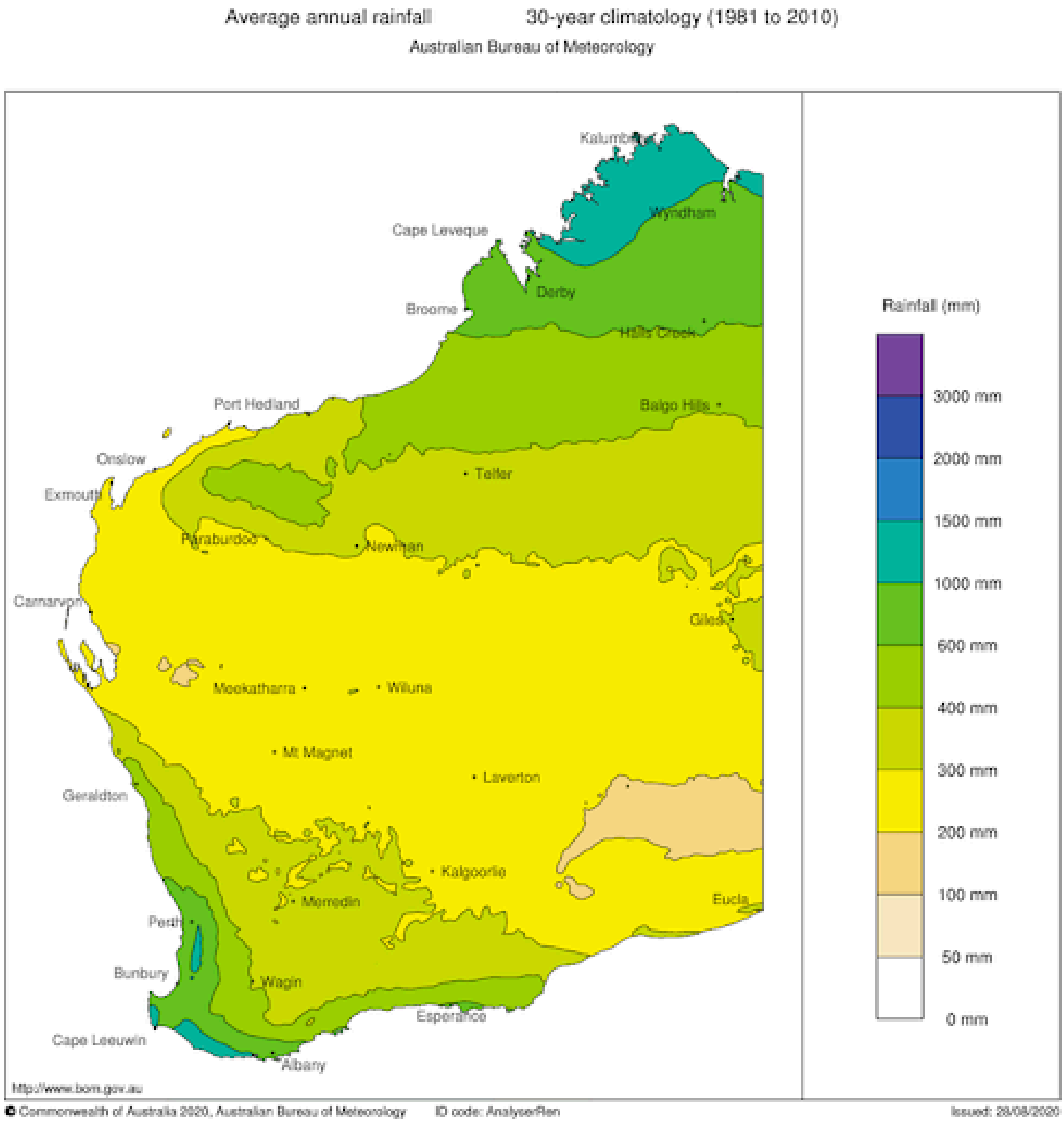


Figure 17: Mean annual precipitation in Western Australia from 1981-2010 [106]

Similarly to Queensland, the majority of central Western Australia meets the minimum average annual rainfall of 200mm, whilst Northern and Southern Western Australia has rainfall ranging from 300-1000mm, with up to 1500mm rainfalls in the extreme south and north. Whilst the average annual rainfall is slightly less than in Queensland, it still meets the requirements, and with some irrigation, Northern and Southern Western Australia are also viable candidates.

The final consideration is the sunlight exposure in each location. As previously mentioned, Elephant Grass thrives in sunlight exposure. According to TrustedSolar, a solar energy company located in Brisbane, Perth is the capital city with the highest sunlight exposure in Australia [107]. Figure 18 shows the rankings of Australian capital cities in order of the average hours of sunshine they receive per year.

1. **Perth** – 3212
2. **Darwin** – 3103
3. **Brisbane** – 2884
4. **Canberra** – 2811
5. **Adelaide** – 2774
6. **Sydney** – 2592
7. **Hobart** – 2263

Figure 18: Annual average hours of sunlight in Australian capital cities

These figures are also backed up by WorldData, which developed a plot showcasing the average hours of sunlight in both Western Australia and Queensland per month for the past 20 years [108][109]. These plots are shown in Figures 19 and 20.

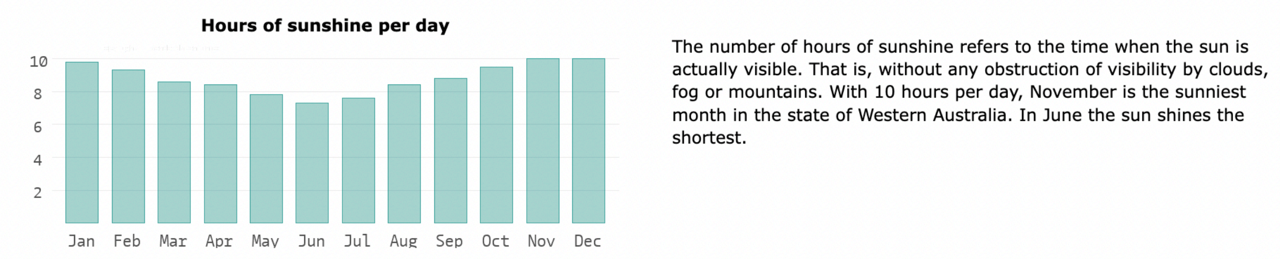


Figure 19: Monthly average hours of sunlight in Western Australia over the past 20 years

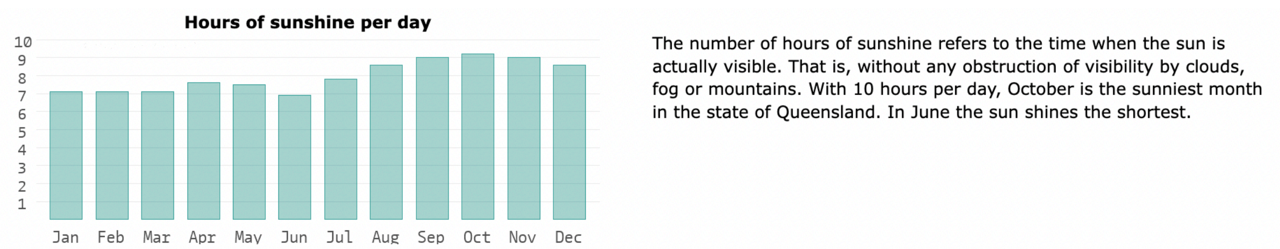


Figure 20: Monthly average hours of sunlight in Queensland over the past 20 years

The plots show that Western Australia has greater sun exposure than Queensland. Although both states have months with the highest sun exposure is 10 hours a day, Queensland has far more months with a low 7-8 hours of exposure a day.

6.3.2 LAND LOCATION: QUEENSLAND

Queensland is one of the central farmlands in Australia. From the Department of Agriculture Fisheries and Forestry (DAFF) June 2022 Report, Wheat production yield was 1,736kT for the

Winter harvest, and Grain sorghum production yield was 1,776kT in 2022 [110]. Figure 21 gives an image of this land area.

Figure 21: Map of Queensland [111] [112]

Of the 378,000 hectares used for Australia's sugar cane production, 95% are in Queensland. Since elephant grass has similar characteristics to wheat and sugar cane, Queensland can be considered an option for this project's farmland. Current Queensland policies towards carbon emission are reaching 50% renewable energy by 2030, 30% emission reduction below 2005 levels by 2030, and zero net emissions by 2050 [113]. Therefore pyrolysis plants may be welcomed in this state, in order to assist the state in reaching its environmental goals.

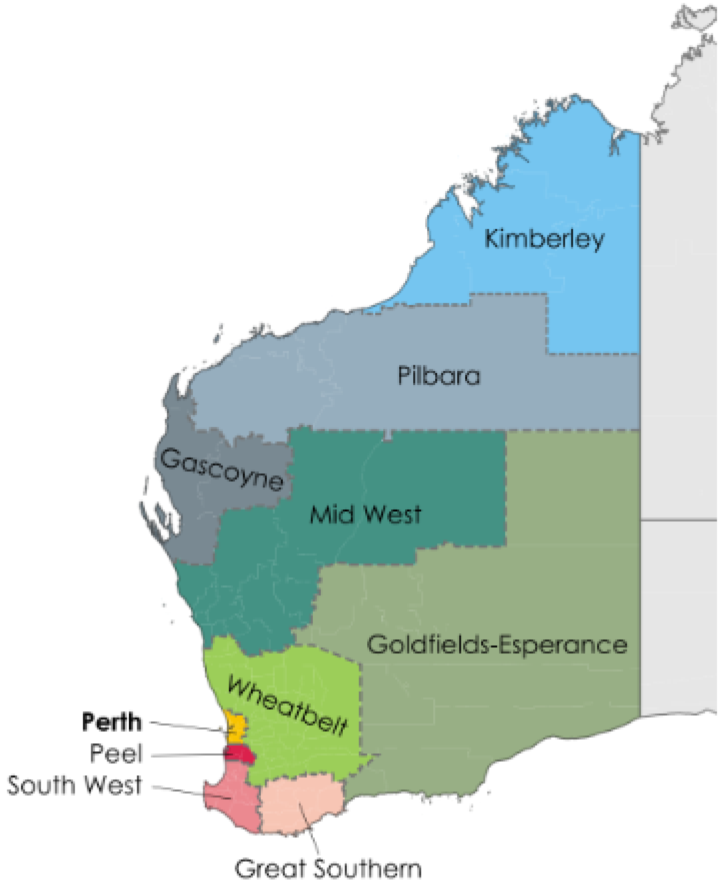


Figure 22: Map of Western Australia [114]

6.3.3 LAND LOCATION: WESTERN AUSTRALIA

Another central farmland in Australia is Western Australia. DAFF stated that the Wheat production in this area was 10,250kT of Barley Production, 4,300kT of Canola production, and 2,600kT of Lupin production over the winter harvest in 2022 [115]. This data shows a strong agriculture industry presence in this area, proving it is suitable for growing Elephant grass. It also allows alternative feedstocks to be used in pyrolysis if the plant is located in this area.

Environmental policies target key aspects to lower the impact of climate change. These policies include requirements in regards to manufacturing, energy generation and use, carbon filtration and storage and caring for our landscapes. Key policies also aim to create transport with lower Co2 emissions and resilient cities and regions throughout WA [116]. Pyrolysis can contribute positively to four out of six of these policies as pyrolysis is a carbon abatement mechanism. Therefore the project is not expected to meet any significant blockage from the State Government.

6.3.4 PROPOSED LAND - GREATER GERALDTON

The Greater Geraldton area is recommended for growing Elephant Grass based on location and climate. With the exact location of the land shown in Figure 23.

Figure 23: Map of Greater Geraldton and the proposed farmland for the project (shown in green)

If the plant were to be located in this area, then the total plantation area, according to Table 10, would require negotiations with landlords across 16 suburbs to build an Elephant grass farm that would abate the 10% carbon emission produced annually by Australia. Although the calculation required for the elephant grass farm is 5440 hectares, the reason why we are proposing to use 6190 hectares is that this land includes areas which are considered natural reserves and large lakes and water sources such as Lake Mappa, Lake Warramboo, Lake Inga, and the Irwin River.

Table 10: Greater Geraldton Area Required for Elephant Grass Plantation [117]

Location	Land Area (sqkm)
Tardun	633
Canna	816
Gutha	668
Merkanooka	611
Mount budd	153
Wongoondy	502
Devils Creek	261
Tenindewa	723
West Casuarinas	684
Ambania	328
Nangetty	401
Holmwood	237
Dudawa	358
Womarden	381
Bowgada	770
Koolanooka	667
Total	**6190**

Besides the land capacity and meeting the rainfall requirements, the farmland proposed has the second lowest median land price per hectare after northern Western Australia at $3,314 per hectare [117]. Additionally, most of the land is currently being used as wheat farming land. Therefore, there is no need to modify the land to fit the purpose of growing elephant grass.

Within the proposed farmland, it includes a small airport which is called Mowara airport. This airport may be used for farmland management such as aircraft pesticide control, aerial fire management incase of accidents, and for surveying the land for the growth of elephant grass. The geraldton seaport is located 182km away from the center of the farmland and there are three train stations: Morawa, Tardun, and Cana. All of these transportation facilities are located around the farmland which enable efficient trade of products produced by the pyrolysis plant.

This area is famous for being the Wheat belt of Australia which also certifies optimal growing conditions for the plants but it also indicates that there are plenty of alternative feedstock for the pyrolysis. If the yield of the elephant grass did not reach the optimal production, the pyrolysis plant can be run by alternative feedstock such as cereal straw from surrounding farms.

6.4 CASE STUDIES OF PYROLYSIS PLANTS

In order to understand how feasible it is to create a large-scale pyrolysis plant in Australia, several large-scale projects were investigated in further detail. These projects' costs and general outlook give essential insights when considering how to implement such a large-scale project.

6.4.1 CASE STUDY 1: RENERGI'S COLLIE PYROLYSIS PLANT

In early 2021, Renergi Pty Ltd's Collie Pyrolysis Plant Project was approved by the Australian Renewable Energy Agency (ARENA) to produce a scalable pyrolysis plant to manage local waste and the possibility to manage significant waste problems that exist in Australia. The feedstock proposed by Renergi was to convert waste such as forestry and municipal solid waste as this biomass typically end up in landfills. This waste is planned to be converted into biochar and pyrolysis oil. According to Professor Chun-Zhu Li from John Curtin University, Collie Pyrolysis Plant is expected to process 4000 tonnes of Municipal Solid waste and 8000 tonnes of Forestry Waste per year. This led to a figure of 1.5 tonnes of waste processed per hour. The total project funding was $9.4 million. Within this funding, $3.9 million has been funded by ARENA, and $2 million by WA Government has supported the project [118].

According to the Collie River Valley Bulletin, the pyrolysis plant will begin use in July 2022. The Collie pyrolysis plant will be operated 24 hours per day and split into four shifts between 12 to 16 people (max four people each). The Department of Water and Environmental Regulation has provided them with an initial two-year license [119].

6.4.2 CASE STUDY 2: PATRIOT HYDROGEN P2H

From the Prominence Energy NL Corporate Presentation Report of Jun 2021, it has been stated that the Patriot Hydrogens' P2H Pyrolysis Unit can process 24 tonnes of woody biomass per day. Twenty-four tonnes of woody feedstock can be converted into approximately four tons of Biochar, two tons of Syngas, and one tonne of Green H2 per day [120]. For its business model, it proposed that they have two revenue sources: operating its pyrolysis P2H units and selling the processed product or selling its P2H unit to its purchaser. The price of each unit is $2.9 million, which includes the initial system module installation cost and annual license fee. Additionally, the unit has a return investment within 12-18 months [120].

Figure 24: Patriot Hydrogens' P2H Pyrolysis Unit [120]

In November 2021, Patriot Hydrogen Ltd and Western Australia's Kimberley Clean Energy (KCE) signed a memorandum of understanding (MOU) to provide 75+ P2H units to power the Kilto Station, Abattoir, in order to make the operation of the facilities carbon neutral [121]. In May 2022, they recently delivered their first P2H unit to the project site and are expected to complete delivery of the remaining units throughout 2022 [122].

6.4.3 CASE STUDY 3: AGBIOEN PROJECT

AgBioEn is a Melbourne-based company that aims to capture carbon from the atmosphere and produce biofuel that produces 80% less carbon dioxide than the equivalent fossil fuel. A pilot plant is being built in early 2023 in Victoria. Other projects throughout many Australian states, including Northern Territory, Queensland and Western Australia, also have pyrolysis plant projects in development. The pyrolysis plant designed by AgBioEn is projected to cost $2 billion, with $1.2 billion for the plant and $800 million for 100,000 hectares of farmland. From this project and using corn as the feedstock, they have claimed it will produce 150 million litres of biofuel annually.

The one-year pilot pyrolysis facility is estimated to reach 25 per cent of the proposed capacity, which means it will process 180,000 tonnes from the originally proposed capacity of 750,000 tonnes per year. From one year of the max processing capacity, Mr Lozevski, Director of AgBioEn, says it will save anywhere up to 500,000 tonnes of CO2. [123]

The processing capacity of these three case studies has been summarised in Table 11.

Table 11: Processing Capacity*

Project Name	Processing Capacity	Processing Capacity (T/hr) (2dp)	Product ratio	Plant size	Cost
Renergi's Collie Pyrolysis Plant	12000T per Year	1.67	Unknown	Unknown	$9.4M
P2H by Patriot	24T per day	1	Biochar - 4T Syngas - 4T Green H2 - 1T	40-Foot Container 2.6x2.4x12.2(m)	$2.9M
AgBioEn	750,000T per year	104	Unknown	Unknown	$1.2B

* Data was calculated with the assumption that the pyrolysis plant will be operated 300 days per year with dry biomass ($< 10\%$ moisture)

6.5 ELEPHANT GRASS FERTILIZER AND HARVEST

In order to continuously use Elephant Grass as a reliable feedstock, the frequency at which the grass is harvested must be considered. It is also necessary to use a fertilizer that will replace the nutrients in the soil that are taken by growing each harvest of Elephant Grass. These considerations are made to obtain the maximum possible yield in the shortest time.

6.5.1 HARVESTING ELEPHANT GRASS

Elephant grass obtains 1 1.2m of height after 3-4 months of growth from seed [124]. When it reaches 1-1.2m, it is assumed to be sufficient enough to be harvested; however, it can reach up to 7m when it is allowed to grow further throughout the year. According to research by Professor Guillermo Siri-Prieto, a single harvest had higher dry matter than a double harvest for elephant grass by 18% [125]. Therefore single harvest is recommended for this project. This is also shown in Figure 25.

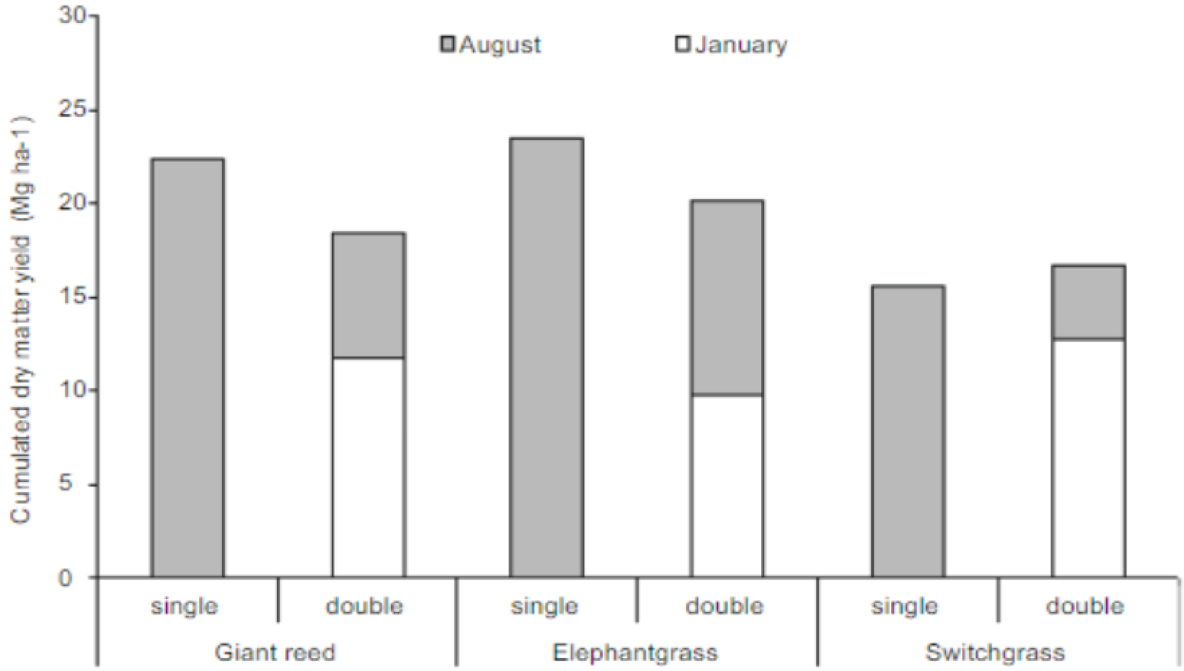


Figure 25: Cumulated dry matter yield (T/Ha/yr) [125]

6.5.2 FERTILIZER

For Elephant Grass to provide a constant amount of biomass every year, the nutrients removed from growing the Elephant Grass must be replaced for the next rotation of the Elephant Grass crop to grow sufficiently. 1.3 tonnes of biochar are required per hectare to amend the soil which has been previously harvested. This total is 707,600 tonnes of biochar annually used to amend the soil. Biochar, however, is not the only component that must be added to the soil. Biochar enhances plant growth and reduces the need for water and fertilizer. It does this by trapping moisture and nutrients in the soil, preventing moisture from leaching into the groundwater [126]. Elephant Grass is still a nutrient-hungry crop and requires fertilizer [101]. The main three nutrient additive chemical components of fertilizer are Nitrogen, Phosphorus and Potassium. The effect of these three chemicals on Elephant Grass growth will be studied in this section in order to create an ideal Elephant Grass biochar fertilizer blend.

The first chemical to be analysed is Phosphorus. Davis from the University of California found that in 60 days, the "Total P absorption of the crop was 161 kg per hectare" [127]. If the phosphorus absorption is 161kg/hec in 60 days, then in a year it would calculate to approximately $161 \times 6 = 966kg/hec$. However, this is an extreme upper estimate due to the Elephant Grass crop being newly planted at the beginning of the 60 days. A graph showing the nutrient absorption rate by corn plants is shown in figure 26 [128].

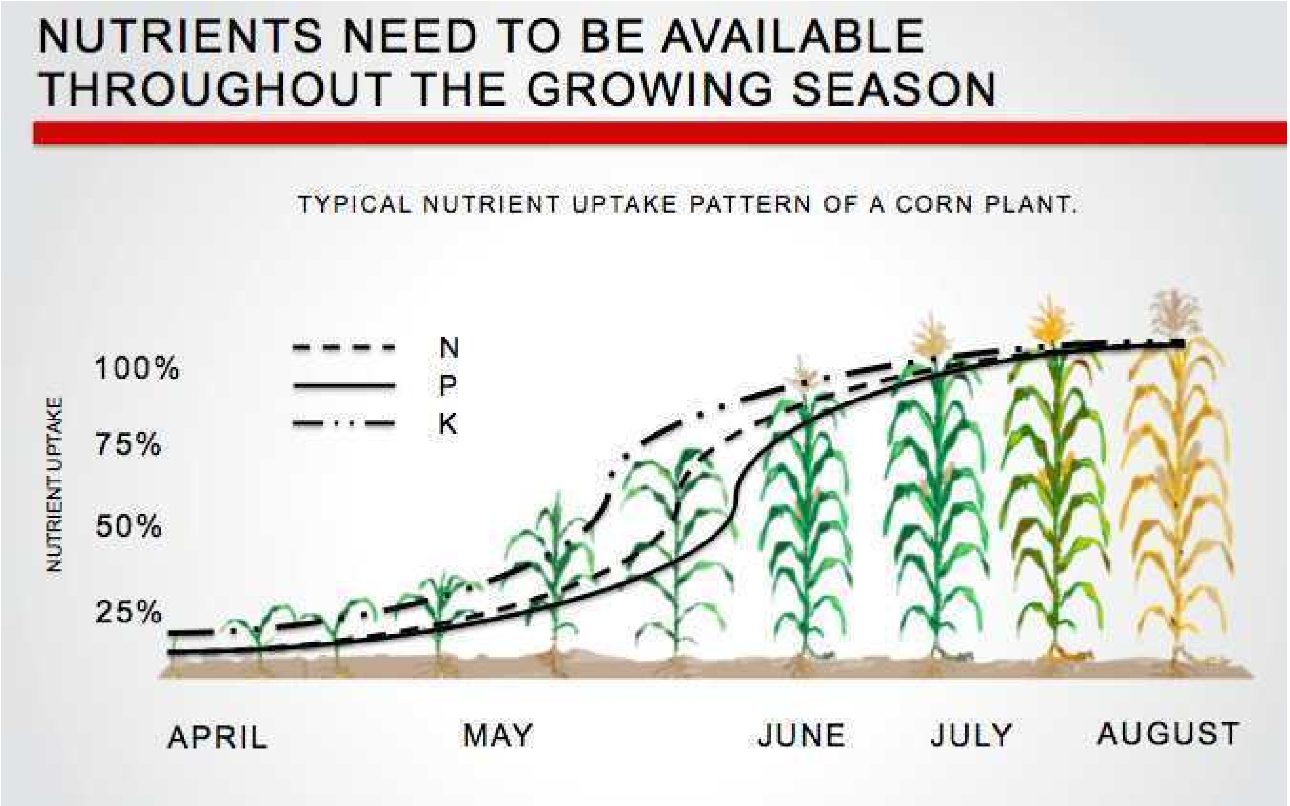


Figure 26: Nutrient uptake rate of corn plants [128]

As seen in Figure 26 the nutrient uptake for all nutrients follows a sigmoid relationship, meaning that during the beginning of the plant's lifecycle, it requires a far more considerable amount of nutrients than during the end. Whilst this relationship is shown is for corn. The same trend is also seen in Elephant Grass. Both crops also have similar life spans. Since the experiment only measured the nutrient uptake for the first 60 days of the Elephant Grass lifecycle, it measured a far higher nutrient uptake than if it was done over a year. Given that the sigmoid graph shown is approximately symmetrical but slightly negatively skewed, we can estimate that the 'real' nutrient absorption over a whole year can be slightly over half that of what was calculated, i.e. 510kg/sec/year of Phosphorus uptake. This corresponds to 277,593 tonnes of Phosphorus per year overall.

The second chemical to be analysed is Nitrogen. Figure 27 shows the effects of Nitrogen fertiliser on Elephant Grass dry matter yield [129].

Nitrogen fertilizer levels (kg ha^{-1})	DM yield (t. ha^{-1})
120	2. 0
80	2. 0
40	1. 7
0	1. 2
L.S.D 5%	0. 18
Harvest intervals (days)	
60	2. 8
45	1. 5
30	0. 8
L.S.D 5%	0. 12
Nitrogen levels x harvest intervals	
120 x 60	3. 2
120 x 45	1. 8
120 x 30	0. 9
80 x 60	3. 3
80 x 45	1. 7
80 x 30	1. 0
40 x 60	2. 8
40 x 45	1. 5
40 x 30	0. 7
0 x 60	2. 0
0 x 45	1. 0
0 x 30	0. 5
L.S.D. 5%	0. 24

Figure 27: The effects of nitrogen fertilizer on Elephant Grass dry matter yield [129]

From Figure 27, it is seen that longer harvest intervals provide larger dry matter yields, and the most efficient nitrogen application is 80 kg/ha, as 120kg/ha gives a similar dry matter yield, and for longer harvest intervals is also not markedly superior in any way. In this study, the maximum harvest interval was 60 days, and after harvest, the same fertiliser amount was applied again. As seen in the nitrogen levels x harvest levels table, the rate of application that resulted in the greatest dry matter yield was 80 x 60, i.e. 80 kg/ha applied every 60 days. This results in approximately 80*6 = 480 kg/ha/year. This value corresponds to 261,264 tonnes of Nitrogen in total per year.

A second study was also analysed to determine the accuracy of the result above. Since the harvest interval was once every 60 days as opposed to the harvest rate previously obtained (once per year), a study was sourced with longer application rates. The CSIRO Division of Chemical Technology performed a similar experiment on the effects of Nitrogen on Elephant Grass yield [130]. Their results are shown in the Figure 28.

Main effects of treatments on annual yields and tiller density

Treatment	Tillers m^{-2}		Total dry matter yield ($t\ ha^{-1}$)		Leaf dry matter yield ($t\ ha^{-1}$)		Stem dry matter yield ($t\ ha^{-1}$)		Trash dry matter yield ($t\ ha^{-1}$)	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Harvest interval										
3-month	125	174	47.2	41.1	13.9	14.1	31.2	25.2	2.1	1.9
6-month	64	68	47.1	31.1	9.5	6.4	32.1	20.6	5.2	4.3
Variable †	23	105	34.1	35.8	3.5	11.9	27.5	23.1	3.1	2.2
s.e. ±	4.0**	3.8**	4.49*	2.48**	0.92**	0.74**	3.28 n.s.	1.85 n.s.	0.31**	0.41**
N rate (kg N ha^{-1} yr^{-1})										
0	52	90	35.4	18.3	6.3	4.8	25.1	10.5	4.0	1.8
500	76	123	49.7	39.2	10.1	10.9	35.4	25.0	3.7	3.9
1000	78	120	45.4	38.1	9.9	11.7	31.8	24.2	3.7	2.4
2000	76	128	40.7	48.3	9.5	15.7	28.8	32.0	2.5	3.1
s.e. ±	4.6**	5.9**	5.19 n.s.	3.87**	1.07*	1.16**	3.79 n.s.	2.89**	0.35**	0.65**
N interval										
3-month	74	120	49.0	37.7	9.9	11.3	34.7	23.4	4.1	2.8
6-month	68	118	40.1	37.2	8.7	10.9	28.2	24.1	3.2	3.1
12-month	69	108	39.3	33.1	8.3	10.2	27.9	21.3	3.1	2.5
s.e. ±	3.5 n.s.	5.3.*	3.45*	2.38 n.s.	0.72 n.s.	0.83 n.s.	2.83*	1.49 n.s.	0.51 n.s.	0.30 n.s.

*Significant at $P < 0.05$. **significant at $P < 0.01$, n.s. not significant.
†In year 1, harvest interval was 12 months. In year 2, two harvests were taken at 3 months and one at 6 months.

Figure 28: The effects of nitrogen fertilizer on Elephant Grass dry matter yield [130]

This paper uses far greater nitrogen values of up to 2000 kg/ha/year rather than 720 kg/ha/year. The most efficient N-rate (kg/ha/year) for Year 1 (assuming yearly harvests) in terms of total dry matter yield is 500, which yields 49.7 t/ha. Using this value, it becomes 272,150 tonnes of Nitrogen per year. This is similar to what was found in the first paper. Thus an intermediate average value of 267,000 tonnes of Nitrogen per year will be the estimated value used.

The final chemical to be analysed is potassium. A study on the effect of potassium on growing Elephant Grass in Brazil published in the African Journal of Agricultural Research found that "the lowest K dose (200 kg ha-1) was enough to generate the best outcomes in characteristics presenting significant effects" [131]. This results in 108,860 tonnes of potassium in total per year. One crucial consideration to note, however, is that the paper only tested potassium values of 200 and 500kg/ha. A lower value or a more intermediate value between 200 and 500kg/ha would be ideal, but 200kg/ha will suffice as an estimate.

Thus, in total, the composition of the biochar soil fertilizer required to fertilize the entire plantation every year properly will be:

- 707590 tonnes biochar
- 277593 tonnes Phosphorus
- 267000 tonnes Nitrogen
- 108860 tonnes Potassium

In total this becomes 1,362,000 tonnes of fertilizer a year. The percentage composition of the fertilizer is 52% biochar, 20% Phosphorus, 20% Nitrogen and 8% Potassium.

6.6 PRODUCTS PRODUCED

In order to generate revenue and offset the carbon emissions created using pyrolysis technology, it is essential to consider what products are being produced through pyrolysis. The main products are biochar, bio-oil and syngas.

6.6.1 BIOCHAR

Biochar is a crucial product produced from the pyrolysis process since it will be used to achieve this project's main objective, which is to sequester 10% of Australia's annual emissions. Biochar has been highly promoted for its potential to increase soil productivity and carbon sequestration while also producing renewable energy [132]. Biochar physical characteristics greatly depend on the pyrolysis conditions such as the reactor, biomass types, drying treatment, chemical activation, heating rate, feedstock particle size, pressure, residence time, and inert gas flow rate. For instance, pyrolysis operating conditions like shorter residence time and higher heating rate will produce finer biochar, while longer residence time and lower heating rate results in a coarser biochar [133].

The structural and physicochemical properties of biochar, such as pore structures, surface area, elemental compositions, and surface functional groups, are affected by pyrolysis temperature. It has been reported by numerous studies that high pyrolysis temperature results in increased carbon (%C) content, high pH, and biochar surface area. Generally, pyrolysis temperature ranging between 500°C – 800°C is considered optimum for producing high-quality biochar for carbon sequestration.

This project initially considered slow pyrolysis to maximise the biochar output for carbon sequestration. However, after the initial calculations, it was determined that this project had a large amount of excess biochar. Hence, a fast pyrolysis method was opted to generate more bio-oil for revenue and energy generation. It was assumed that the pyrolysis temperature used for this project was 650°C and had a recovery of 20% of biochar. This assumption was made based on the research study by Iowa State University [134]. Therefore, after conducting a mass balance analysis, it was determined that the amount of biochar produced for this project was 5,486,400 tonnes per year, and about 707,600 tonnes were used as a soil additive in fertiliser. The remaining 4.8 million tonnes of biochar were sold to the market and given to the farmers to be used. These assumptions and considerations were further explained in the scenarios section. All of the scenarios that were considered would be able to generate revenue either from the Australian Carbon Credit Unit (ACCU) or from selling off the biochar.

6.6.2 BIO-OIL

Bio-oil is one of the leading products created from the condensation of the vapours produced from the pyrolysis process. Bio-oil comprises a mixture of about 300 – 400 oxygenated compounds, carboxylic acids, and traces of water. It has been reported that bio-oil can be used as a substitute for conventional fuels that generate power. Bio-oil has the potential to be used in existing power plants or for further refinement to access other products. Figure 29 shows some applications of bio-oil that exist. Long-term applications include being used for turbines and diesel engines.

In contrast, bio-oil applications in the short term usually involve being used for boilers and furnaces (including power stations). It is technically feasible to upgrade bio-oil to a transportation fuel quality. However, this needs further development [133].

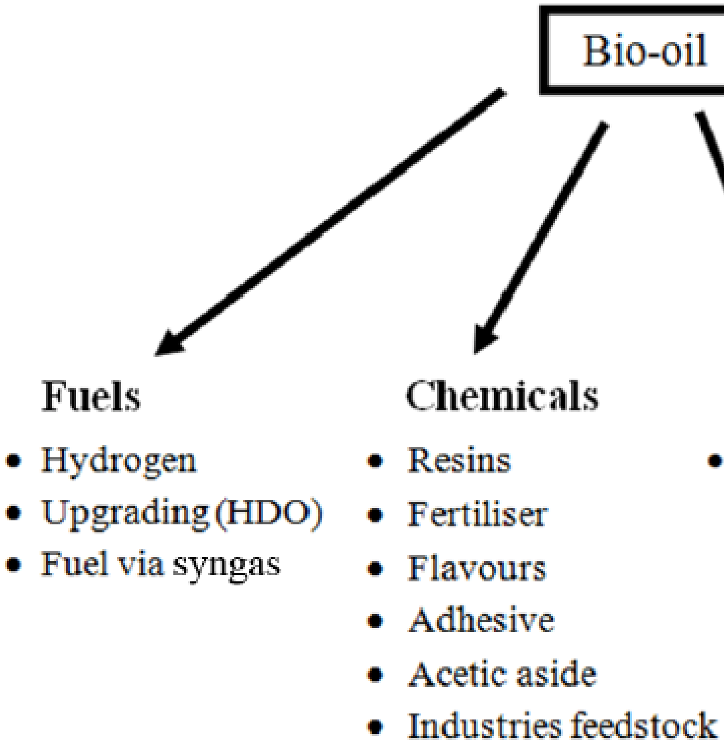


Figure 29: Various applications of pyrolysis bio-oil [133]

Table 12 shows the physical properties and characteristics of pyrolysis bio-oil.

Table 12: Physical properties and characteristics of pyrolysis bio-oil [133]

Properties	Characteristics	Reasons
Odour	Distinctive odour – an acrid smoky smell	Low molecular weight of aldehydes and acids
Density	Very high compared to fossil fuel – 1.2 kg/L	Heavy molecule contamination and high moisture
Appearance	Dark red brown to dark green	Micro-carbon and chemical composition
Viscosity	Vary from 25 centistokes (cSt) to 1000 (cSt)	Water content, wide range of feedstock, and the amount of light ends collected
Aging	Volatility decrease, viscosity increase phase separation and deposition of gum occur with time	High pH value and complex structure
Heating value	Significantly lower than fossil fuel	High oxygen content
Miscibility	Miscible with polar solvent but immiscible with petroleum fuel	Polar in nature

As a fast pyrolysis method is utilised with a heating rate of 50 C/min, the amount of bio-oil produced from this project could be determined. An analysis of the mass balanced equation for the process occurring was conducted. This is detailed in Appendix C. The main produced products were considered, including bio-oil, biochar, syngas, and ash. From these products, the total amount of bio-oil produced could be determined. For the whole project, this value was 7,188 million litres per annum. It is worth noting, however, that some of this bio-oil is intended for use in order to power the pyrolysis process. This is calculated to be 596 million litres per year. This leaves a total amount of 6,592 million litres of bio-oil per year. This amount of bio-oil was assumed to be sold off to the market within Western Australia and will be the source of revenue for this project.

6.6.3 SYNGAS

Syngas is the non-condensable gases produced from the condensation of the vapours created during the pyrolysis process. These gases mainly consist of carbon monoxide (CO), hydrogen (H2), and a small amount of carbon dioxide (CO2), water, and hydrocarbons such as methane

(CH4), tar, and ash. These components depend on the pyrolysis conditions and feedstock type and usually are obtained during several endothermic reactions at high temperatures. Carbon monoxide and carbon dioxide occur mainly due to the presence of oxygen in the pyrolysis process. At the same time, light hydrocarbons such as CH4 are produced from the reforming and cracking heavier hydrocarbons and tar in the vapour phase. Hydrogen gas is produced from the cracking of hydrocarbons at high temperatures [133].

The amount of hydrogen and carbon monoxide gases increases as the temperature of the pyrolysis process increases, while other components show an opposite tendency. The molar ratio of hydrogen gas and carbon monoxide in the syngas is crucial in determining the possible applications. For instance, a high molar ratio of H2/CO is desirable to produce Fisher-Tropsh that can be used for transportation fuel and hydrogen for ammonia synthesis. Syngas has been used in various applications such as an alternative renewable fuel for internal combustion (IC) engines and industrial combustion processes [133].

Mass balance calculations determined that the amount of syngas produced for this project was four million tonnes per annum. The syngas produced for this project will be recycled and used as heat recovery to heat the pyrolysis process. Therefore, an energy balance was conducted to determine the amount of energy that syngas can provide. This is also further detailed in Appendix D. It was determined that the amount of 24.16 billion MJ/year of energy could be used as heat recovery from syngas products. This approach to recycling syngas has been considered to reduce the project's cost and greenhouse emissions.

6.6.4 LAND COST

The land cost was calculated by obtaining the median hectares for regions throughout the Geraldton area from the Annual Ruralbank report 2021. This data has been attached to the Appendix B. The property price, purchase price with interest for a monthly payment over 20 years and leasing price per month can be calculated.
Firstly a few terms are defined:

- Median Hectare Price of the Region = MPR (AUD)
- Area of the Region = AR
- Estimated Property Price = EP
- Purchase Price = PP
- Purchase Price per Month = PPM
- Interest rate = r

- Number of time interest is compounded per unit t = n
- Time = nt
- Lease per Month = LPM

A value of 0.07 was used for LPM as it is the average value of a lease payment ratio for a given property, according to the NSW DPI report. For the interest, 1.63% was used according to the reserve bank of Australia's interest rate for large businesses.

$$MPR \times AR = EP \quad (1)$$

$$PP = EP(1 + \frac{r}{n})^{nt} \quad (2)$$

$$PPM = \frac{PP}{240} \quad (3)$$

$$LPM = PP \times \frac{0.07}{12} \quad (4)$$

$$(5)$$

Table 13 shows that Northern WA has the lowest Purchase Price per Month and LPM, and southern WA has the highest PPM and Lease per Month when accounting for 544,000 hectares of farmland in order to grow Elephant Grass.

Table 13: Costs of Owning and Leasing Land over a 20-Year Period [133]

	Cost of Owning Over 20-Years (Billions)	**Cost of Leasing Land over 20-Years (Billions)**
Northern QLD	$7.65	$7.73
Central QLD	$3.01	$3.04
Northern WA	$1.37	$1.39
Southern WA	$10.05	$10.16
Central WA	$2.50	$2.53

7 SCENARIOS

In order for this project to be physically and economically viable, the products produced must be able to be sold for a profit. This section outlines several scenarios for revenue generation along with an evaluation of the suitability of each scenario, limiting factors and critical points. A summary of the scenarios is shown in Figure 30.

- Scenario 1: Greater Geraldton - Free Biochar (No delivery cost) & Selling Bio oil
- Scenario 2: Greater Geraldton - Selling Biochar & Bio oil
- Scenario 3: Hall Creek (Ord River) - Selling Biochar & Bio oil

Figure 30: Map of the three scenarios for the pyrolysis project

7.1 SCENARIO ONE: GREATER GERALDTON - FREE BIOCHAR (NO DELIVERY COST INC) & SELLING BIO-OIL

Scenario one is located in Greater Geraldton, where the farmland has been previously used for wheat or grain agricultural purposes. Therefore there is no need to clear land for growing elephant grass. Due to the negligible difference between buying and leasing the land used to grow Elephant Grass., this project proposes that the required properties all be bought. This is due to the cost of leasing and buying being essentially the same for 20 years. For this scenario, biochar will be distributed free of charge, and the transportation cost will be paid by the person who is willing to obtain biochar.

7.1.1 ASSUMPTIONS

One of the assumptions is that ACCU income was calculated with a base price of AUD $30 [135] per unit. The overall amount of carbon sequestered is the previously outlined 10% of Australian emission (50.2 MT/year) [136]. The actual sequestration of carbon might differ as plants produce carbon dioxide through respiration (generally at night), which is assumed to be negligible, and the total amount of sequestered carbon dioxide is 50.2MT. This value and hence be converted into ACCU credits.

The transportation cost was calculated based on the Bureau of Infrastructure, Transport and Regional Economics, BITRE. The cost for train transportation of the produced products is 4c/km/T, and for transport via truck, the price was found to be 9c/km/T [137]. However, for this scenario, the cost of transportation will only be calculated using trucks and bio-oil transportation for bio-oil revenue. The bio-oil revenue will be calculated according to Australia's current raw bio-oil market price of $1.34/L [138].

7.1.2 EVALUATION

A benefit of this scenario is that there is no need to research the biochar market and the management of potential biochar customers. If we are sequestering biochar at a rate of 10T/ha, the land required is calculated to be 4779 sqkm. This means the project can use biochar on the elephant grass farmland or nearby grain farm located in Greater Geraldton free of charge (except for the transportation cost to the receiver of the biochar). This also provides free biochar to the local agricultural land and allows local soil nutrient levels to be maintained throughout the year to increase crop yields and water retention.

A negative aspect of this project is that it produced the lowest revenue out of the three scenarios proposed, with total revenue of $3.8B per year and an ROI of 1.8% which is not suitable considering the lifetime of the pyrolysis plant is generally 15 years [139]. It is also important to note that there is an optimal concentration of biochar in a given volume of soil for agricultural purposes, which is between 20-30%(v/v). This will ultimately force the project to find new customers or land owners located further away from the pyrolysis plant and increase the transportation cost, nullifying the merit of obtaining free biochar. Due to the free biochar produced, the market price of biochar is expected to drop significantly. This could also lead customers to prefer local biochar over the one produced in scenario one. This will slow the flow of biochar distribution from the project pyrolysis plant. From this prediction, our team recommends having a price for biochar. This will allow for better predictability in the biochar market and minimizes the effect that adding such a large amount of biochar would do on the market. Doing this also ensures that the situation does not escalate to a point where the cost of transporting the product exceeds the cost of buying the actual product.

7.2 SCENARIO TWO: GREATER GERALDTON - SELLING BIOCHAR & SELLING BIO-OIL

Scenario two is similar to scenario one, where the farmland for elephant grass will be located in greater Geraldton, and the land will be purchased. However, for this scenario, the project proposes to sell biochar and bio-oil as recommended in previous scenario one.

7.2.1 ASSUMPTIONS

Similarly to scenario one, the ACCU and the bio-oil revenue cost will be calculated using the same method. However, the project has included transportation costs for both bio-oil and biochar. Although the process of shipping flammable liquid and non-reactive solid differs in regulation, management, and machinery required. The project has assumed the freight is equal for both products, and the total price differs only according to the mass of the product shipped. The biochar cost was calculated according to the market price of $1150/T [140].

7.2.2 EVALUATION

The Greater Geraldton area shown in Figure 31 is well known for being part of the wheat belt of Australia with many local lakes and water bodies as shown in Figure 32. Purchasing farmland in this area will save the project money as the land does not need to be prepared for farming, this is also shown in Figure 33. Additionally, the proposed Greater Geraldton farmland covers 16 LGAs, which include three train stations (Morawa, Tardum, Cana), Morawa airport and Seaport (Geraldton port 182km away). Having four modes of transportation will allow the project to be more flexible toward the customers' needs and reduce the cost of transportation. The cost of transportation via train is 4c/km/T[137] which is substantially cheaper than the truck freight rate.

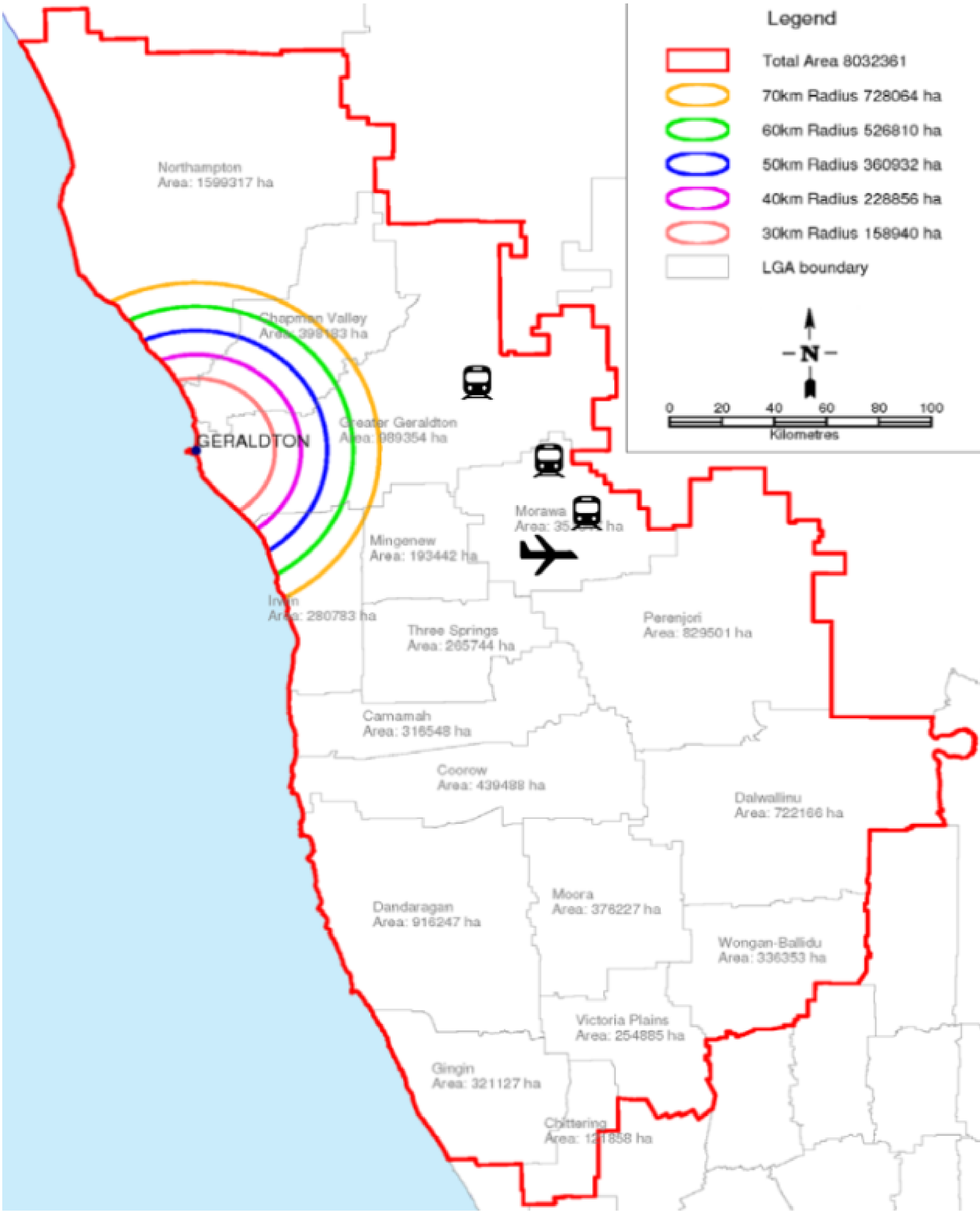


Figure 31: Map of Greater Geraldton and agricultural land

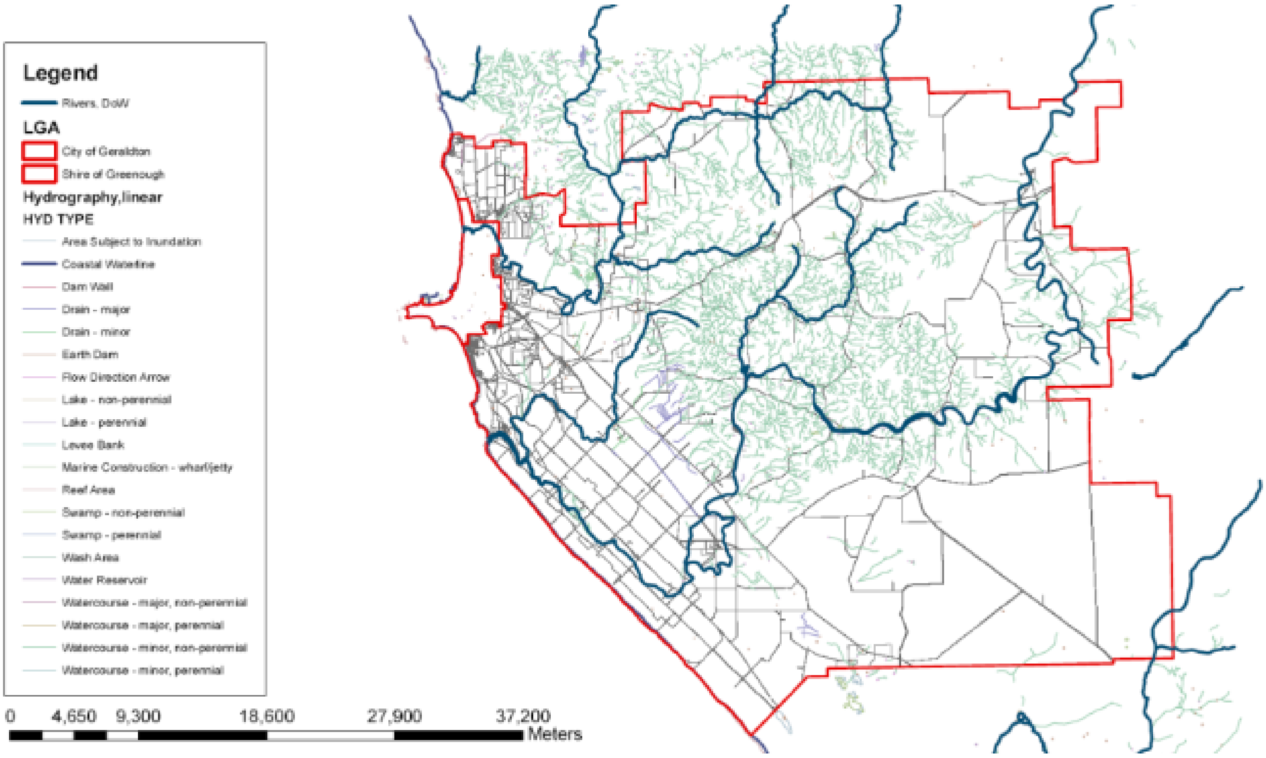


Figure 32: Greater Geraldton hydrography [141]

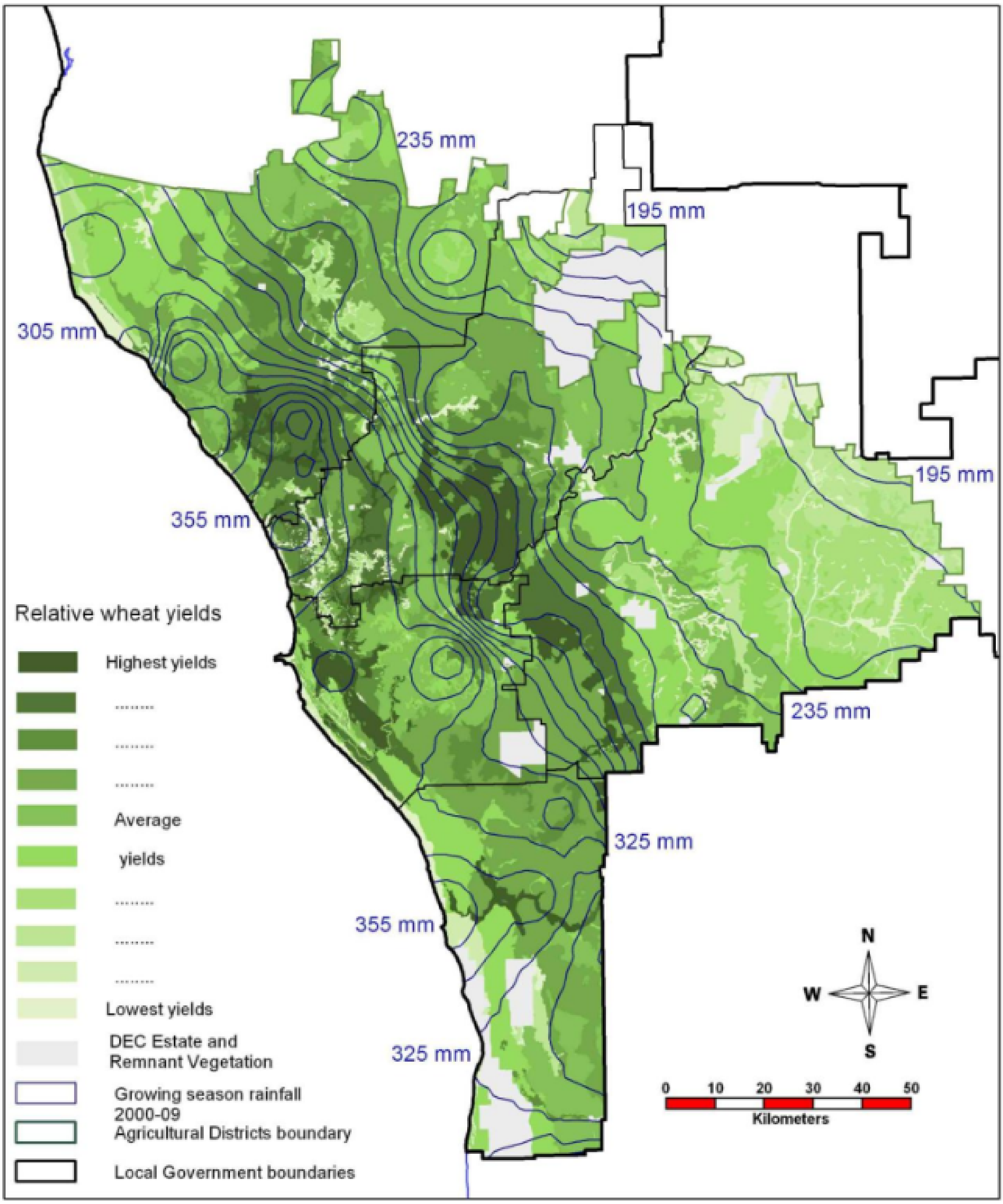


Figure 33: Rainfall and relative wheat yield of Greater Geraldton [142]

As shown in Figure 32, the Greater Geraldton area has a good array of sufficient water resources from artificial structures and natural bodies of water. These water sources can be considered an alternative water source in case there is ever a need for extra water outside of the 314mm of annual rainfall expected in the Greater Geraldton area [143].

Also, agricultural lands near the area could provide customers with the biochar product produced. Having a local customer reduces the transportation cost, which could save billions of dollars per year.

Table 14: Areas of Greater Geraldton Land Required (sqkm)

Local Government Area	Land Area (sqkm)
Tardun	633
Canna	816
Gutha	668
Merkanooka	611
Mount Budd	153
Wongoondy	502
Devils Creek	261
Tenindewa	723
West Casuarinas	684
Ambania	327
Nangetty	400
Holmwood	237
Dudawa	357
Womarden	380
Bowgada	770
Koolanooka	667
Total	**6190**

As the project requires farmland across 16 LGAs (Table 14, it is expected that obtaining the land required for this project would require complex negotiations with the current landlords and could potentially negatively impact the wheat price in Australia. Also, there is no reasonable amount of alternative feedstock nearby. According to the Biomass scoping study conducted by the Department of Primary Industries and Regional Development, there is insufficient biomass feedstock around the Geraldton area to accommodate an alternative feedstock for pyrolysis. Regardless, different types of Biomass have different carbon sequestration potential [144]. Compared to the 30 MT of Elephant Grass grown annually, there is no suitable alternative feedstock in the Greater Geraldton area.

7.3 SCENARIO THREE: HALL CREEK (ORD RIVER) - SELLING BIOCHAR & SELLING BIO-OIL

The project management of scenario three is similar to scenario two as the project proposes selling biochar and bio-oil. Scenario three, however, is located near the ord river in the Hall Creek area.

7.3.1 ASSUMPTIONS

Most assumptions, including the ACCU cost, transportation cost, biochar and bio-oil revenue, are calculated using the same method as scenario two. The difference between scenarios two and three is that the land requires land clearing. The land clearing cost for the project has been estimated using two scenarios: hiring contractors and renting bulldozers to clear the land. Assuming the only machinery required is bulldozer D11 (which is not true).

7.3.1.1 Costs to Clear Land when Hiring workers without a contractor

- Diesel Fuel: 2.46 (diesel price)[145] x 61 (L/hr used by D11)[146] = 150 AUD / hr
- D11 Rent Fee: Average of Wet and Dry $600 / per hour [147]
- Hour pay of Bulldozer driver: 48.90 / per hour [148]
- 0.375 acre per hour [149] (1,451,500 hours to clear 544,300 hectares of land)
- **Total: $799 per hour**

Overall Cost to clear the land is: AUD $ 1,160 M

7.3.1.2 Costs when Hiring contractors

Table 15 shows the standard prices for land clearing based on the type of terrian to be cleared. By assuming the land type is average, the average price can be taken to determine the total cost per hectare.

$$1500 + 3000/2 = 2250 \quad (6)$$

Taking the average cost gives a price of **$2250 / acre = $5560 / ha**. For a total land area of 544,300 hectares the total cost comes to **AUD $ 3,026 M**.

Table 15: Cost of land clearing Depending on The Land Type

Type of Land	Cost of Clearing per acre	Description of type of land
Low	$200 - $1,000	Land clearing of levelled 1-arce land with very little vegetation
Average	$1,500 - $3,000	Land clearning of a completely or moderately flat 1-acre lot with some rocks and moderate vegetation
High	$3,500 - $6,750	Tree removal and excessive vegetation of a hilly land

From these assumptions and calculations, the project assumes having a **$3 billion** land clearing cost as this is a more realistic estimation since this value was determined based on rugged terrain similar to what is expected as shown in Figures 34 and 35. This method also accounts for various other machinery that would be required for clearing land.

Figure 34: Image of the property land

Figure 35: Map of Hall Creek property

According to Rural Bank of Australia 2021, scenario three farmland had the lowest median land price per hectare. It is located at the midpoint of two central agricultural states: WA and QLD. This may be cost efficient as biochar will likely only be transported to these states. Figure 6 shows abundant water sources (Ord River); therefore, the farmland is less dependent on rainfall sources in droughts. One owner owns the above property, which could make negotiations easier than in scenario two. There are also plenty of Parkinsonia and woody weeds around the area, with an estimated 2904 MT available in Australia [150]. These woody weeds can be used as an alternative feedstock.

However, there is no nearby railway, and hence there is no opportunity to reduce the annual cost of transportation (AUD $1.5 billion to $3.5 billion per year). The cost and the time required for clearing land will also be a large portion of the project.

7.3.2 ECONOMIC FEASIBILITY ANALYSIS

An economic feasibility analysis was carried out to determine whether this project would be feasible or infeasible. An estimation of the investment is crucial as it is required to assess the profitability of a project. Capital Expenses (CAPEX), Operational Expenses (OPEX) and Return on Investment (ROI) values were hence calculated. This enables companies to ascertain which marketing strategies are adequate, as it provides insights into the effectiveness of the current marketing strategy and areas which require improvement [151] [152]. The economic analysis has considerable uncertainty due to the AACE Class 4 estimations. This is mainly driven by the concern that this project has limited data on cost and design details [153].

7.3.3 CAN WE SELL BIOCHAR AND BIO-OIL LOCALLY IN WA?

To consider the sale of biochar and bio-oil, we first need to consider whether Western Australia has enough need for the products produced by the pyrolysis factory proposed or whether the products must be exported to sell in overseas markets.

As mentioned previously, the total remaining biochar after using 707,590 tonnes as a soil amendment for the elephant grass plantation is 4,778,800 tonnes. Biochar is a valuable soil amendment that assists the yield of crops by increasing the nutrients and the moisture retention properties of the soil [126]. Hence, it is mainly used by farmers who grow crops. The most grown crop in Western Australia is wheat, with over 4 million hectares of wheat fields in the state[154]. In general, an application of 10 tonnes of biochar/hectare has been shown to improve the yield of crops [155]. Assuming that all wheat farmers will want to apply biochar to their fields, this results in a total need of 40 million tonnes of biochar for wheat farmers in Western Australia. Other crops are also grown in Western Australia, such as barley, canola, oats, lupins, and peas [156]. Thus, as can be seen, the upper estimate of biochar needed by crop farmers in Western Australia is far greater than the leftover biochar produced by the pyrolysis factory. For these reasons, Western Australia is a good local market for biochar sales.

Bio-oil, also known as bio-crude oil, is widely used in almost every industry, from being used as a transportation fuel, a lubricant, a source of energy for electricity generation, or as a feedstock for chemicals, plastics and synthetic materials. Petroleum products are indispensable and ubiquitous in the modern world [157]. Western Australia's annual crude oil production in 2016-2017 was 5.4 billion litres, or 34 million barrels, and produced 2.1 billion dollars in revenue [157]. The proposed pyrolysis facility produces 6.6 billion litres of bio-oil, or around 42 million barrels, a little higher than Western Australia's annual production. Whilst a lot of Western Australia's crude oil is sold, Australia had a total crude oil consumption rate of 890 thousand barrels per day in 2020 [158], or 324.5 million barrels a year. Hence, the amount of bio-oil produced via pyrolysis can cover around 13% of Australia's yearly crude oil consumption and thus meet a large amount of Western Australia's crude oil needs (although specific statistics surrounding Western Australia's crude oil usage cannot be sourced). This results in more of Australia's crude oil being exported to other countries, resulting in more significant revenue for Australia.

7.3.4 TRANSPORT COSTS

Since Western Australia is considered a good market for both bio-char and bio-oil, transportation costs must be determined to move the products produced in the pyrolysis factory to the different farms and oil refineries in Western Australia. A few assumptions must be made first, however. Given that the pyrolisis facility's potential location is in Greater Geraldton, we can find the maximum distance the transport vehicles can travel. The maximum distance used is the distance from Perth (central-southern WA, and slightly below the Greater Geraldton area) to Wyndham (top most Northern WA) is 3211 km [159]. The two main modes of transport of large quantities of products are either via freight train or freight truck. According to the Department of Infrastructure and Regional Development, the prices are 4c/km/tonne for train travel and 9c/km/tonne for truck travel [160]. The following upper-limit prices can be derived for the total cost of transporting 4.78 million tonnes of biochar and 7,188 million Litres (7.18 million tonnes, assuming a modest weight estimate of 1kg/litre):

Table 16: Transport Costs for Biochar and Bio-Oil

	Freight Train Price (Billion)	Freight Truck Price (Billion)
Bio-oil	$0.924	$2.08
Biochar	$0.614	$1.38

Thus, the price range for an upper estimate of the total yearly transportation costs of both biochar and bio-oil is $1.5 - $3.5 Billion.

7.3.5 AUSTRALIAN CARBON CREDIT UNIT (ACCU)

Australian Carbon Credit Units (ACCU) are one of the revenue sources for our project. An ACCU is a unit that the Clean Energy Regulator issues to a person. These units are recorded in the individual's electronic account in the Australian National Registry of Emissions Units [161]. Each ACCU issued represents one tonne of carbon dioxide equivalent (T CO2) stored or avoided by a project [161]. Individuals can only be granted an ACCU if they have a Registry account. An individual can only open a Registry account once the Regulator has determined if they are a ”fit and proper person” [161]. Eligible activities are undertaken as 'eligible offset's projects. Several requirements must be satisfied before a project can be declared an 'eligible offsets project, and there are ongoing requirements in undertaking an eligible offsets project. The requirements include:

- The project proponent must pass a 'fit and proper person test.
- There must be an approved methodology for the type of project.
- The project must deliver abatement that is additional to what would occur in the absence of the project.
- The project must meet the applicable additionality requirements.
- The project must be undertaken in accordance with the methodology and comply with other scheme eligibility requirements.
- The project proponent must report to the Regulator about the conduct of the project and the abatement achieved. Specific reports must be accompanied by a report prepared by a registered greenhouse and energy auditor.

7.3.6 CAPITAL EXPENDITURES (CAPEX)

CAPEX calculations were based on an Azure-based pyrolysis plant in Victoria, which can process 750,000 tonnes per annum (TPA) [153]. CAPEX calculations were done using a linear model for scaling up the plant due to a lack of information on the capacities and prices of the pyrolysis plants investigated. The plants should be able to sequester 10% of Australia's annual carbon emissions, which requires us to process 30.5 million tonnes of biomass per annum. These calculations determined that this project requires 41 plants, each of which can process 750,000 tpa. The cost of each plant was AU$ 1.2 billion. When accounting for the 41 plants which are required, the total price comes to AU$ 49.2 billion [34].

The cost of the purchased plant was assumed to include all the direct costs (ISBL) such as installation cost, instrument and control, piping, electricity, building, service facility, and insulation cost, except for the land cost. The indirect cost (OSBL), which includes contractor and construction fees, was also considered for the CAPEX calculations with the cost assumptions of 2% and 10% of the total installed cost (TIC), respectively [162]. The additional cost such as engineering and project contingency were also included in the CAPEX calculations. The details of the calculations can be found in Appendix E.

One of the reasons for the high cost of each plant is the increased demand for steel, which has increased steel prices. Also, due to the covid pandemic, supply from countries such as Brazil, the second largest iron ore producer, has remained impacted. This has placed more significant stress on the demand for Australian iron ore exports [163]. Lastly, the price of coking coal has increased, resulting in higher steel costs as it is one of the major elements used in producing steel [164]. Multiple locations were selected for the pyrolysis plant to be built. The economic analysis was carried out on each chosen site with two different scenarios: buying or leasing the land. Central WA was chosen as the ideal location for the pyrolysis plant to be built, as the justification was provided earlier in the report.

Table 17: CAPEX calculation for plants in different locations with buying and leasing of the land

Location	Overall CAPEX after buying land (Billions)	Overall CAPEX after leasing land (Billions)
North WA	$66.1	$64.3
Central WA	$67.5	$64.3
Central QLD	$68.2	$64.3
Northern QLD	$74.3	$64.3
South WA	$77.3	$64.3

7.3.7 OPEX

An OPEX calculation was carried out by calculating the workers required for 41 pyrolysis plants and the labour required for harvesting and collecting the Elephant Grass for pyrolysis. It was found that the operating expense in Central WA will be AU $5.1 billion if the land is leased. South WA was the most expensive place to lease land for the pyrolysis plant and the agriculture of Elephant Grass. The detailed breakdown of the operating expenses and the assumptions included with the calculations for Central WA are shown in Appendix F.

One of the main drivers for the operational expenses for the pyrolysis plant was the purchase of the raw materials such as Phosphorus, Potassium, Nitrogen, Elephant Grass seeds and the water required for irrigation [165] [166] [167] [168]. It was estimated to be approximately AU $2.7 billion per year, which accounted for approximately 36% of the operational expenses. The cost of fertilisers has increased as supply chains were impacted by COVID-19, particularly those from China, a significant fertiliser manufacturer [169]. The cost of the raw materials is shown in Appendix G.

Table 18: OPEX for leasing lands and without leasing lands in different locations

Location	OPEX with leasing the land (Billions)	OPEX without leasing the land (Billions)
North WA	$5.1	$5
Central WA	$5.2	$5
Central QLD	$5.2	$5
North QLD	$5.4	$5
South WA	$5.6	$5

The bar chart shown in Figure 36 shows the breakdown of different components for the operational cost. The energy was not included in the bar graph below as the pyrolysis process was self-sustaining through the energy balance calculations shown in Appendix D. A literature investigation also found that pyrolysis plants are generally self-sustaining [170] [171] [172]. The energy generated from the pyrolysis plant will offset the energy expenses. This process is self-sustaining, and the excess energy can be sold to the grid, adding to the revenue.

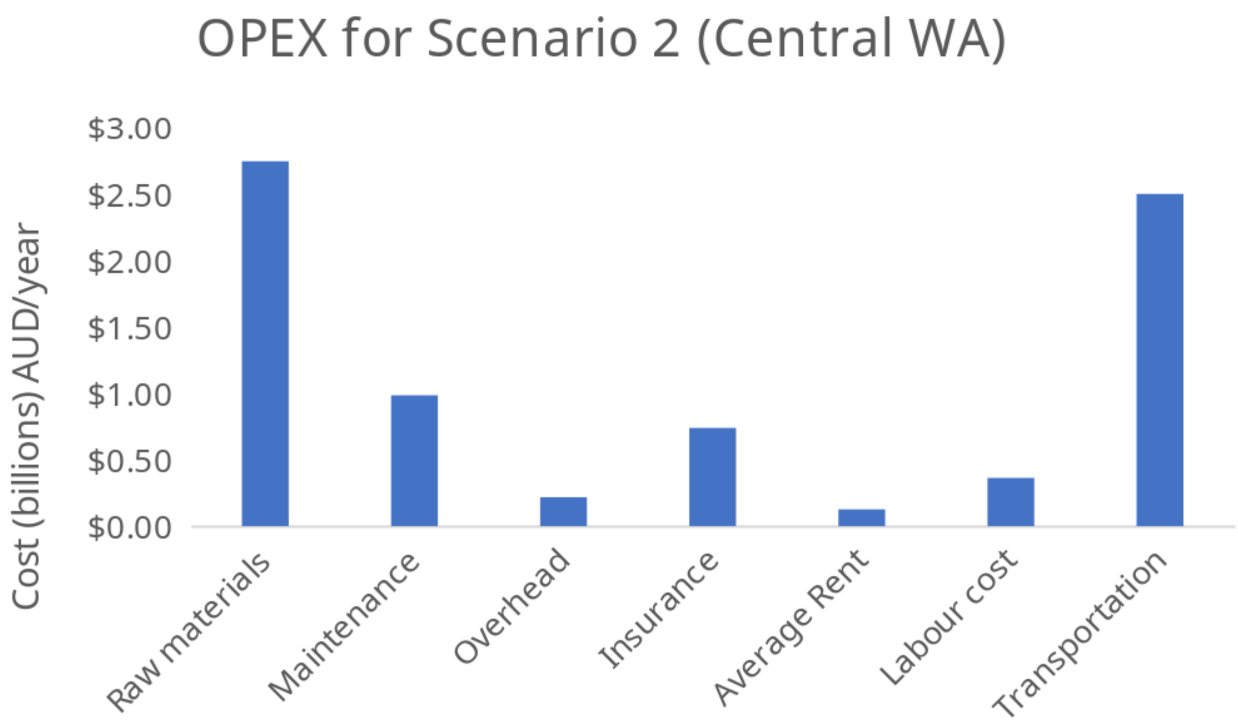


Figure 36: Bar chart showing the breakdown of different components of the OPEX

The pie chart shown in Figure 37 gives a breakdown of different costs in their % on OPEX, and it has been shown that maintenance contributes the second most of the expenses for the operation. It was estimated that the maintenance is approximately 13% of the equipment cost. The maintenance cost was estimated to be approximately AU $980 million per year. Regular maintenance is essential for a plant, as an effective maintenance program will make the plant more reliable [173]. Fewer breakdowns will result in less risky machinery contact, saving money while improving production and efficiency [173].

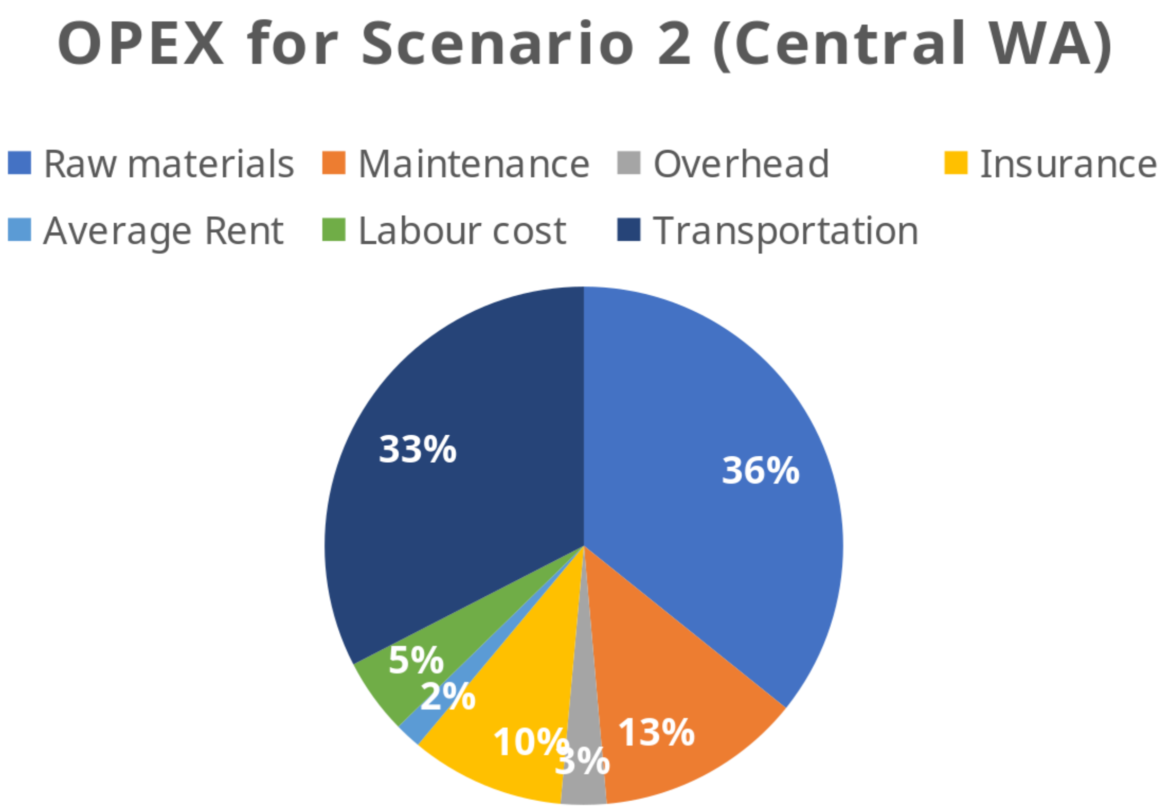


Figure 37: Pie chart illustrating the breakdown of different components of OPEX

Insurance is the third primary contributing source for the operational expenses for the pyrolysis plant, and it was assumed that it would be 1.5% of the total installed capital. Based on the assumption, it was calculated that the insurance would cost approximately AU $740 million per year. Bio-oil and biochar are the significant products of the pyrolysis plant, which can later be sold to the local and international markets. Some of the biochar produced from the pyrolysis process will be converted to fertilizer for the Elephant Grass. The plant can benefit from a chemical manufacturing industry as the business can choose to take insurance which will address pollution liability, property damage, and product liability [174].

According to our estimates, it was found that we need approximately 5000 workers for the 41-pyrolysis plant, out of which around 3500 workers will be responsible for harvesting, drying the Elephant Grass under natural light and transporting it to the plant. Rest of the workers are specialised workers such as plant engineers, operators, lab technicians, plant managers, and administrative workers. It was assumed that each plant will have 1 plant engineer, general manager, maintenance supervisor and lab manager [175]. It was assumed that each plant will have 5 maintenance technicians, 4 shift supervisors, 2 administrative assistants and 20 operators for each plant [175]. It was calculated that the annual labour fees will be approximately AU $360 million per year, and the workers are expected to work 48 weeks a year. The detailed salary cost can be found in Appendix H.

7.3.8 RETURN ON INVESTMENT ROI

An analysis of the Return on Investment for this project was carried out. Return on Investment, also commonly referred to as ROI, is a performance measure that investors can use to evaluate the profitability or efficiency of an investment and determine how well a particular investment has performed compared to others [176]. ROI directly measures the return on a particular investment relative to the investment's cost [177].

Since this project considers three different scenarios, an ROI analysis was carried out for each case. Table 19 shows the sample of ROI analysis for Scenario two that includes the assumptions for some of the components involved in the calculations. The analysis of ROI for other locations can be found in Appendix I.

Table 19 summarises the ROI values for all scenarios that have been considered. Based on the summarised ROI values, it can be deduced that scenario two has the highest ROI measure with the value of 8.61%, followed by scenario three and scenario one

Table 19: ROI analysis for Scenario Two Located at Central Western Australia

Components	Assumptions	Calculated Cost ($)	Units
Production cost			
Total production cost	Direct production cost + Overhead charges	$51,917M	
Total production rate		750,000	tonnes/year
Production cost	Total production cost/Total production rate	69,000	$AU/year
Profitability analysis			
Selling price	From bio-oil, biochar and excess energy	$15,874M	$AU/year
Profit	Selling price- production cost	$8,329M	$AU/year
Total income		$15,874M	$AU/year
Gross profit		$13,130M	$AU/year
Taxes	Assuming rate of 30%	$3,939 M	$AU/year
Depreciation	Pyrolysis unit depreciation period is 15 years	$3,377M	$AU
Net profit	Gross profit - Taxes - Depreciation	$5,814M	$AU/year
Rate of return			
Rate of return	Net profit/TCI $\times$ 100	8.61	%

Table 20 shows the ROI values for all the scenarios investigated.

Table 20: ROI values for all scenarios

Location	ROI (%)
Scenario One	1.80
Scenario Two	8.61
Scenario Three	5.96

Many financial investors have reported that an ROI value that ranges between 5% to 7% is considered a good return on an investment, where >7% is an excellent return rate for most and 5% is enough to be considered a good return. Since all the proposed locations have ROI values ranging between 5% to 7%, it can be determined that these locations are suitable and worthy to be considered for this project [178]. Since scenario two has the highest ROI value, which is approximately close to 7%, it is suggested to execute this scenario for this project as it is considered to have the best return on investment compared to other scenarios.

7.3.9 REVENUE SOURCES FOR EACH SCENARIOS

Three different scenarios were considered for the economic analysis. For scenario one, it was assumed that none of the biochar produced would be sold to the customers. Instead, it is intended to be given away for free to the local farmers while generating revenue only from ACCU (Australian Carbon Credit Units) and from bio-oil. Whereas scenarios two and three considered selling all the bio-oil, biochar, and the revenue from ACCU.

The pie chart below shows the revenue generated from scenario one, with the excess revenue generated from selling bio-oil at 85%, followed by ACCU at 14.65% and a negligible amount of revenue generated from selling excess energy to the grid at 0.24%. It was assumed that the revenue generated from ACCU would be AU $30.25 per tonne of CO2 sequestered.

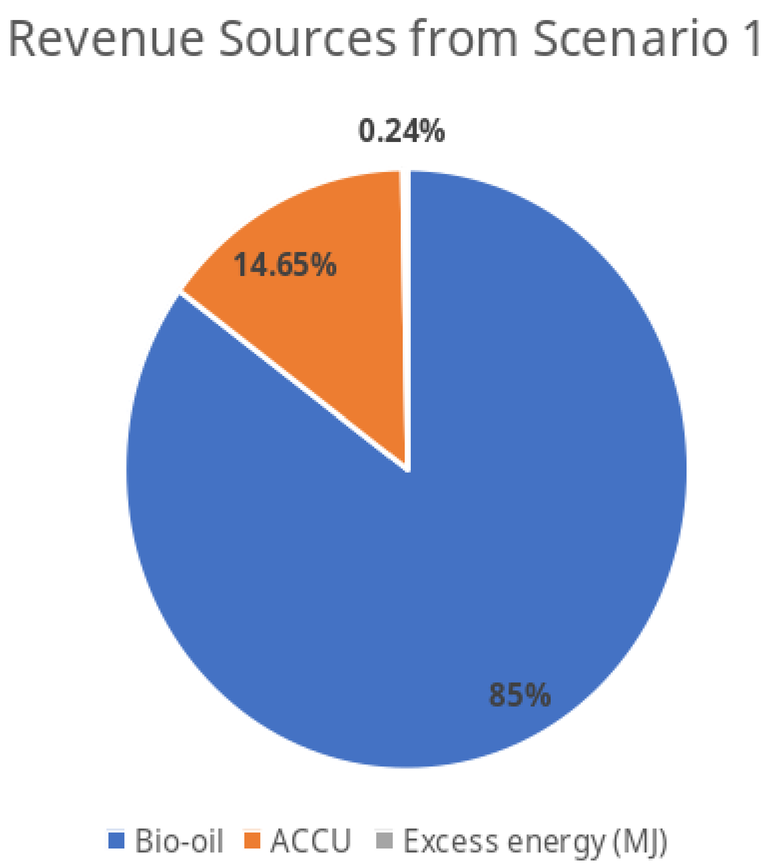


Figure 38: Revenue sources from scenario one

The main products of the pyrolysis process are biochar, bio-oil, and ash. The biochar market is currently developing in Australia [179]. Supporters and early users of biochar are aware of its advantages, which include improved crop yield, lower greenhouse gas emissions, and carbon sequestration [179]. It was discovered that 13% of consumers use biochar as a crop yield enhancer and 16% of customers use it as a feed supplement [179]. The figure below displays a breakdown of all biochar's practical applications [179].

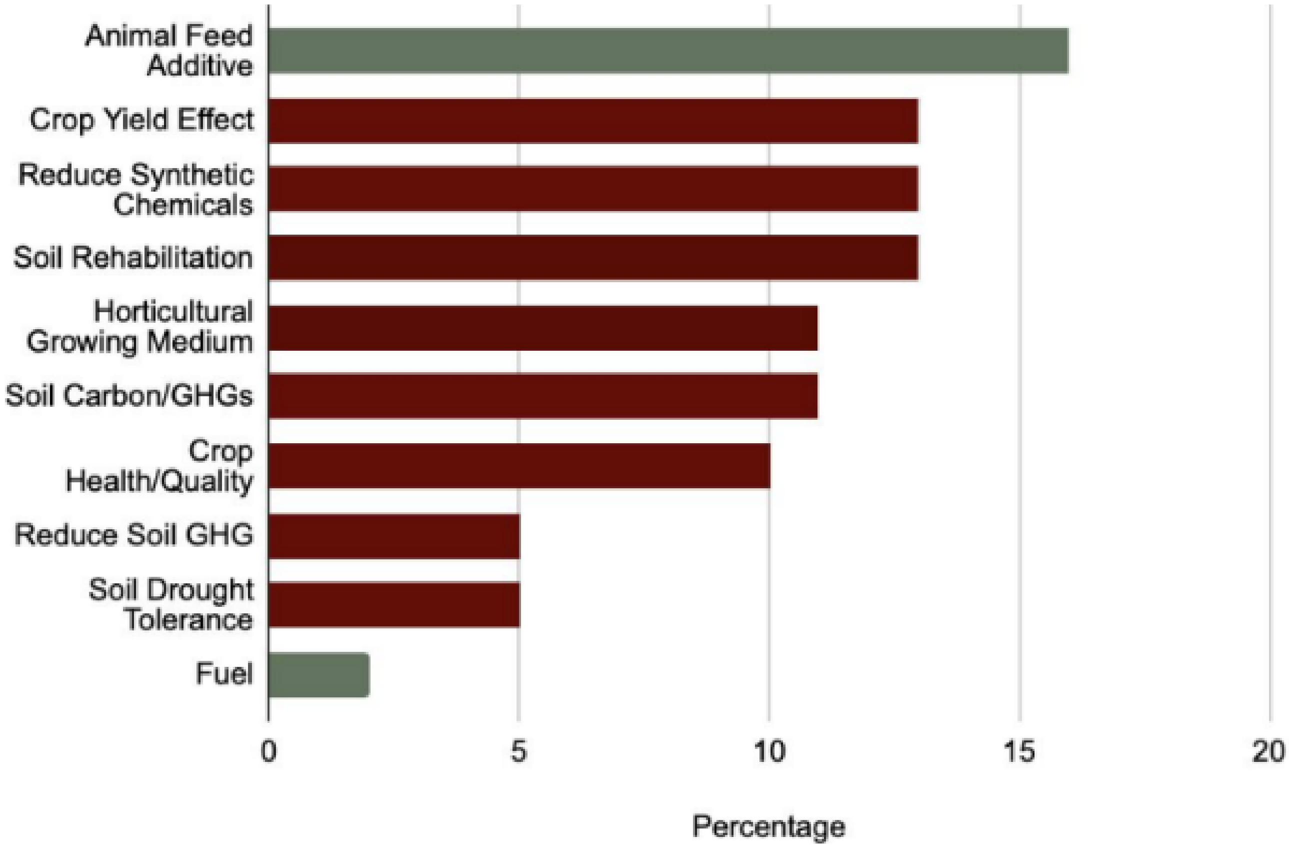


Figure 39: Different uses of biochar in Australia [179]

The pyrolysis plant will produce 2.6 million tonnes of excess biochar in scenarios two and three. This excess can be sold as an animal feed additive as 16% of consumers of biochar for this purpose. Regular use of biochar is necessary when it is used as a feed additive. This results in a high annual requirement of biochar ranging from 0.2 to 18.75 tonnes [179]. The price per tonne of biochar ranges from AU $100 to AU $6750, with the average being AU $1807 per tonne. We have assumed that the selling price of the biochar will be AU $1150 per tonne for our calculations [179]. According to the calculations, the revenue generated from selling biochar per annum would be approximately AU $5.5 billion, assuming all the biochar is sold. There is also significant pressure on the iron and steel industry to cut back on energy use, greenhouse emissions, and carbon footprint [180]. Biochar can help reduce greenhouse emissions when used for steel making. The Australian steel industry is an essential part of the Australian economy generating approximately AU $29 billion in revenue, and using biochar as their feedstock can help reduce the greenhouse emissions [181].

Bio-oil is another primary product sold to petroleum industries to manufacture gasoline, biodiesel, and jet fuel. Bio-oil needs to be cleaned and stabilized to make it more suitable for storage, downstream processing, and end use [182]. Bio-oil clean-up consists of filtering out particulates and ash before the bio-oil is condensed to a liquid. As bio-oil treatment is expensive and out of scope, it can be sold to the petroleum industries to pre-treat bio-oil for fuel processing [182]. Due to the lack of data on the selling prices of raw bio-oil, it was estimated that the bio-oil would be sold for AU $ 1.34 per Litre to the petroleum industries.

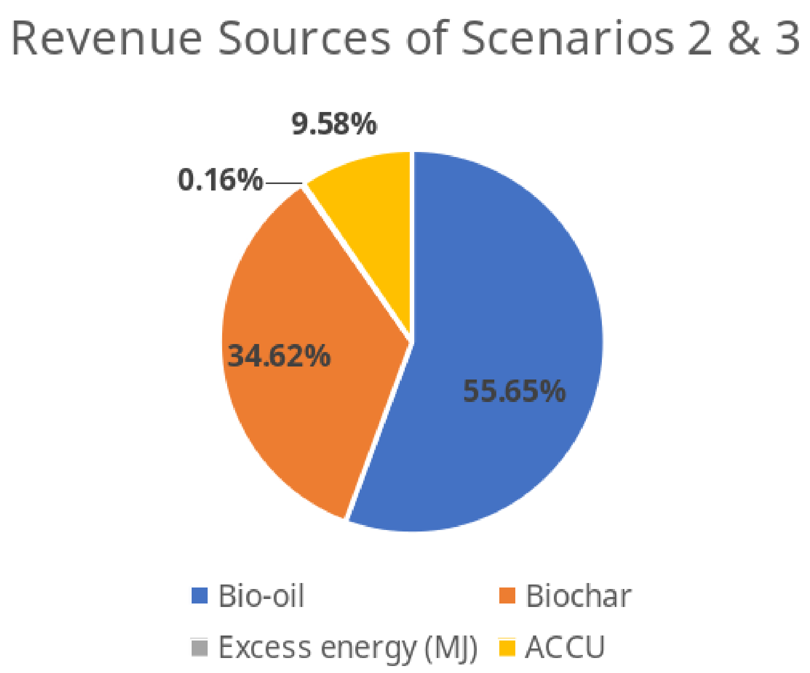
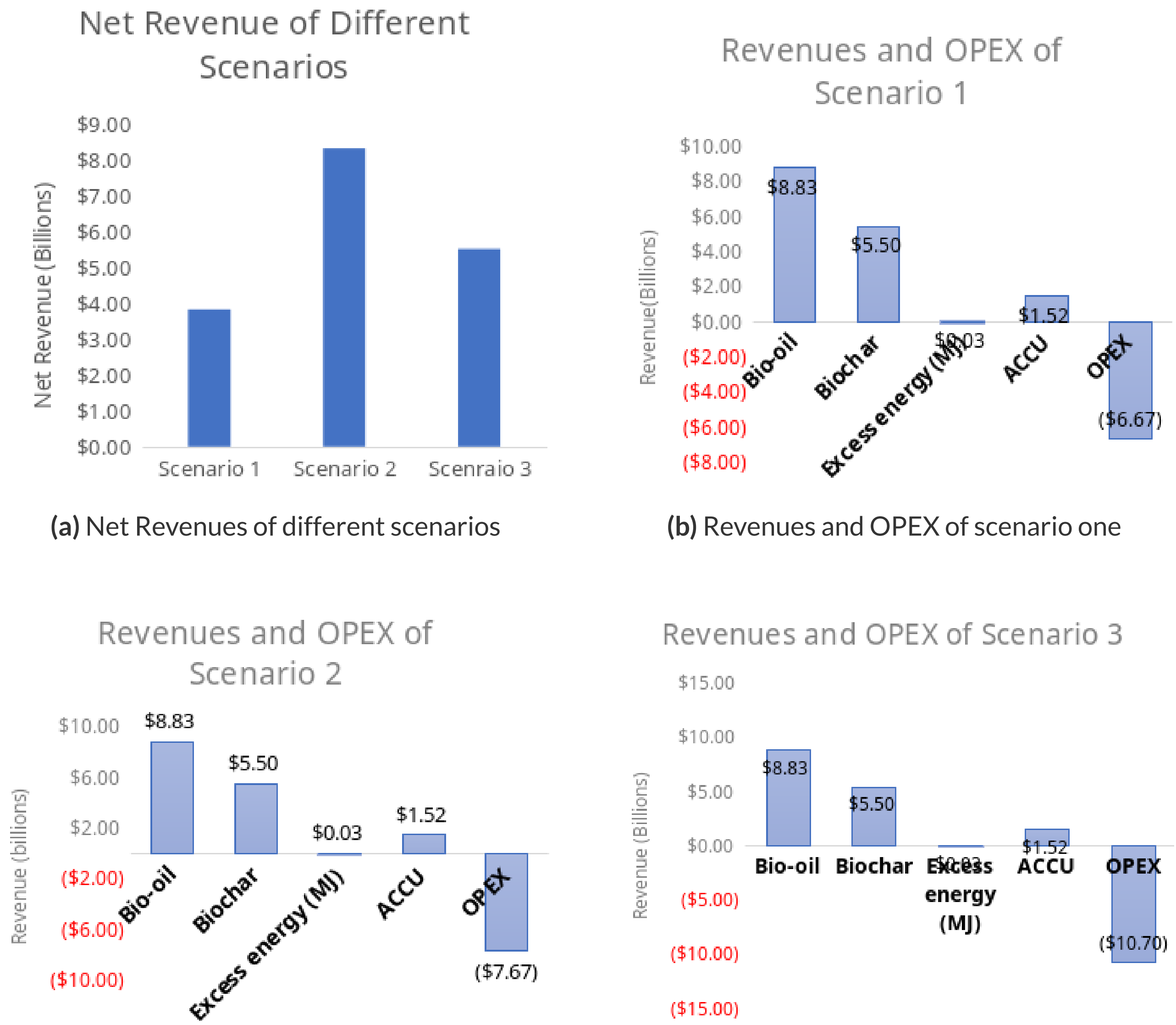


Figure 40: Pie chart representing % of revenue generated from sources

According to the pie chart below, it was found that bio-oil is the highest revenue contributor at 55.65% of the total revenue generated from this project. This was followed by biochar at 34.62%, ACCU at 9.58% and the remaining 0.16% being the revenue generated from selling off excess energy to the grid, as this plant produces excess energy as shown in Appendix D and C [183]. The revenue generated from excess energy might differ as the energy prices for businesses in Western Australia were unavailable. Therefore, the domestic energy prices were used to calculate the revenue when selling electricity back to the grid [184].

7.3.10 NET REVENUES OF DIFFERENT SCENARIOS

A net revenue analysis was carried out based on all three different scenarios. The net revenue included all the revenue sources for the three scenarios mentioned above and the OPEX. The depreciation was not accounted for in the calculations for net revenue but was included in the ROI calculations. A straight-line depreciation was assumed over twenty years, around AU $3.4 billion per year. The bar charts below show net revenues for all three scenarios and the revenues and operational expenses. After the depreciation was factored in, a profit and loss analysis was carried out.



(a) Net Revenues of different scenarios

(b) Revenues and OPEX of scenario one

(c) Revenues and OPEX of scenario two

(d) Revenues and OPEX of scenario three

Figure 41: Net revenue of the investigated scenarios

A profit and loss (P&L) statement table for Year two is given in Table 21. Year one was avoided as it is assumed that the plant is being constructed during the first year, and there are additional initial costs. Year two is when the plant is planned to be operational (although this may take longer than a year to produce). The table below shows the profit and loss statements for the three scenarios mentioned above. The prices for the raw materials and the revenue sources are subject to change due to currency fluctuations, increased demand for biochar and bio-oil, excess supply of biochar and bio-oil, or the increased demand for the raw materials. The prices mentioned on the PL statement are average in Australia except for the biochar, which has an average price of AU $1807 per tonne, but a competitive market price of AU $1150 per tonne was used as the biochar market in Australia is still developing. It can be predicted that the biochar market in Australia will increase due to the increased efforts by the government to reduce Australia's carbon emissions.

Table 21: Profit and Loss statement for Year Two

Year Two				
Full Scale Plant		**Scenario One (Billions)**	**Scenario Two (Billions)**	**Scenario Three (Billions)**
Revenue Sources	Bio-oil	$8.83	$8.83	$8.83
	Biochar	-	$5.5	$5.5
	ACCU	$1.52	$1.52	$1.52
	Excess Energy	$0.03	$0.03	$0.03
	Total Revenue	**$10.4**	**$15.9**	**$15.9**
Operational Expenses (OPEX)	Raw Materials	$2.74	$2.74	$2.74
	Maintenance	$0.98	$0.98	$0.98
	Overhead	$0.22	$0.22	$0.22
	Insurance	$0.74	$0.74	$0.82
	salary	$0.36	$0.36	$0.36
	Transportation of Bio-oil	$1.50	$1.50	$1.50
	Transportation of Biochar	-	$1.00	$1.00
	Total OPEX	**$6.55**	**$7.54**	**$7.63**
Capital Expenditures (CAPEX)	Purchased eqiupment cost	$49.2	$49.2	$49.2
	Cost of Land	$2.50	$2.50	$2.50
	Cost of Clearing Land	-	-	$3.03
	Field Expenses	$1.03	$1.03	$1.09
	Construction Fee	$5.17	$5.17	$5.47
	Engineering Design	$4.63	$4.63	$4.90
	Project Contingency	$5.00	$5.00	$5.30
	Total Capital Investment	$67.54	$67.54	$71.49
Depreciation	Depreciation	$3.38	$3.38	$3.57
Profit	Profit	$0.45	$4.95	$4.67

7.3.11 PILOT SCALE

A pilot scale plant has been proposed to be developed in Central WA, further determining whether this technology is feasible on a large scale. The knowledge obtained from the pilot scale can then be used for the design of full-scale production systems and commercial products, as well as to identify further research objectives and support investment decisions. Other non-technical purposes include gaining public support for new technologies. Some pilot plants are built in laboratories using stock lab equipment. In contrast, others require substantial engineering efforts, cost millions of dollars, and are custom-assembled and fabricated from process equipment, instrumentation, and piping. They can also be used to train personnel for a full-scale plant. The chosen pilot plant will have a capacity to process 750000 tonnes per annum of dry biomass. A PL statement is shown below for the pilot scale based on all three different scenarios. The calculations were done simply by dividing the values by 41 as it required 41 plants on full scale to sequester 10% of Australia's carbon emissions. A profit and loss (P&L) statement table for the pilot plant is given in Table 22.

Table 22: Profit and Loss Statement for pilot scale

Year Two				
Full Scale Plant		**Scenario One (Millions)**	**Scenario Two (Millions)**	**Scenario Three (Millions)**
Revenue Sources	Bio-oil	$215	$215	$215
	Biochar	-	$134	$134
	ACCU	$37	$37	$37
	Excess Energy	$1	$1	$1
	Total Revenue	**$253**	**$387**	**$387**
Operational Expenses (OPEX)	Raw Materials	$67	$67	$67
	Maintenance	$24	$24	$24
	Overhead	$5	$5	$5
	Insurance	$19	$19	$20
	salary	$9	$9	$9
	Transportation of Bio-oil	$37	$37	$37
	Transportation of Biochar	-	$24	$24
	Total OPEX	**$161**	**$185**	**$186**
Capital Expenditures (CAPEX)	Purchased eqiupment cost	$1,200	$1,200	$ 1,200
	Cost of Land	$61	$61	$61
	Cost of Clearing Land	-	-	$74
	Field Expenses	$25	$25	$27
	Construction Fee	$126	$126	$133
	Engineering Design	$113	$113	$120
	Project Contingency	$122	$122	$129
	Total Capital Investment	$1,650	$1,650	$1,740
Depreciation	Depreciation	$82	$82	$87
Profit	Profit	$10	$120	$114

7.3.12 BREAKEVEN ANALYSIS

Using the previous values of CAPEX = 67.5 billion and Yearly Net Revenue (gross revenue - OPEX) = 8.33 billion, Figure 42 was produced.

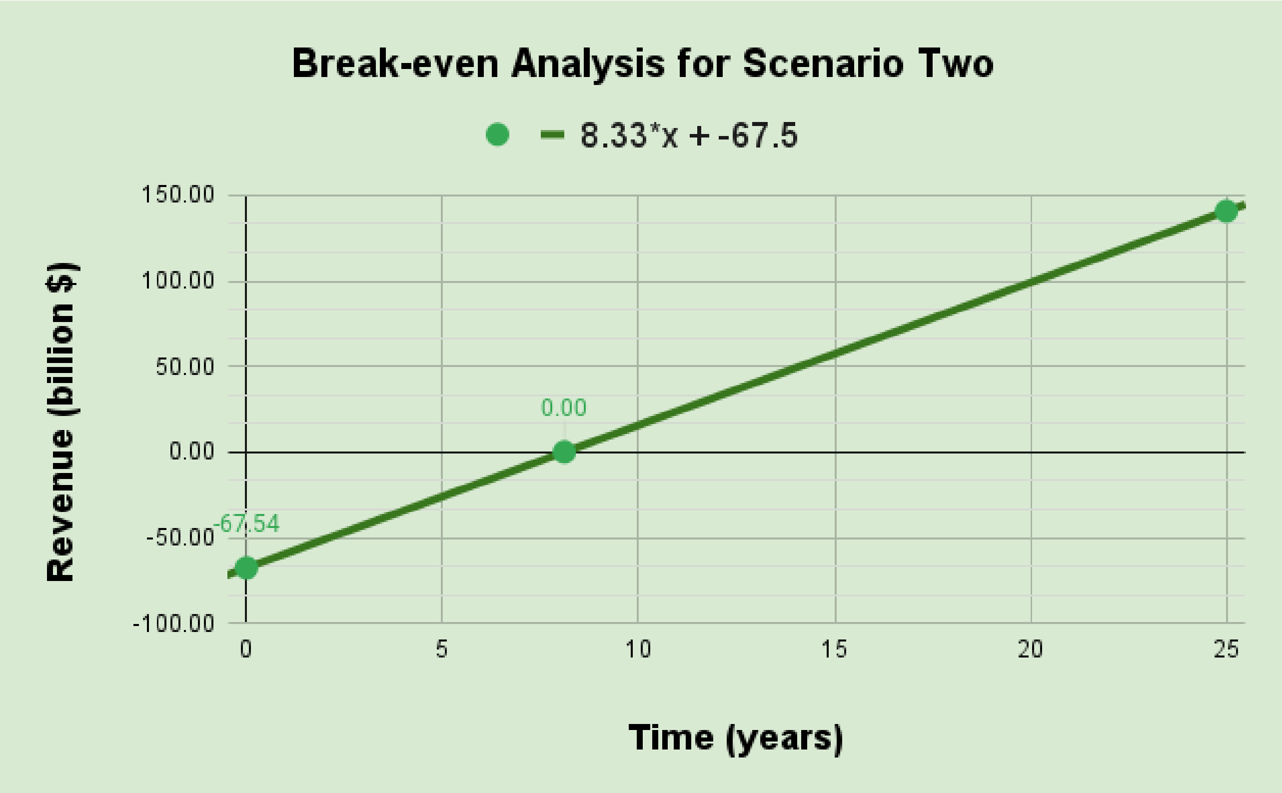


Figure 42: Break-even analysis for scenario two

The y-intercept is equal to the negative CAPEX value (since it is an upfront cost), whilst the gradient is equal to the yearly net revenue. The x-intercept is the break-even point, i.e. when the project breaks even by nullifying any capital costs. This point is at 8.108 $\approx$ eight years. Given that the project lifetime is estimated to be 20 years from the lifetime of a single pyrolysis plant, the total net revenue over the project lifetime is $99.1 billion.

7.3.13 ECONOMIC ANALYSIS SUMMARY

An economic analysis was carried out for a full-scale pyrolysis plant and a pilot scale. A linear model was used for estimating the cost of the pyrolysis plants, as there was no economic data for a pyrolysis plant that can process more than 750000 tpa of dry biomass. Therefore, a linear model was used to calculate the capital cost for the 41 pyrolysis plants instead of the six-tenth rule. As previously mentioned, the economic analysis was based on three different scenarios. For Scenarios one and two, the full-scale pyrolysis plant will cost approximately AU $67.5 billion, whereas, for scenario three, it will cost approximately AU $71.5 billion due to the additional cost of clearing the lands. Secondly, economic analysis was carried out for a pilot scale based on the previously mentioned three scenarios. It was estimated to cost approximately AU

$1.65 billion for scenarios one and two, and AU $1.74 billion for scenario three. The analysis suggests that the pyrolysis plant will be economically beneficial based on scenario two.

OPEX calculations suggest that a full-scale model will be the cheapest for scenario one, costing approximately AU $6.5 billion per year, followed by Scenarios two and three at AU $7.5 billion and AU $7.6 billion per year, respectively. This difference is due to the added cost of transporting biochar to the local markets. A pilot scale plant would cost approximately AU $161 million per annum for scenario one, followed by AU $185 billion and AU$186 billion per year, respectively.

Based on the three different scenarios carried out, it was found that scenario two will be economically viable as this has a profit of approximately $4.9 billion per year, followed by scenarios three and one, with a profit of AU $4.7 billion and AU $0.5 billion per year respectively. The ROI values also backed this at 8.61, 5.96 and 1.8 for Scenarios two, three and one, respectively. The prices of the raw materials are subject to market change due to fluctuations in the cost of raw materials due to global events. For the profit and loss statement, the prices were assumed to stay constant for the following year. The cost of raw materials and the products produced from the pyrolysis plants were average prices and therefore is not a good indicator of an overall profit.

8 RISK ASSESSMENT

Table 23: Risk Assessment for Pyrolysis Project

Risk	Description	Severity
Critical Factors	Fluctuating yield of biochar and bio oil, chemical content of feedstock, capital cost, and market cost. For instance, the market price may decline as more bio oil and biochar are available to the market. ACCU price may drop depending on the government policies and reduced net carbon emission.	High
Feedstock availability	There is no assurance on mass harvesting of Woody Weed for this large scale project and shipping large amount of waste to pyrolysis plant site. It may breach chemical or biological regulations	Low / Medium
Permit and Licensing	There was no previous case of reshaping this large scale of land and no regulation allowing this type of large project impacting the environment. The study is based on that there will be no regulation or law that prevents the project to proceed.	High
Limited source and access of information	There is no detailed information available in regards to pyrolysis unit that can process 10% emission of Australia annually. Also other private companies are not willing to share their information publicly.	Medium

9 CONCLUSIONS

Overall the feasibility study showed the possibility of implementing a large-scale pyrolysis unit, which can process 10% of Australia's annual carbon emission by using Elephant Grass as the primary feedstock. It also explored the possibility of using feedstock such as invasive plant species, tyres, and agricultural wastes instead of having a fixed plantation area where plants must be grown for biomass to reduce Australia's net carbon emissions for the Paris agreement. After considering three scenarios and different pyrolysis technology, we recommended that fast pyrolysis was the choice of pyrolysis technology to the high percentage of bio-oil products and the ease of scaling. Also, the study found that in the optimal scenario, the revenue was $8.3 billion per year, with an ROI of 8.61%. Although the study results are primarily positive, constructing this large-scale project in Australia in 2022 should be further considered. This is because most critical factors such as consistent ACCU, accurate pyrolysis plant capacity, stable biochar and bio-oil market price, and non-fluctuating transportation cost are all based on the assumption that does not fully reflect the real world. Most of the information obtained needed to be analysed to fit the project's purpose, and some critical data was out of reach for the study due to the non-disclosure agreement of private companies and research groups. Also, pyrolysis technology is still in the developing stage. Therefore, future versions of pyrolysis technology will increase the likelihood of proceeding with a real-world project. This feasibility study hopes to provide an objective view of the pyrolysis technology in 2022 and areas for improvement for the future pyrolysis plant project.

10 FURTHER RECOMMENDATIONS

This report has provided a feasibility analysis of building a large-scale pyrolysis system acting as a carbon siphon to sequester 10% of Australia's yearly emissions from the atmosphere. However, this analysis did not consider some aspects and is recommended for further research.

The calculated costs are very high, and whilst possibly feasible, considering that large-scale Government projects such as the WestConnex project cost 16.8 billion dollars, it would still be better to reduce costs. Further research to achieve this can include more profound research into feedstock other than biomass, performance optimisation and up-scaling of pyrolysis machines to be more efficient and faster and efficient methods of torrefaction (drying) of biomatter.

Another key point not considered in this report is the automation of some processes in the process-flow diagram, such as the automated feeding system of dried biomass into a pyrolysis machine via an extensive conveyor belt system, the methods and machinery required to harvest, and the transport the biomass from the plantation to the pyrolysis plants. For an efficient and working system, these must be considered. Costs for these processes will also be an essential addition to the overall feasibility of such a project

The effects of a change in the market price of biochar, bio-oil and ACCU were not considered in this project. When calculating revenue, only the current market prices were considered. Small changes in these values can drastically change the revenue, hence the project's full cost analysis and break-even time. Also, the effects of a sudden appearance of millions of tonnes of biochar and bio-oil onto the open market would theoretically lower the price. Thus, our cost estimate can be considered an idealised upper estimate. These factors should be researched and considered for more in-depth cost analysis.

This project also illustrates the viability of the pyrolysis project in general. It could be further applied to pyrolysis for waste management, and some of the aspects of our report (such as efficient pyrolysis methods and technologies, as well as revenue-generating byproducts) can be built further upon.

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11 APPENDIX

A ALTERNATIVE FEEDSTOCK

The estimation of mass for Parkinsonia is given below:

$$0.4 \times 2200 \times 3.3M = 2904MT \tag{7}$$

where 0.4 is the estimated tonnes per tree [185], 2200 is the trees per hectare [186] and 3.3M is the total land area covered by the Parkinsonia plant in hectares [186].

B LAND COST

Municipality	Median $/ha				Number of transactions	
	2021	5yr CAGR	10yr CAGR	20yr CAGR	2021	YoY +/-
Central						
Banana	$4,822	11.2%	6.6%	8.4%	73	18
Central Highlands	$4,935	23.1%	9.3%	11.5%	38	7
Gladstone	$5,008	14.6%	3.7%	7.7%	110	37
Goondiwindi	$2,136	0.7%	2.9%	7.8%	75	31
Isaac	$3,216	20.5%	6.7%	9.6%	38	12
Livingstone**	$6,741	-	-	-	41	-10
North Burnett	$3,604	5.3%	9.0%	6.8%	81	-17
Rockhampton	$6,491	10.9%	5.8%	7.3%	64	21
Western Downs	$2,655	3.7%	0.5%	7.9%	200	50
Central	**$3,992**	**11.4%**	**5.4%**	**8.8%**	**720**	**149**
North						
Burdekin	$17,884	7.7%	8.2%	5.3%	38	10
Cairns	$14,338	5.7%	8.5%	7.9%	18	7
Cassowary Coast	$10,148	6.0%	5.8%	3.2%	47	1
Charters Towers	$4,634	35.5%	17.9%	10.6%	19	0
Cook	$2,116	-10.5%	0.5%	4.6%	17	9
Croydon	$157	30.0%	17.5%	14.0%	5	5
Douglas**	$14,485	-	-	-	7	1
Etheridge	$836	-8.4%	28.5%	17.9%	5	3
Hinchinbrook	$10,229	14.7%	27.2%	5.8%	33	14
Mackay	$10,585	5.1%	2.3%	7.3%	120	45
Mareeba**	$10,103	-	-	-	40	7
Tablelands	$11,559	4.3%	4.0%	7.8%	63	5
Townsville	$8,565	0.9%	3.9%	7.9%	22	12
Whitsunday	$6,541	23.3%	3.5%	8.8%	40	19
North	**$10,150**	**6.0%**	**5.4%**	**7.9%**	**474**	**138**

Figure 43: Northern and Central Queensland Land Price

Municipality	Median $/ha				Number of transactions	
	2020	5yr CAGR	10yr CAGR	20yr CAGR	2020	YoY +/-
Central						
Beverley	$3,578	-0.2%	0.2%	4.6%	20	3
Boyup Brook	$4,260	12.0%	4.0%	3.5%	17	0
Brookton	$4,248	5.7%	5.2%	5.6%	6	-5
Broomehill-Tambellup	$3,461	7.0%	3.6%	5.1%	5	2
Bruce Rock	$1,603	15.8%	5.3%	5.3%	8	-2
Corrigin	–	19.9%	8.9%	8.4%	2	-1
Cranbrook	$3,200	10.7%	3.7%	5.9%	14	2
Cuballing	$3,317	-1.8%	5.3%	6.1%	5	1
Cunderdin	$2,715	5.3%	2.2%	7.3%	10	4
Dowerin	–	-19.4%	-6.6%	-0.4%	3	0
Dumbleyung	$1,266	-3.6%	-2.6%	4.2%	6	4
Goomalling	$1,303	-8.6%	-0.4%	1.8%	7	1
Katanning	$2,768	3.4%	-3.5%	6.2%	8	3
Kellerberrin	$1,646	11.0%	3.3%	6.7%	9	-1
Kojonup	$4,482	14.4%	2.8%	6.0%	19	6
Narrogin	$3,780	5.7%	4.8%	4.6%	11	-1
Northam	$6,278	10.9%	2.8%	5.1%	26	17
Pingelly	$4,334	7.2%	8.3%	3.9%	8	2
Quairading	$2,501	10.0%	4.6%	6.0%	7	0
Tammin	–	-6.2%	-5.7%	0.4%	2	2
Toodyay	$6,320	18.4%	2.1%	8.3%	7	-4
Trayning	$1,427	8.7%	2.6%	4.3%	11	10
Victoria Plains	$2,710	-2.4%	-0.3%	4.5%	7	1
Wagin	–	-21.8%	-3.1%	1.7%	2	-4
Wandering	$4,303	11.6%	6.7%	7.1%	5	2
West Arthur	$3,820	22.4%	4.5%	5.7%	10	0
Wickepin	$3,073	5.7%	6.2%	7.5%	5	-2
Williams	$4,971	7.1%	5.1%	6.8%	5	0
Wongan-Ballidu	–	4.0%	1.2%	6.7%	3	-3
Woodanilling	–	16.0%	0.0%	5.7%	3	-4
Wyalkatchem	–	25.3%	13.3%	7.3%	1	-2
York	$5,012	0.7%	-0.5%	5.4%	12	1
Central	**$3,314**	**6.9%**	**3.7%**	**5.9%**	**264**	**32**

Figure 44: Central Western Australia Land Price

Municipality	Median $/ha				Number of transactions	
	2020	5yr CAGR	10yr CAGR	20yr CAGR	2020	YoY +/-
Northern						
Carnamah	–	-17.1%	-6.1%	-0.3%	3	-1
Chapman Valley	$1,737	-6.9%	-2.2%	2.9%	7	3
Coorow	$1,642	22.3%	16.7%	7.4%	8	6
Dalwallinu	$677	6.0%	3.6%	2.1%	10	2
Dandaragan	$1,969	2.4%	2.1%	4.3%	17	7
Greater Geraldton	$878	-1.3%	1.5%	0.8%	14	2
Irwin	$2,720	13.6%	10.4%	3.7%	4	-4
Mingenew*	–	6.4%	8.2%	10.0%	0	-3
Moora	$2,352	3.6%	5.0%	6.7%	7	-1
Morawa	$395	-8.1%	-2.9%	-0.5%	6	2
Northampton	$546	-16.6%	-8.5%	0.0%	11	-5
Perenjori	$1,605	14.0%	9.1%	8.6%	4	-6
Three Springs	$1,793	-1.4%	2.9%	6.3%	12	8
Northern	**$1,310**	**-1.0%**	**4.6%**	**4.7%**	**103**	**10**
South Coast						
Albany	$6,734	3.3%	-0.1%	3.7%	28	-6
Esperance	$2,535	4.4%	5.1%	7.5%	15	-2
Gnowangerup	$2,766	13.3%	3.7%	5.9%	7	0
Jerramungup	$1,912	4.5%	4.1%	5.4%	4	-10
Kent	$1,702	12.0%	7.0%	4.9%	9	-2
Plantagenet	$6,794	11.9%	2.6%	6.5%	30	-3
Ravensthorpe	$2,502	15.2%	6.7%	9.2%	10	-3
South Coast	**$4,145**	**16.3%**	**7.8%**	**7.8%**	**103**	**-26**
South West						
Boddington	–	21.8%	8.8%	8.2%	2	-7
Bridgetown-Greenbushes	$6,460	9.6%	-0.2%	3.9%	6	-11
Busselton	$12,395	3.9%	2.4%	4.0%	6	-4
Capel	$11,913	-2.2%	-0.4%	4.4%	6	0
Collie	–	2.9%	-8.0%	3.0%	3	1
Dardanup	–	-9.8%	-2.7%	2.7%	3	1
Denmark	$7,903	-3.1%	-2.6%	4.3%	13	4
Donnybrook-Balingup	$9,069	2.4%	0.9%	4.0%	16	-2
Harvey	$11,620	4.0%	-1.9%	3.1%	15	4
Manjimup	$10,184	8.1%	-2.5%	3.4%	14	-3
Murray	$10,583	1.0%	-7.0%	4.1%	5	0
Nannup	$5,346	-5.3%	-2.9%	-1.6%	6	5
Waroona	$8,552	0.0%	-3.6%	1.2%	9	3
South West	**$9,099**	**0.9%**	**-1.4%**	**3.5%**	**104**	**-9**
WESTERN AUSTRALIA	**$3,066**	**8.9%**	**7.3%**	**6.2%**	**664**	**-21**

Figure 45: Northern and Southern Western Australia Land Price

C MASS BALANCES

Table 24: Yields of pyrolysis products at 50 C/min [187]

Products	Yield (%)
Biochar	20
Bio-oil	54.3
Ash	11
Syngas	14.7
Total	100
Balance Biomass *	10

* Assuming only 90% of the biomass is converted

Sample calculation for the mass flow rate at 50 C/min is shown below. It was assumed that the biochar yield will be 20% as obtained by Isah Yakub. It was also assumed that only 90% of the biomass will be converted.

$$Biochar = BiomassMass \times Conversion \times Yield \quad (8)$$

$$= 30.5 \times 10^6 \times 90\% \times 20\% \quad (9)$$

$$= 5,486,400tpa \quad (10)$$

Table 25: Mass flow rate at 50 C/min

Conversion	90% Recovery (Tpa)
Mass flow rate of biomass	30,480,000
Mass flow rate of biochar	5,486,400
Mass flow rate of bio-oil	14,901,062
Mass flow rate of syngas	4,027,018
Mass flow rate of ash	3,017,520
Mass flow rate of unreacted biomass	2,743,200

Table 26: Yields of pyrolysis products at 10 C/min [187]

Products	Yield (%)
Biochar	20
Bio-oil	44.7
Ash	9.3
Syngas	26
Total	100
Balance Biomass *	10

* Assuming only 90% of the biomass is converted

$$Biochar = BiomassMass \times Conversion \times Yield \quad (11)$$

$$= 30.5 \times 10^6 \times 90\% \times 44.7\% \quad (12)$$

$$= 12,262,104 tpa \quad (13)$$

Table 27: Mass flow rate at 10 C/min [187]

Conversion	90% Recovery (Tpa)
Mass flow rate of biomass	30,480,000
Mass flow rate of biochar	5,486,400
Mass flow rate of bio-oil	12,262,104
Mass flow rate of syngas	7,132,320
Mass flow rate of ash	2,551,176
Mass flow rate of unreacted biomass	2,743,200

D ENERGY BALANCE

Table 28: Energy balance for the heating rate of 50 C/min

Compound	Calorific Value (MJ/kg	Mass flow rate (kg/yr)	Energy (MJ/yr)
Biomass (Elephant Grass	16.7	30480000000	509,016,000,000
Syngas	10	2416210560	24,162,105,600
Bio-oil	20	596042496	11,920,849,920
Excess Energy			18,157,858,020

Table 29: Energy balance for the heating rate of 10 C/min

Compound	Calorific Value (MJ/kg	Mass flow rate (kg/yr)	Energy (MJ/yr)
Biomass (Elephant Grass)	16.7	30480000000	509016000000
Syngas	10	4279392000	42,793,920,000
Bio-oil	20	0	0
Excess Energy			24,868,822,500

The calorific values, also known as high heating value (HHV) for the input and output, are determined based on the research and mass flowrate was used from the mass balance calculations. Therefore, sample calculations for the energy balance of heating rate at 50 C/min are as the following:

$$\text{Energy } \frac{MJ}{yr} = \text{Calorific Value } \frac{MJ}{kg} \times \text{ Mass Flow Rate } \frac{kg}{yr}$$

The amount for energy required for the biomass (elephant grass) is as follows:

$$\text{Energy } \frac{MJ}{yr} = 16.7 \ \frac{MJ}{kg} \times 30{,}480{,}000{,}000 \ \frac{kg}{yr} = 509{,}016{,}000{,}000 \ \frac{MJ}{yr}$$

The same equation was used to calculate the amount of energy required for other compounds for both heating rates and is summarised in the tables above. However, as it can be seen from the table for 10 C/min, we have excess energy generated from syngas; therefore, we are not required to burn bio-oil, and all of the bio-oil produced can be used as revenue. Since the biomass (elephant grass) contains a high moisture content, it will need to go through the drying process, which requires energy. The biomass will first be left to be dried under the sun, leaving elephant grass's moisture content from 50% to 15%. However, the moisture content of 15% is too high for the biomass to undergo pyrolysis. Therefore, a further drying process is required. After the drying process, the moisture content was assumed to be under 10%, which is suitable for the pyrolysis process. The energy required for the drying process was calculated as the following:

Q $=$ mc Δ T $=$ 6858000000 kg $\times$ 4182 $\frac{J}{kg}{}^{\circ}$C $\times 650^{\circ}$C - 25°C $= 1.79251 \times 10^{16}$ J $=$ 17,925,097,500 $\frac{MJ}{yr}$

Therefore, the excess energy of the process can be calculated as shown below:

Excess Energy $\frac{MJ}{yr}$ $=$ Energy for syngas + Energy for bio-oil - Energy for the heating process

The sample calculation of the excess energy for heating rate of 50 C/min can hence be determined:

Excess Energy $\frac{MJ}{yr}$ $=$ 24,162,105,600 $\frac{MJ}{yr}$ + 11,920,849,920 $\frac{MJ}{yr}$ - 17,925,097,500 $\frac{MJ}{yr}$ $=$ 18,157,858,020 $\frac{MJ}{yr}$

This amount of excess energy can be used as the revenue for this project.

E CAPEX CALCULATIONS

E.1 CAPEX CALCULATIONS BASED ON NORTH-WESTERN AUSTRALIA LOCATION

Table 30: Direct Cost (ISBL)

Components	Assumptions	Percentage (%)	Calculated Cost (AU$ Billion)	Without Land Cost (AU$ Billion)
Purchased Equipment Cost	Based on Australia Pyrolysis Plant Projects	100%	49.20	
Land		100%	1.37	
Total Installation Cost			50.57	49.20

Table 31: Indirect Cost (OSBL)

Components	Assumptions	Percentage (%)	Calculated Cost (AU$ Billion)	Without Land Cost (AU$ Billion)
Contractor Fee	2% - 8% of TIC	2%	1.01	0.98
Construction Fee	10% of TIC	10%	5.06	4.92
Total			6.07	5.90

Table 32: Additional Costs

Components	**Assumptions**	**Percentage (%)**	**Calculated Cost (AU$ Billion)**	**Without Land Cost (AU$ Billion)**
Engineering	8% of ISBL + OSBL	8%	4.53	4.41
Project Contingency	8% of ISBL + OSBL + Engineering	8%	4.89	4.76
Total Capital Investment			66.06	64.27
Total Project Investment			66.06	64.27

E.2 CAPEX CALCULATIONS BASED ON SOUTH-WESTERN AUSTRALIA LOCATION

Table 33: Direct Cost (ISBL)

Components	**Assumptions**	**Percentage (%)**	**Calculated Cost (AU$ Billion)**	**Without Land Cost (AU$ Billion)**
Purchased Equipment Cost	Based on Australia Pyrolysis Plant Projects	100%	49.20	
Land		100%	10.00	
Total Installation Cost			59.20	49.20

Table 34: Indirect Cost (OSBL)

Components	**Assumptions**	**Percentage (%)**	**Calculated Cost (AU$ Billion)**	**Without Land Cost (AU$ Billion)**
Contractor Fee	2% - 8% of TIC	2%	1.18	0.98
Construction Fee	10% of TIC	10%	5.92	4.92
Total			7.10	5.90

Table 35: Additional Costs

Components	**Assumptions**	**Percentage (%)**	**Calculated Cost (AU$ Billion)**	**Without Land Cost (AU$ Billion)**
Engineering	8% of ISBL + OSBL	8%	5.30	4.41
Project Contingency	8% of ISBL + OSBL + Engineering	8%	5.73	4.76
Total Capital Investment			77.34	64.27
Total Project Investment			77.34	64.27

E.3 CAPEX CALCULATIONS BASED ON CENTRAL-WESTERN AUSTRALIA LOCATION

Table 36: Direct Cost (ISBL)

Components	Assumptions	Percentage (%)	Calculated Cost (AU$ Billion)	Without Land Cost (AU$ Billion)
Purchased Equipment Cost	Based on Australia Pyrolysis Plant Projects	100%	49.20	
Land		100%	2.50	
Total Installation Cost			51.70	49.20

Table 37: Indirect Cost (OSBL)

Components	Assumptions	Percentage (%)	Calculated Cost (AU$ Billion)	Without Land Cost (AU$ Billion)
Contractor Fee	2% - 8% of TIC	2%	1.03	0.98
Construction Fee	10% of TIC	10%	5.17	4.92
Total			6.20	5.90

Table 38: Additional Costs

Components	Assumptions	Percentage (%)	Calculated Cost (AU$ Billion)	Without Land Cost (AU$ Billion)
Engineering	8% of ISBL + OSBL	8%	4.63	4.41
Project Contingency	8% of ISBL + OSBL + Engineering	8%	5.00	4.92
Total Capital Investment			67.54	64.27
Total Project Investment			67.54	64.27

E.4 CAPEX CALCULATIONS BASED ON CENTRAL QUEENSLAND LOCATION

Table 39: Direct Cost (ISBL)

Components	Assumptions	Percentage (%)	Calculated Cost (AU$ Billion)	Without Land Cost (AU$ Billion)
Purchased Equipment Cost	Based on Australia Pyrolysis Plant Projects	100%	49.20	
Land		100%	3.00	
Total Installation Cost			52.20	49.20

Table 40: Indirect Cost (OSBL)

Components	Assumptions	Percentage (%)	Calculated Cost (AU$ Billion)	Without Land Cost (AU$ Billion)
Contractor Fee	2% - 8% of TIC	2%	1.04	0.98
Construction Fee	10% of TIC	10%	5.22	4.92
Total			6.26	5.90

Table 41: Additional Costs

Components	Assumptions	Percentage (%)	Calculated Cost (AU$ Billion)	Without Land Cost (AU$ Billion)
Engineering	8% of ISBL + OSBL	8%	4.68	4.41
Project Contingency	8% of ISBL + OSBL + Engineering	8%	5.05	4.76
Total Capital Investment			68.19	64.27
Total Project Investment			68.19	64.27

E.5 CAPEX CALCULATIONS BASED ON NORTHERN QUEENSLAND LOCATION

Table 42: Direct Cost (ISBL)

Components	Assumptions	Percentage (%)	Calculated Cost (AU$ Billion)	Without Land Cost (AU$ Billion)
Purchased Equipment Cost	Based on Australia Pyrolysis Plant Projects	100%	49.20	
Land		100%	7.65	
Total Installation Cost			56.85	49.20

Table 43: Indirect Cost (OSBL)

Components	Assumptions	Percentage (%)	Calculated Cost (AU$ Billion)	Without Land Cost (AU$ Billion)
Contractor Fee	2% - 8% of TIC	2%	1.14	0.984
Construction Fee	10% of TIC	10%	5.69	4.92
Total			6.82	5.90

Table 44: Additional Costs

Components	Assumptions	Percentage (%)	Calculated Cost (AU$ Billion)	Without Land Cost (AU$ Billion)
Engineering	8% of ISBL + OSBL	8%	5.09	4.41
Project Contingency	8% of ISBL + OSBL + Engineering	8%	5.50	4.76
Total Capital Investment			74.27	64.27
Total Project Investment			74.27	64.27

F OPEX CALCULATIONS

Table 45: OPEX calculations based on North-Western Australia

Components	Assumptions	Calculated Cost ($\$/year$)
Raw material		$2,744,093,000
Maintenance	2% of equipment cost	$984,000,000
Overhead	60% of labour cost	$217,555,000
Insurance	1.5% of total installed capital	$738,000,000
Average Rent		$69,268,000
Labour cost	Based on the current annual salaries	$362,592,000
Total		$5,115,509,000
Total without leasing		$5,046,241,000

G RAW MATERIALS

Table 46: Cost of raw materials per year

Material	Price per ton (AU$)	Required Amount tonnes/year	Total (AU$/year)
Phosphorus	900	277,593	$ 249,834,000
Potassium (Potash)	260	108,860	$ 28,391,776
Nitrogen	1,400	267,000	$ 373,800,000
Elephant Grass seeds		2.7	$ 5,726,000
Irrigation			$ 2,086,342,100
Total			$ **2,744,093,000**

H LABOUR COST

Table 47: Breakdown of workers required and the annual salary

Components	Workers required	Annual salary ($AUD)	Calculated salary
Plant Engineer	41 [175]	$ 96,900 [188]	$ 3,972,900
Plant /General manager	41 [175]	$ 110,000 [189]	$ 4,510,000
Maintenance supervisor	41 [175]	$ 84,662 [190]	$ 3,471,000
Lab manager/chemist	41 [175]	$ 111,630 [191]	$ 4,577,000
Maintenance tech	205 [175]	$ 86,775 [192]	$ 17,789,000
Shift supervisor	164 [175]	$ 72,613 [193]	$ 11,909,000
Administrative assistants	82 [175]	$ 67,774 [194]	$ 5,557,000
Number of operators	820 [175]	$ 63,375 [195]	$ 51,968,000
Number of gardeners	3,500	$ 73,954 [196]	$ 258,839,000
Total	**4935**	**$ 767,683**	**$ 362,592,000**

I RETURN ON INVESTMENT (ROI)

Table 48: ROI analysis for Scenario One Located at Northern Queensland

Components	Assumptions	Calculated Cost ($)	Units
Production cost			
Total production cost	Direct production cost + Overhead charges	$51,917M	
Total production rate		750,000	tonnes/year
Production cost	Total production cost/Total production rate	69,000	$AU/year
Profitability analysis			
Selling price	From bio-oil, biochar and excess energy	$10,379M	$AU/year
Profit	Selling price- production cost	$3,830M	$AU/year
Total income		$10,379M	$AU/year
Gross profit		$6,548M	$AU/year
Taxes	Assuming rate of 30%	$1,964 M	$AU/year
Depreciation	Pyrolysis unit depreciation period is 15 years	$3,377M	$AU
Net profit	Gross profit - Taxes - Depreciation	$1,206M	$AU/year
Rate of return			
Rate of return	Net profit/TCI $\times$ 100	1.79	%

Table 49: ROI analysis for Scenario Three Located at Central Western Australia

Components	Assumptions	Calculated Cost ($)	Units
	Production cost		
Total production cost	Direct production cost + Overhead charges	$51,917M	
Total production rate		750,000	tonnes/year
Production cost	Total production cost/Total production rate	69,000	$AU/year
	Profitability analysis		
Selling price	From bio-oil, biochar and excess energy	$15,874M	$AU/year
Profit	Selling price- production cost	$5,303M	$AU/year
Total income		$15,874M	$AU/year
Gross profit		$10,571M	$AU/year
Taxes	Assuming rate of 30%	$3,171 M	$AU/year
Depreciation	Pyrolysis unit depreciation period is 15 years	$3,575M	$AU
Net profit	Gross profit - Taxes - Depreciation	$4,023M	$AU/year
	Rate of return		
Rate of return	Net profit/TCI × 100	5.96	%