Use of biomass fuel at Redbank Power Station – Life Cycle Assessment

UNDERTAKEN BY LIFECYCLES FOR VERDANT EARTH TECHNOLOGIES LIMITED

November 2023
Update to report of March 2022

lifecycles.

Citation

Boyden, A. & Grant, T. (2023) Use of biomass fuel at Redbank Power Station - Life cycle assessment. Lifecycles, Melbourne, Australia.

Copyright

© 2023 Lifecycles. To the extent permitted by law, all rights are reserved and no part of this publication covered by copyright may be reproduced or copied in any form or by any means except with the written permission of Lifecycles.

Important disclaimer

This report is an update to the March 2022 LCA report cited 'Boyden, A. & Grant, T. (2022) Life cycle assessment of biomass fuel use at Redbank Power Station. Lifecycles, Melbourne, Australia.' The following updates have been made in line with new EIS submission requirements:

- Update to title, project description, discussion of restart measures
- Update to results with latest AQIA, fuel supply mix, and water source

Lifecycles advises that the information contained in this publication comprises general statements based on scientific research. The reader is advised and needs to be aware that such information may be incomplete or unable to be used in any specific situation. No reliance or actions must therefore be made on that information without seeking prior expert professional, scientific and technical advice. To the extent permitted by law, Lifecycles (including its employees and consultants) excludes all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this publication (in part or in whole) and any information or material contained in it.

Contents

Figures

Tables

1 Introduction

1.1 Context

The Redbank Power Station is an approved baseload power station located at 112 Long Point Road West, Warkworth (Lot 450 DP 1119428). Originally commissioned in July 2001, the Redbank Power Station was designed to use beneficiated dewatered coal tailings (BDT) left over from coal processing to create electricity. The power station uses FiCirc® fluidised bed combustion technology and a single 151MW steam turbine and associated equipment. The power station is designed to burn low value fuels such as coal tailings and is a preferred technology for energy generation from biomass. The technology has demonstrated excellent performance and a low emissions profile.

The power station was approved in 1994 (DA183/93) and the development consent was modified in 1997. Tailings were transferred by conveyor from the Warkworth mine to the power station as a source of fuel. The power station also relied on supplementary fuel in the form of Run of Mine (ROM) coal to assist in electricity generation. Due to the unavailability of coal tailings from Warkworth mine, the power station has been in care and maintenance since October 2014.

Verdant Earth Technologies Limited (the Applicant) has acquired the power station and is seeking approval to restart the plant using biomass (excluding native forestry residues from logging) ("Redbank Biomass") as a sustainable fuel to produce near net zero CO_2 emissions and enable the power station to continue to produce "green" electricity on an ongoing basis (the Proposal).

To address concerns expressed by the community in relation the use of native forestry residues as fuel, the Applicant has developed an alternative biomass fuel strategy which specifically excludes this fuel source. Verdant will also relinquish the current approval to use coal tailings as a fuel at Redbank.

It is proposed that Redbank will be fueled with ecologically sustainable biomass (in compliance with all relevant legislative requirements and excluding native forestry residues from logging) to deliver near net zero CO2 power generation using standard fuels and eligible waste fuels from the following sources:

<u>Standard fuels:</u>

- Purpose grown energy plantations;
- Perennial grasses;
- Energy crops;

<u>Eligible waste fuels:</u>

- Biomass with no higher order uses arising from invasive native species control on agricultural land;
- Biomass with no higher order uses from approved land clearing activities such as major infrastructure developments for approved civil infrastructure, road clearing works, right of ways and related approved projects;
- Agricultural waste biomass products or residues with no higher order uses;
- End of life waste woody biomass manufactured and produced into a fuel to specification ("Domestic Biomass") (subject to EPA approval as an eligible waste fuel); and
- Other sources of eligible waste fuels with no higher order uses.

Note that at the initial startup of the power station, and following boiler maintenance and restart of the boilers, a startup supplementary fuel (diesel or a similar fuel) will be used to achieve the temperature required to use biomass as fuel. Once the boiler is operating at the design temperature, the Redbank Power Station will use only approved biomass as fuel.

The Proposal will use up to 700,000 tonnes of dry equivalent biomass per annum (approximately 850,000 tonne per annum at 25% moisture) as a fuel for conversion into electricity. Fuels for the Redbank Power station will be implemented in two stages.

The first stage will involve the start-up of operations using biomass (with no higher order uses) sourced primarily from approved land clearing operations (from existing civil and road works), biomass from invasive native species on agricultural land as approved by Local Land Services NSW and potentially a limited amount of purpose grown biomass.

The second stage will involve the introduction or increased use of purpose grown biomass which will be further increased over a period of two to four years from approval, and, if approved and declared an eligible waste fuel by the NSW EPA, the introduction and use of Domestic Biomass.

Verdant will, where appropriate, seek separate Specific Resource Recovery Orders and Exemptions (RROE) and notification by the NSW EPA in the New South Wales Government Gazette as required prior to the use of the biomass fuels.

Ash generated by the Proposal will be regularly tested and transported off-site for beneficial use as a soil amendment in agriculture in accordance with EPA requirements. Trucks used to deliver biomass to the site will be backloaded with the ash for removal to an approved site for reuse in accordance with the *Ash from Burning Biomass Order and Exemption* 2014. Once Domestic Biomass is approved, Verdant will apply for a separate RROE for the resulting ash derived from Domestic Biomass.

To enable the power station to use biomass as a primary fuel source, some modifications to the plant and operations will be required. These changes are summarised below:

- Maintenance, repair and recommissioning works within the power station to permit recommencement of electricity generation;
- Delivery of biomass in B-doubles (42-44 tonnes per load) via Long Point Road on a 24/7 basis. Deliveries will be prioritised to 12-hour shifts on Monday through Sunday between 6am and 10pm;
- The existing conveyor from the Warkworth mine for transfer of coal tailings into the plant will remain in the first instance;
- Two 28m long weighbridges to be installed along the (western) inbound lane into the site and the (eastern) outbound lane out of the site;
- Conversion of the power station to enable the use of up to 700,000 tonnes dry equivalent per annum of biomass as feedstock fuel for electricity generation with near net zero CO_2 emissions equivalent;
- Construction of a 160m sealed road at the rear of the site to enable to delivery of biomass to the fuel storage area;
- Establishment of a new fuel delivery area adjacent to the existing stockpiling area directly south of the existing power plant. The system will incorporate two dual-lane drive over truck unloaders, two additional conveyors that supply two radial telescopic conveyors to unload the biomass. One telescopic conveyor will direct fuel to the existing fuel storage area (i.e. the area approved for storage of coal tailings), and the second to two moving floor bulk unloader bins, which directly feed existing Conveyor 76. Swales to be provided around biomass stockpile area to minimise movement of biomass fuel from the designated storage area;
- Use of the existing Conveyors 34 and 35 to supply Boilers 1 and 2 respectively with biomass fuel. An extension to Conveyor 76 and removal of the crusher house is required to enable the even transfer of fuel via Conveyors 34 and 35 to Boilers 1 and 2;
- Modifications to two reversing conveyors within the power station to transfer the biomass into each of six fuel silos that will store the biomass. These silos previously stored ROM coal for delivery into the plant's fluidised bed combustion chambers;
- Modifying of the 'trouser legs' of the six fuel silos within the power station to enable the more efficient flow of biomass into the plant's fluidized bed combustion chambers;
- Ash generated from the combustion process will be sampled, tested and potentially used as a fertiliser in accordance with the EPA's *The Ash from Burning Biomass Order* 2014. The existing ash slurry system previously used to transfer coal tailings ash back to Warkworth

mine will remain in place, though it will not be used and may be removed at a later date. A Specific Resource Recovery Order and Exemption will be sought for ash from use of DBF as a fuel; and

- Other work, including landscaping, fire detection and suppression systems, and refurbishment of internal elements of the power station as required. This will also include the purchase of a water access licence, reconnection to the electricity grid, development of a spare parts inventory and purchase and storage of a fuel invention for the power station.

When fully operational the Proposal will supply the grid with approximately 1 million megawatt hours of 24/7 dispatchable or baseload electricity per year, equivalent to supplying around 200,000 homes. The Proposal will also drive significant progress towards the NSW Government's Net Zero Plan Stage 1: 2020-2030, the foundation for NSW's action on climate change and goal to reach net zero emissions by 2050.

The facility is located on land zoned RU1 under the Singleton Local Environmental Plan 2013. The proposed development is permissible as a 'electricity generating works' with consent in RU1 zoning under Clause 2.36 of the State Environmental Planning Policy (Transport and Infrastructure) 2021.

The Proposal is considered a State Significant Development (SSD) under Clause 20(a) of Schedule 1 of State Environmental Planning Policy (Planning Systems) 2021 as it involves a development for the purpose of electricity generating works or heat or their co-generation (using any energy source, including gas, coal, biofuel, distillate, waste, hydro, wave, solar or wind power) that has a capital investment value of more than $30 million. The Secretary's Environmental Assessment Requirements for the Proposal were issued by the Department of Planning and Environment (SEARs 56284960) on 30th August 2023.

The Proposal requires assessment under Part 4 of the Environmental Planning and Assessment Act 1979 and the consent authority for the development will be the Minister for Planning. An Environmental Impact Statement (EIS) must accompany the development application. An amended licence from the NSW EPA under Schedule 1 of the Protection of the Environment Operations Act 1997 will also be required.

This LCA study is critical to provide evidence of the sustainability claim through an analysis of the cumulative environmental impacts being assessed over the total supply chain from cradle to grave.

1.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is a methodology for assessing the full 'cradle-to-grave' environmental impacts and benefits of products and processes by assessing environmental flows (i.e. impacts) at each stage of the life cycle. In doing so, LCA seeks to avoid shifting impacts from one life cycle stage to another or from one environmental impact to another.

The method and guidance for undertaking LCAs of bioenergy products and projects developed by the Australian Renewable Energy Agency (ARENA) [1] requires LCAs to be undertaken using the framework, principles and specific requirements defined in both of the international standards ISO 14040:2006 and ISO14044:2006 [2]. The general structure of the LCA framework is shown in Figure 1.

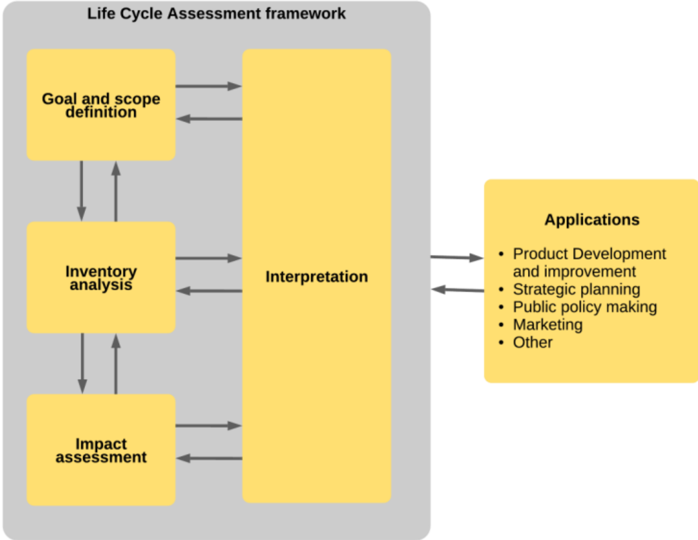

Figure 1 Framework for Life Cycle Assessment.

The first stage (goal and scope) describes the reasons for the LCA, scenarios, boundaries, indicators and other methodological approaches used. The second stage (inventory analysis) builds a model of the production systems involved in each scenario and describes how each stage of the production process interacts with the environment. The third stage (impact assessment) assesses the inventory data against key indicators to produce an environmental profile of each scenario. The final stage (interpretation) analyses the results and undertakes systematic checks of the assumptions and data to ensure robust results.

LCA aims at measuring the exchange between the natural world (the *'biosphere'*) and human activities (the *'technosphere'*), either via the extraction of natural resources or the emissions of pollutants to air, water and soil. The measurement is done at the level of the system analysed, which is broken down into a series of unit processes leading to the delivery of the functional unit, as defined in the goal and scope. A single unit process is illustrated in Figure 2. It includes flows to and from the *'biosphere'* as well as flows to and from other the *'technosphere'*.

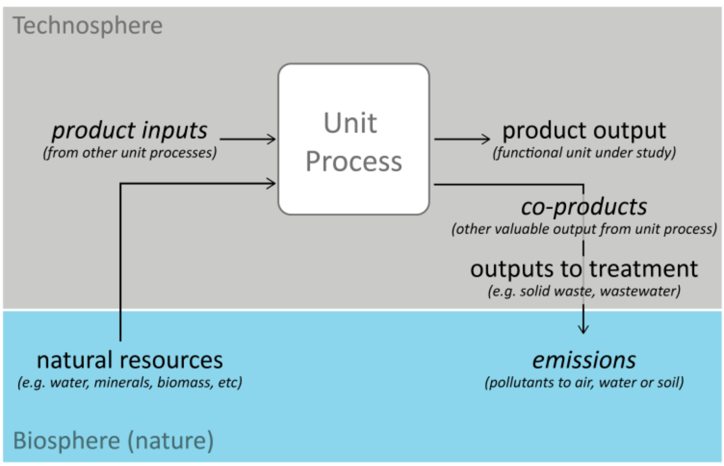

Figure 2 Inputs and outputs of a unit process in LCA

Figure 3 shows how unit processes were linked to create a system that produces the functional unit of the study. They can be categorised into foreground unit processes and background unit processes, as defined below:

- **Model foreground** includes unit processes for which specific data are collected for the study, refer to as foreground processes. The model foreground may also include secondary data from published papers and modified background processes from LCA databases.
- **Model background** includes unit processes for which data are typically sourced from pre-existing databases. The background data are either less important to the study outcomes or are already well-characterised in the existing data sets and therefore do not warrant specific modelling. In some instances, background unit processes may be modified to better reflect the conditions of the study. (e.g. to reflect greenhouse gas intensity of local electricity supply). In that case, they become part of the foreground.

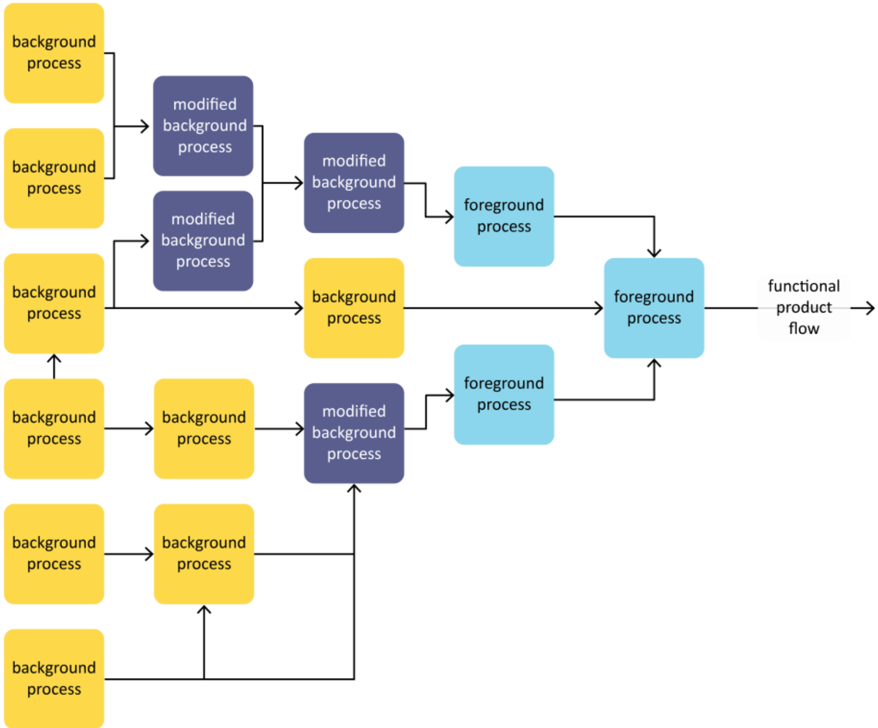

Figure 3 Linking unit processes in an LCA to product the functional unit

1.3 Compliance with guidelines

This LCA complies with the Australian Renewable Energy Agency (ARENA) Guidelines as specified in the Planning Secretary's Environmental Assessment Requirements (SEARs) (SEARs 56284960) dated 30th of August 2023.

The SEAR requirements are to address:

- Life Cycle Assessment – including a detailed life cycle assessment in accordance with the Australian Renewable Energy Agency guidance Life Cycle Assessment of Bioenergy Products and Projects [1].
- Greenhouse gas – a quantitative assessment of the proposal's greenhouse gas emissions (reflecting the Government's goal of net zero emissions by 2050).

See Appendix A for a detailed assessment of how this study addresses the specific requirements of the ARENA guidelines.

2 Goal and scope

2.1 Goal

Verdant Earth aims to assess the environmental benefits of the conversion of Redbank Power Station to use biomass as a fuel to produce electricity. The fuel will be procured from the market meeting the plant's fuel specifications, and will involve the sourcing of biomass from a variety of sources.

The results are intended to provide data for an Environmental Impact Statement and planning allocation for Verdant Earth, meeting the specific requirements laid out in the Planning Secretary's Environmental Assessment Requirements (SEARs). These requirements specify the need for an LCA to be undertaken following ARENA guidelines [1] and to complete a quantitative assessment of the proposal's greenhouse gas emissions.

The study also has the more general goal to evaluate the environmental benefits of using biomass as an alternative and sustainable fuel for electricity generation, compared to a baseline of coal-fired generation. An explanation of the choice of this reference scenario is provided in Section 2.2.2.

The intended audience for this report is primarily the Department of Planning and Environment, other agencies and the wider community. Verdant Earth will also use the results internally to identify strategies to mitigate their own environmental impacts.

2.2 Scope

2.2.1 Product system

The product or process under examination in this study is the production of electricity from biomass at Redbank Power Station. The product system describes the collection of processes that are required for this function, across the life cycle of the product or process. For the production of electricity from biomass at Redbank Power Station, the following processes are required:

Modifications to the power station (from here referred to as 'plant and process changes')

Minor changes to the power station will be required to convert it from a coal tailings facility to a biomass facility. This includes the installation of weighbridges, construction of a road and fuel delivery area, modifications to two existing reversing conveyors, and widening of the 'trouser legs' of the six fuel silos.

Collection and processing of fuel sources

The power station is expected to begin operating with biomass as fuel from five separate sources: purpose-grown fuel crops (70% by dry matter), residues from invasive species control (13%), agricultural residues (7%), residues from approved land clearing (3%), and Domestic Biomass Fuel (7%). While use of biomass at the facility will be ramped up over the first 6 years of operation, this LCA assesses the impacts of the plant once fully operational, with an estimated annual throughput of 850,000t biomass at 25% moisture content. Actual throughput will be dependent on availability and market dynamics.

For all feedstock types, the biomass proposed to be used at the facility is readily available and would otherwise be burned on site, mixed with soils and buried or landfilled. The use of these fuels would therefore not divert woody waste material from higher order uses. Stockpiles will be sampled, tested for compliance, with specifications and then bulk transported to the plant. All preparation of fuel including drying, chipping and screening will be performed off site. Further details on each of the five fuel types is shown below.

Energy crops

The production of feedstock from energy crops will involve the cultivation of purpose-grown biomass within managed plantations. These energy crops will be planted in annual rotations, and will take approximately four years before they contain enough above ground biomass to be harvested. This will be done using coppicing to allow the harvest biomass to regrow during the following four years. Once harvested, the plant material will be air dried, chipped and screened before being transported to the power station for combustion. These plantations are planned to be located within a 50km radius of the power station.

Several species are under investigation, with the two most likely crops to consist of quick-rotation coppicing of eucalypts and mallees, as well as Bana grass. For the quick-rotation eucalypts and mallees, seedlings will be planted on an annual basis over four years, from which point harvest will begin, with four years of growth between each harvest. For Bana grass, seedlings will be planted and allowed to grow for 1 year, after which, the tops are harvested and replanted to thicken the crop or for energy. After 3 to 4 years, the plants are coppiced on a regular rotation.

In terms of land use, Verdant Earth are seeking to use areas that currently have no alternative economic value to farmers/land owners. For example, they will target buffer zones of mines in the area, semi-arable land parcels without other economically viable economic agricultural uses.

Residues from land clearing of invasive species on agricultural land

Verdant Earth have been working with the Civil Industries and Local Landcare Services LLS NSW as well as landowners who have trees and shrubs that are classified as noxious weeds and may be cleared from land for agricultural uses. This includes native scrub vegetation that has reached unnatural densities and dominate an area on agricultural land. Verdant Earth have determined that the current practices for weed control is the removal of trees, which are then left to dry for a few weeks before being pushed into a pile and burnt in situ. They will be harvested in accordance with land management codes, then chipped on site and transported to Redbank Power Station.

Approved land clearing for infrastructure works

Verdant Earth is also targeting residues from approved land clearing as a result of major infrastructure development (in accordance with native vegetation land management codes), such as road clearing works, road maintenance, and extensions. Correspondence with Verdant Earth indicates that this biomass is currently mulched or mixed with soils and buried. This fuel source will be chipped on site before being collected and transported to Redbank Power Station.

Agricultural residues

Agricultural waste from biomass will include plant or crop residues produced directly from agricultural practices and will include non-putrescible natural organic fibrous materials and organic residues from harvest activities including fibres, roots, stalks, stubble, leaves, seed pods, nut shells and some waste from agricultural processing such as cotton and cane trash. The majority of available sources consist of straws from different cereal crops (e.g. wheat, barley, oat etc.). Current practices for managing agricultural residues vary, but may include burning, degradation on site, or collection for use in products or energy. For Verdant Earth, agricultural residues collected will be ground and pelletised off-site before being transported to the power station.

Domestic biomass fuel

The domestic biomass fuel (DBF) Verdant Earth are targeting as potential fuel includes Construction and Demolition (C&D) and Dry Sorted Commercial and Industrial (C&I) waste sourced primarily from industry skip and bulk bin collection, and demolition works, where this material is presently destined for landfill.

A summary of the types of residues modelled and their current fates are shown in Table 1

Table 1 Summary of biomass feedstock types

Biomass feedstock category	% of total	Modelled current fate	Source/comments
Purpose-grown fuel crops	70%	Grassland	
Invasive species control	13%	100% air-dried and burnt on site	Information provided by Verdant Earth
Agricultural residues	7%	20% burnt 80% left to degrade on site	20% burn based on date from National Inventory report for barley straw [3] Assumed remaining left on site
Approved land clearing	3%	100% mulched	Information provided by Verdant Earth
Domestic biomass fuel	7%	100% landfill	Information provided by Verdant Earth

Electricity production from biomass

The production of electricity from biomass involves their combustion and the conversion of the heat generated into electricity. This operation requires further inputs and produces emissions.

Treatment of ash

The combustion of biomass produces ash as a by-product. This is primarily fly ash from the boiler and is collected by the bag filters. The ash collected at Redbank Power Station may be used as fertiliser in forestry and agriculture. If this is the case, it will avoid the production of fertilisers containing potassium, phosphorous and calcium.

A specific Resource Recovery Order and Exemption will be applied for, to permit the beneficial reuse of the ash, in a manner that protects human health and the environment. This application is made under Clauses 91 and 92 of the Protection of the Environment Operations (Waste) Regulation 2014, or it may meet the Ash from Burning Biomass Order and Exemption 2014.

2.2.2 Functional unit and scenarios

The international standard on LCA describes the functional unit as defining what is being studied, and states that all analyses should be expressed relative to the functional unit. The definition of the functional unit needs to clearly articulate the function or service that is under investigation.

The functional unit defines the common basis for comparison of alternative options being assessed. In this case, the common basis for comparison is the production of electricity. Thus, the functional unit is as follows:

"the generation of 1 MWh of electricity in New South Wales."

In this study, the two scenarios assessed against this functional unit are:

1. **A 'reference' scenario**, which represents 'business-as-usual', i.e., no conversion of Redbank Power Station, and therefore the continued reliance on coal-fired power stations to provide baseload electricity (Figure 4). The potential biomass feedstock streams continue going to their current fate and are not diverted for electricity production.
2. **A 'biomass' scenario**, where Redbank Power Station is converted to burn biomass fuel. Biomass is obtained from various sources and is used to generate electricity at Redbank Power Station, providing baseload electricity to the grid of New South Wales (Figure 5).

When selecting a reference scenario, we aim to evaluate the effects of the introduction of the product system under assessment to the market. To do this, we need to think about what our current system is, and how will this change when the new technology is introduced. i.e. how will the system change when Redbank Power Station is converted to a biomass facility.

In the current system, we produce electricity to meet demand from a range of technologies. When electricity from biomass produced at Redbank is introduced into this mix, one of these technologies will be removed from grid to keep production matching demand. We call this technology the marginal supplier, i.e. the technology which is most likely to come on or off the market depending on demand. This marginal supplier is therefore what we compare to, as its use forms the alternative if Redbank Power Station is not converted.

Coal-based electricity is chosen as the marginal supplier and hence reference scenario. Unlike renewable energy generation, which is in the short term determined by investment, electricity from thermal sources fluctuates with demand and can be ramped up and down accordingly. Given the expected closures of coal-fired plants, and increased investment in electricity generation from gas, it is assumed that electricity from black coal is the most likely to be displaced as a result of the reopening of Redbank Power Station as a biomass facility, and hence the most suitable comparison.

2.2.3 System boundary

The system boundary describes what processes and life cycle stages are included and excluded in the LCA. Typically, system boundaries should include everything that is substantially affected by demand for the product under assessment. This includes extraction and production processes and any additional activities required to make each option functionally equivalent, such as the manufacturing of inputs or the production of heat and electricity. It also includes the effects of co-products along the supply chain. The system boundary diagrams for the two scenarios are shown in Figure 4 and Figure 5.

In the reference scenario, electricity is generated from black coal (see Section 2.2.2), the potential biomass feedstock streams are sent to their current fates, and fertiliser is produced. In the biomass scenario, the equivalent amount of electricity is generated at Redbank Power Station using 100% biomass. Ash is produced an applied as a fertiliser, which displaces the production of conventional fertilisers. Beyond the plant and process changes listed in Section 2.2.1, the restart of the plant as a biomass facility will require maintenance, refurbishment, minor construction, repair activities, and grid connection. These restart measures are not included within the system boundary, as the associated impacts are considered to be very small from a life cycle perspective.

The impacts associated with electricity distribution do not change between the two scenarios and are therefore excluded from the system boundary. The impacts associated with land clearing, agricultural production, and, and manufacturing of timber products are not included within the system boundary. See Section 2.2.4 for a detailed explanation of these decisions.

Note that the reference scenario does not include any current management for energy crops. This is because the energy crops are the only feedstock that do not exist without implementation of the counterfactual biomass scenario. Only unproductive land is targeted, meaning no displacement of agricultural products are included in the biomass scenario.

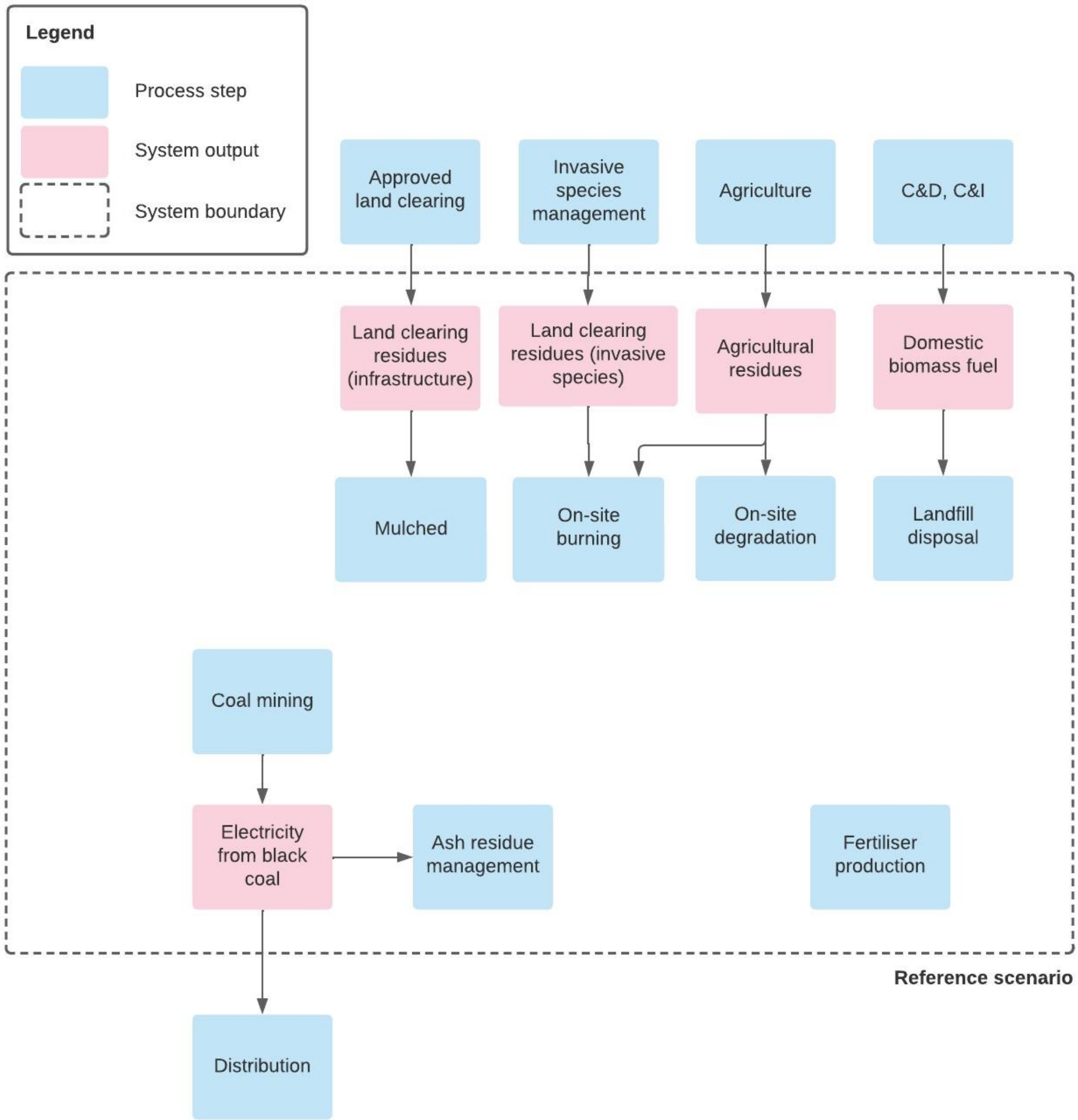

Figure 4 System boundary diagram, reference scenario

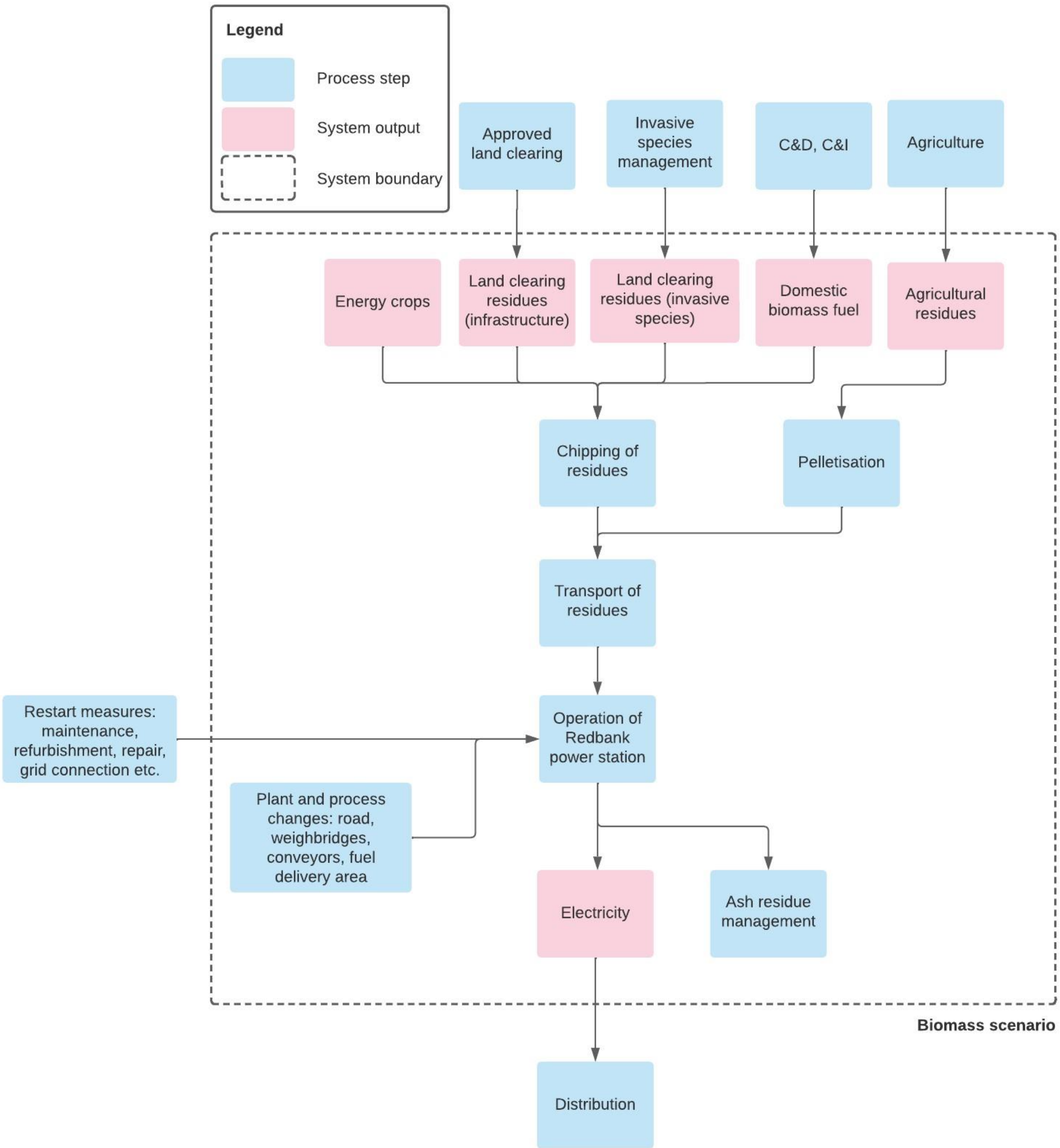

Figure 5 System boundary diagram, biomass scenario

The system boundary may exclude elements that fall below the cut-off threshold. It can also exclude processes that are common to all options assessed and are therefore not affected by the choice of option. The proposed cut-off threshold for this study was less than 1% of any impact category included in the LCA. Minor inputs considered to be well below this threshold are not considered.

2.2.4 Multi-functionality

Multi-functionality occurs when a single process or group of processes produces more than one usable output, or 'co-product'. ISO defines a co-product as "any of two or more products coming from the same unit process or product system". A product is any good or service, so by definition it has some value for the user. This is distinct from a 'waste', which ISO defines as "substances or objects which the holder intends or is required to dispose of", and therefore has no value to the user. As LCA identifies the impacts associated with a discrete product or system, it is necessary to separate the impact of co-products arising from multi-functional processes.

Co-products are commonly used for the generation of electricity from biomass, in the form of residues. In line with the ARENA requirement this study uses system expansion to avoid allocation of co-products. System expansion looks at how a co-product is used in the economy and provides a credit to the determining product equal to its displacement effect. For example, when bagasse is produced as a co-product of sugar production, the sugar product is given a credit for displaced electricity made from the bagasse. The type of electricity which is offset should be the marginal supply – that being the one which will change when bagasse-based electricity is added or subtracted from the grid. A summary of the approach for each co-product is presented in Table 2.

Table 2 Summary of co-production management.

Process	Determining product	Co-product	System expansion substituted commodity / allocation key
Approved land clearing for infrastructure works	Cleared land	Biomass cleared	100% of the impacts of land clearing are allocated to the main product – cleared land. The residues are assumed to have a zero or less economic value in the field (or else these residues would find a market). The current use of these materials is assumed to be 100% mulching. The impacts of these current fates are added to the reference scenario.
Land clearing for invasive species control	Cleared land	Biomass cleared	100% of the impacts of land clearing are allocated to the main product – cleared land. The residues are assumed to have a zero or less economic value in the field (or else these residues would find a market). The current use of these materials is assumed to be 100% burnt on site. The impacts of these current fates are added to the reference scenario.
Agriculture	Agricultural products	Agricultural residues	100% of the impacts of agricultural production are allocated to the main product – the agricultural produce. The residues are assumed to have a zero or less economic value in the field (or else these residues would find a market). The current use of these materials is assumed to be: • 20% burnt on site • 80% left to degrade on site
Timber product manufacturing	Timber products	Domestic biomass fuel (EOL timber products)	100% of the impacts of timber product manufacturing are allocated to the timber main products. The domestic biomass fuel is assumed to have a zero or less economic value in the field (or else these wastes would find a market). The current fate of these materials is assumed to be landfill – the impacts of which are added to the reference scenario.
Electricity generation	Electricity	Incinerator ash as fertiliser	The impacts of electricity generation are fully allocated to the electricity products. The ash is assumed to displace small quantities of Potassium, Phosphorus, and Calcium from conventional sources. The impacts of producing these fertilisers are included in the reference scenario.

2.2.5 Temporal Aspects

The overall project is estimated to have an economic life of 40 years, and all infrastructure modelled in this LCA use 40 years as a basis for the lifespan of the equipment. Energy crops are also assumed to have a 40 year lifetime.

2.2.6 Treatment of fossil, biogenic and atmospheric carbon

Special attention is given to the sources and fate of carbon in the LCA. When developing an inventory of carbon dioxide (CO_2) emissions in LCA, a distinction is made between molecules of biogenic and fossil origins. Biogenic carbon originates from biomass, while fossil carbon originates from geological fossil fuel reserves (oil, coal and gas).

In LCA, the term biogenic carbon is used to refer to solid carbon contained in products and waste streams, as well as carbon in GHGs (i.e. CO_2 and methane), which are emitted from biogenic material. Atmospheric carbon is carbon held in the atmosphere, which can be absorbed by biomass through photosynthesis. This process is referred to as 'biogenic uptake' of CO_2.

In this analysis, the biomass used to generate process electricity includes a portion of absorbed atmospheric carbon. By utilising the molar masses of carbon and carbon dioxide, and a carbon content of 50%, it can be estimated that 1.83 kg CO_2 is absorbed per kg of biomass feedstock (dry mass basis).

When the biomass is combusted, not all carbon becomes carbon dioxide. Some is converted to carbon monoxide and some to methane. To capture this, biogenic carbon absorption and emission are included in the analysis. In essence, in this analysis, the carbon neutrality assumption is not applied.

2.2.7 Land use change (LUC)

In this project, the only dedicated production system used to feed the power plant is the use of energy crops. The remaining feedstocks will be obtained from existing residue streams. For the energy crops, Verdant Earth are seeking to use areas that currently have no alternative economic value to farmers/landowners. For example, they will target buffer zones of mines in the area, semi-arable land parcels without other economically viable economic agricultural uses.

As the crops grow, both the above and below ground biomass will store carbon. For rotational energy crops, if biomass is harvested every 4 years, at any given time a quarter of the biomass is 3-4 years old, a quarter 2-3 years old and other quarter is 1-2 years old and the last quarter is being harvested and replanted. Once the crops are established, the carbon storage in both the above and below ground biomass will reach an equilibrium and will remain stored for the duration of the project.

The growth of energy crops is modelled considering the above and below ground carbon storage which occurs as result of the crop growth. It is assumed that the crops consist of Red Gum eucalyptus, and require 4 years of growth before they can be harvested. From this point, they are harvested on a 4-year rotation. All the above ground biomass is removed, and the plant regrows until the next harvest. A carbon content of 50% is assumed for the biomass feedstock (both above and below ground, green), which, along with an estimated yield of 70 tonnes per ha per year, is used to calculate the above ground carbon storage associated with the growth of the crops. The below ground carbon storage is then calculated using root-to-shoot ratios from the IPCC [8].

This carbon storage is included in the model to represent the land use change effects of converting land from mining buffer zones or non-utilised semi-arable parcels to energy crops.

2.2.8 Impact assessment

In LCA, the impact assessment stage relates the inventory flows to the indicators selected. This is done by classifying which flows relate to this impact category and selecting a characterisation model that quantifies the relationship of each inventory type to the indicator in question. The calculation of the category indicator results is the sum of all inventory flows multiplied by their relevant characterisation factors.

For this study, the impact assessment model is based on requirements of the ARENA Guidelines [1]. A summary of the selected impact assessment models can be found in Table 3.

By including a range of impact categories in the analysis, the full picture of environmental impacts becomes clear. For example, improvements in one impact category may relate to detrimental effects in another, and hence shifting of impacts between categories can be identified.

For the climate change impact category, the carbon neutrality assumption is not applied. That is, biogenic carbon uptake is given a characterisation factor of -1, and biogenic carbon emissions are given a characterisation factor of 1. This decision was made to fully account for carbon flows through the system, as during combustion of biomass, some carbon is converted to carbon monoxide.

Table 3 Impact categories and characterisation models of the study

Indicator	Unit	Description	Characterisation model
Climate change	kg CO_2-eq	Measured in kg of carbon dioxide equivalence. This is governed by the increased concentration of gases in the atmosphere that trap heat and lead to increasing global temperatures. These gases are principally carbon dioxide, methane and nitrous oxide.	IPCC model based on 100-year timeframe [4]
Fossil fuel depletion	MJ NCV	Measured in megajoules net calorific value. This indicator measures the decrease of availability of the total reserve of potential resources.	CML-IA V4.8 August 2016 method [5], depletion based on Guinee et al. [6]
Ozone layer depletion	kg CFC-11-eq	Measured in CFC 11 equivalent. Ozone depletion leads to break down in ozone layer, leading to increases in skin cancers and other effects.	CML-IA V4.8 August 2016 method [5]
Photochemical oxidation	kg C_2H_4-eq	Measured in kg ethene eq. Potential of hydrocarbons and nitrogen oxides in the atmosphere to combine with sunlight to produce stratospheric ozone, which has significant respiratory and other health effects.	CML-IA V4.8 August 2016 method [5]
Acidification	kg SO_2-eq	Measured in sulphur dioxide equivalent. Acidification is a relevant impact for processes releasing NOx and SOx, acidic gases and ammonia. NOx and SOx, the species that tend to contribute most of acidification impacts, are released from the burning of fossil fuels in electricity, steam and heat generation.	CML-IA V4.8 August 2016 method [5]
Eutrophication	kg PO_4^{3-}-eq	Measured in kg of phosphate equivalences. This indicator measures algal growth from nutrient enrichment in freshwater and marine environments. Emissions of nitrogen and phosphorus contribute, with the model being based on the relative nutrient.	CML-IA V4.8 August 2016 method [5], eutrophication potentials based on Heijungs et al [7]
Particulate matter	kg $PM_{2.5}$-eq	Measured in kg fine particulate matter (2.5 microns) equivalence. This impact category looks at the health impacts from particulate matter for PM_{10} and $PM_{2.5}$. This is one of the most dominant immediate risks to human health as identified in the global burden of disease	World impact+ method [8]

Indicator	Unit	Description	Characterisation model
Water scarcity	m^3 H_2O-eq	Measured as cubic metres of water equivalent. This impact category is an indicator of water scarcity, assessing water deprivation to other users due to water extraction.	Water depletion characterisation model of Pfister et al. [9]
Land use	kg C deficit	Measured as kg soil organic carbon (SOC) deficit (kg $C/m^2/a$). This indicator is a measure of the soil's ability to fix carbon, relative to potential natural vegetation. Changes in soil organic carbon are causally associated with other important indicators such as soil fertility and biotic production, carbon and nutrient cycling and water infiltration and erosion protection.	ILCD 2011 Midpoint+ [10]

3 Inventory

The life cycle inventory provides a detailed list of all parameters used within the model. This section is broken down into the foreground data, which were collected specifically for the study (primarily from Verdant Earth and secondary sources) and background data, which were sourced from existing databases.

3.1 Foreground data

A summary of data sources and assumptions for the foreground data are described here. Section 3.1.1 focuses on the reference scenario data, while Section 3.1.2 focuses on the biomass scenario.

Operation of Redbank Power Station is expected to begin with five main sources of biomass fuel: purpose-grown fuel crops, residues from invasive species control, agricultural residues, residues from approved land clearing, and Domestic Biomass Fuel.

The chemical properties of the biomass feedstock are used to determine flows of materials through the system, as well as inform the calculations for values such as energy production, ash production, and emissions. The chemical properties of the biomass feedstock types assessed are shown in Table 4.

Table 4 Chemical properties of biomass

	All feedstocks	Source/comments
Ash content (as fired)	0.4%	[11]
Carbon content (dry basis)	50%	Estimation
Nitrogen content (dry basis)	0.14%	[11]
Moisture content (as fired)	25%	[12] Average
Calorific value (GCV, MJ/kg)	15.2	[11] Gross calorific value (GCV) used rather than net calorific value (NCV) since supplied efficiency of plant given in terms of GCV. Some fuels may have higher calorific value, but this value indicates the minimum requirement and is chosen for conservativeness.

3.1.1 Reference scenario

This section details the data collected for the reference scenario, which are reported in Table 5 below. The reference scenario includes the production of electricity with coal feedstock and also the current fates of the biomass feedstock. This refers to the current disposal practices that are avoided when the residues are collected for firing at Redbank Power Station. See Section 2.2.1 for details on the current fates.

Table 5 Foreground data for reference scenario, per year

		Unit	Value	Assumptions/comments
Input				
	Land clearing residues from invasive species control, burnt on site	kt	110.5	
	Agricultural residues, burnt on site	kt	11.9	Assumed 20% of agricultural residues currently burnt
	Agricultural residues, left on site to degrade	kt	47.6	Assumed 80% of agricultural residues left on site to degrade. Assumed all carbon is released during degradation.
	Residues from approved land clearing, to mulch	kt	255	Assumed residues are chipped and transported 100km. Assumed all carbon released during breakdown of mulch
	Domestic biomass fuel, to landfill	kt	59.5	Assumed DBF is transported 100km to landfill
	Fertiliser, potassium sulphate	t	340	Fertiliser equivalent of ash applied to soil in wood waste residues scenario. Calculation based on ash analysis from [11]
	Fertiliser, triple superphosphate	t	102	Fertiliser equivalent of ash applied to soil in wood waste residues scenario. Calculation based on ash analysis from [11]
	Limestone, milled	t	1,207	Fertiliser equivalent of ash applied to soil in wood waste residues scenario. Calculation based on ash analysis from [11]
Output				
	Electricity, from black coal, in NSW	GWh	976	Same as annual generation of Redbank, see Table 8.

3.1.2 Biomass scenario

The modelling assumptions for transport and processing of each of the biomass feedstocks are shown in Table 6 and Table 7 below.

Table 6 Feedstock processing assumptions, biomass scenario

Fuel type	Processing	Assumptions/comments
Energy crops	Chipping	Diesel consumption 13.8L per tonne chipped feedstock [13] 2% loss assumed [14]
Land clearing residues, invasive species control	Chipping	Diesel consumption 13.8L per tonne chipped feedstock [13] 2% loss assumed [14]
Agricultural residues	Pelletisation	Electricity consumption of 152.41 kWh [14] 2% loss assumed [14]
Residues, approved land clearing	Chipping	Diesel consumption 13.8L per tonne chipped feedstock [13] 2% loss assumed [14]
Domestic biomass fuel	Chipping	Diesel consumption 13.8L per tonne chipped feedstock [13] 2% loss assumed [14]

Table 7 Transport assumptions, biomass scenario

		Transport distance	Assumptions/comments
Inputs			
	Energy crops	50km	Verdant Earth have indicated that energy crops will be located in close proximity to Redbank Power Station
	Land clearing residues, invasive species control	300km	Fuels will be targeted within 300km radius
	Agricultural residues	350km	Fuels will be targeted within 300km radius. Extra 50km is added to account for transport to pelletisation facility.
	Residues, approved land clearing	300km	Fuels will be targeted within 300km radius
	Domestic biomass fuel	300km	Fuels will be targeted within 300km radius
Outputs			
	Ash	200km	Assumption

The production of electricity from biomass requires a power plant, fuel source, water, and transport. The construction of Redbank Power Station is not included in the inventory, since the existing facility is being utilised. The additional infrastructure required for the conversion of the plant is included. However, the modifications to existing conveyors and trouser legs are excluded under the expectation that they will have a negligible effect to the overall impacts. Electricity consumption of conveyors is included and it is assumed that the lifetime of the plant and existing infrastructure is 40 years. Table 8 describes the foreground data for the production of electricity in the biomass scenario, while Table 9 provides information on the combustion process and operation of the power station. Table 10 describes the modelling assumptions surrounding the use of ash as fertiliser.

For the agricultural residues, the removal of these from site for electricity production could result in a loss of nutrients to the soil, and hence potentially require additional fertilisers. In this model, it is assumed that sufficient agricultural residues remain on site to maintain soil health and hence no changes occur to nutrient levels. The amount of residues required to remain on site depends on multiple variables. It is assumed that this is managed by the land owners, and that only excess residues will be targeted by Verdant Earth.

Table 8 Foreground data for biomass scenario, per year

		Unit	Value	Assumptions/comments
Input				
	Occupation of industrial land	km^2a	0.18	Based on site area of 180,000 m^2
	Conveyor belt	m	0.7	Added as part of the 'plant and process changes'. Calculated as 20m added, divided by expected lifetime of plant
	Concrete	m^3	3.4	Added as part of the 'plant and process changes'. Estimated concrete needed for two weighbridges (dimensions 28m x 3m x 0.6m)
	Road	m	5.3	Added as part of the 'plant and process changes'. Calculated as 160m of road added, divided by expected lifetime of plant
	Energy crops	kt	595	
	Land clearing residues from invasive species control	kt	110.5	
	Agricultural residues	kt	59.5	
	Residues from approved land clearing	kt	255	
	Domestic biomass fuel	kt	59.5	
	Water, from river	ML	3069	3069ML annual water consumption
	Electricity, for conveyor belt operation	MWh	105	Based on four conveyors operating full time at estimated power of 3kW
	Onsite diesel consumption	kL	175	Diesel consumption for on site biomass handling [15]
Output				
	Electricity	GWh	976	Energy content of biomass feedstock assumed to be 15.2 MJ/kg, based on 25% moisture content, and plant efficiency assumed to be 27.2% (GCV basis).
	Water, to air	ML	3069	3069ML annual water consumption, assumed released as steam
	Ash treatment	t	3400	Assumed ash content of 0.4%
	Particulate matter <2.5µm	kg	522	Fugitive emission [15] Emissions assumed to occur in low-population area.
	Particulate matter 2.5-10µm	kg	2035	Fugitive emission [15] Emissions assumed to occur in low-population area.
	Particulate matter >10µm	kg	7681	Fugitive emission [15] Emissions assumed to occur in low-population area.

Table 9 Biomass combustion data, per tonne biomass

		Unit	Value	Assumptions/comments
Output				
	Carbon dioxide, biogenic	kg	1,374	Calculated, based on moisture and carbon content of feedstock (Table 4), and subtracting carbon released as CO. Emissions assumed to occur in low-population area.
	Methane, biogenic	kg	0.058	[16]
	Dinitrogen monoxide	kg	0.067	[16]
	Carbon monoxide, biogenic	kg	0.70	Data from project Air Quality Impact Assessment report [15], original source [17]. Emissions assumed to occur in low-population area.
	Nitrogen oxides	kg	1	Data from project Air Quality Impact Assessment report [15], original source [17]. Emissions assumed to occur in low-population area.
	Sulfur dioxide	kg	0.17	Data from project Air Quality Impact Assessment report [15], original source [17]. Emissions assumed to occur in low-population area.
	Particulates, < 10um	kg	0.03	Data from project Air Quality Impact Assessment report [15], original source [17]. Derived from PM2.5 and PM10 values. Emissions assumed to occur in low-population area.
	Particulates, < 2.5 um	kg	0.03	Data from project Air Quality Impact Assessment report [15], original source [17]. Emissions assumed to occur in low-population area.
	VOC, volatile organic compounds	kg	0.12	Data from project Air Quality Impact Assessment report [15], original source [17]. Emissions assumed to occur in low-population area.
	TSP	kg	0.03	
	Antimony	mg	27	Data from project Air Quality Impact Assessment report [15]. Emissions assumed to occur in low-population area.
	Arsenic	mg	85	Data from project Air Quality Impact Assessment report [15]. Emissions assumed to occur in low-population area.
	Beryllium	mg	3	Data from project Air Quality Impact Assessment report [15]. Emissions assumed to occur in low-population area.
	Cadmium	mg	3	Data from project Air Quality Impact Assessment report [15]. Emissions assumed to occur in low-population area.
	Copper	mg	10	Data from project Air Quality Impact Assessment report [15]. Emissions assumed to occur in low-population area.
	Chromium	mg	142	Data from project Air Quality Impact Assessment report [15]. Emissions assumed to occur in low-population area.
	Lead	mg	369	Data from project Air Quality Impact Assessment report [15]. Emissions assumed to occur in low-population area.
	Manganese	mg	166	Data from project Air Quality Impact Assessment report [15]. Emissions assumed to occur in low-population area.
	Nickel	mg	14	Data from project Air Quality Impact Assessment report [15]. Emissions assumed to occur in low-population area.
	Mercury	mg	32	Data from project Air Quality Impact Assessment report [15]. Emissions assumed to occur in low-population area.

Table 10 Foreground data for use of wood waste residues ash as fertiliser, per kg ash

		Unit	Value	Assumptions/comments
Inputs				
	Ash, from biomass combustion	kg	1	
	Transport, 40t truck	kgkm	200	Transport of ash to location for use as fertiliser. transport distance of 200km. Process modified for low-population particulate matter emissions.
Outputs				
	Silicon	g	74	From report 'Redbank Power Station – Description of Proposed Modifications for Conversion to Fire Biomass fuels' [11]
	Aluminium	g	90	From report 'Redbank Power Station – Description of Proposed Modifications for Conversion to Fire Biomass fuels' [11]
	Iron	g	49	From report 'Redbank Power Station – Description of Proposed Modifications for Conversion to Fire Biomass fuels' [11]
	Calcium	g	142	From report 'Redbank Power Station – Description of Proposed Modifications for Conversion to Fire Biomass fuels' [11]
	Magnesium	g	78	From report 'Redbank Power Station – Description of Proposed Modifications for Conversion to Fire Biomass fuels' [11]
	Sodium	g	7	From report 'Redbank Power Station – Description of Proposed Modifications for Conversion to Fire Biomass fuels' [11]
	Potassium	g	83	From report 'Redbank Power Station – Description of Proposed Modifications for Conversion to Fire Biomass fuels' [11]
	Titanium	g	3	From report 'Redbank Power Station – Description of Proposed Modifications for Conversion to Fire Biomass fuels' [11]
	Manganese	g	25	From report 'Redbank Power Station – Description of Proposed Modifications for Conversion to Fire Biomass fuels' [11]
	Sulfur	g	20	From report 'Redbank Power Station – Description of Proposed Modifications for Conversion to Fire Biomass fuels' [11]
	Phosphorus	g	13	From report 'Redbank Power Station – Description of Proposed Modifications for Conversion to Fire Biomass fuels' [11]

Modelling energy crops

It is assumed that the production of energy crops does not displace productive agricultural land, and that the harvest yield is consistent over a 40-year period. While the crops may sequester more carbon initially as the crops are established, the benefits are presented as an average over the entire lifetime. The crops are modelled assuming the Red Gum eucalyptus species is employed.

Information obtained from energy crop trials conducted by the NSW Department of Primary Industries indicates that no fertilisers will be required and that periodic mowing of the site may occur (annual mowing assumed).

Table 11 Modelling parameters for production of energy crops

Parameter	Unit	Value	Source/comments
Bulk density of energy crop wood	kg/m3	600	[18]
Annual yield	t/ha	70	[19]
Total land use	ha	80,000	[19]
Project lifetime	y	40	[19]
Harvest lifetime	y	36	[19]
Loss factor	%	5	[19]

The parameters used in the table above are used to develop the inventory for energy crop production, shown in Table 12.

Table 12 Foreground data for energy crop production, per year, averaged over crop lifetime

		Unit	Value	Assumptions/comments
Inputs				
	Land occupation	ha a	80,000	
	Land transformation, from grassland to shrub land	ha	2,000	Transformation occurs once over project lifetime
	Seedlings	million	5	Assumed 2,500 stems per hectare, based on direct contact with NSW DPI
	Glyphosate	t	731	[20]
	Transport	thousand tkm	4,368	Transport of inputs to crop site [20]
	Mowing	ha	80,000	Assumed annual mowing required
	Harvest and haulout	kt	4,788	
	Ripping, large implement	ha	2,000	Performed once for site preparation
Outputs				
	Red gum wood, green	kt	4,788	

3.2 Background data

While hundreds of background processes contribute to the analysis, the most important processes are described here, particularly those affecting the results or those that have been modified from the original source to better represent the inputs to this assessment. The processes, data sources and modifications are summarised in Table 13.

Table 13 Summary of significant background data used throughout the model

Unit process name	Source	Used in	Comments
Potassium sulphate, as K2O, at regional storehouse/RER U/AusSD U	[21]	Fertiliser production, reference scenario	
Triple superphosphate, as P2O5, at regional storehouse/RER U/AusSD U	[21]	Fertiliser production, reference scenario	
Limestone, milled, loose, at plant/CH U/AusSD U	[21]	Fertiliser production, reference scenario	
Electricity, low voltage, New South Wales/AU U	[21]	Conveyor belt operation	
Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH U/AusSD U	[21]	Ash to landfill	
Electricity, black coal NSW, at power plant/AU U	[21]	Electricity production	Modified with low-population particulate matter emissions
Electricity, natural gas, GT, at power plant/AU U	[21]	Electricity production	Modified with low-population particulate matter emissions. Process only used in sensitivity analysis.
diesel, burned in building machine, <30 MW /AU U	[21]	Chipping, on-site diesel consumption	Modified with low-population particulate matter emissions
Transport, truck, 40t load/AU U	[21]	Transport of feedstock and ash	Modified with low-population particulate matter emissions
Conveyor belt, at plant/RER/I U/AusSD U	[21]	Plant and process changes	
Concrete 32 MPa, at batching plant/AU U	[21]	Plant and process changes	
Road/CH/I U/AusSD U	[21]	Plant and process changes	
Waste treatment, wood and wood-waste, at landfill/AU U	[21]	Domestic biomass fuel to landfill	Carbon content and moisture content adjusted to match assumptions of this study.
Glyphosate, at regional storehouse/RER U/AusSD U	[21]	Energy crop production	

Mowing, by motor mower/CH U/AusSD U	[21]	Energy crop production	
harvest and haulout, green cane/AU U	[21]	Energy crop production	
ripping, large implement, horticulture/AU U	[21]	Energy crop production	
barley grain, dryland, Darling Downs, NSW_Qld, at farm/AU U	[21]	Current fate of agricultural residues	Impacts of burning only extracted. NIR and NPI. A burn efficiency of 96% was assumed [3] and the resulting values were calculated using values for dry matter content, nitrogen content, and carbon content as shown in Table 4.

4 Results and interpretation

A summary of the LCA results is shown in Table 14 below. The reference scenario represents the production of 1MWh of electricity from black coal in NSW, including the current fates of the biomass feedstock streams. The biomass scenario represents the same production amount from biomass feedstock at Redbank Power Station.

The difference between the two scenarios represents the impacts of a shift from the reference scenario to the biomass scenario. Environmental savings are seen in most of the impact categories as a result of this shift, with the exception of ozone layer depletion and water scarcity. The sources of emissions for both scenarios are explored and compared in the following contribution analysis, Section 4.1.

The results show that the production of electricity from biomass at Redbank Power Station will save 882 kgCO_2-eq for every MWh generated (Figure 6). Based on estimated annual production, this equates to an annual saving of 862 ktCO_2-eq. The relative impacts of the two scenarios are shown in Figure 6.

Table 14 Results summary, per MWh

Impact category	Unit	Reference scenario	Biomass scenario	Difference between scenarios	Difference between scenarios (%)
Climate change	kg CO2 eq	944	62	-882	-93%
Fossil fuel depletion	MJ NCV	10,224	1,162	-9,062	-89%
Ozone layer depletion	mg CFC-11 eq	1.6	8.8	7.2	458%
Photochemical oxidation	kg C_2H_4 eq	0.5	0.04	-0.5	-93%
Acidification	kg SO_2 eq	1.4	0.8	-0.6	-43%
Eutrophication	kg PO_4^{3-} eq	0.4	0.3	-0.1	-26%
Particulate matter	kg PM2.5	0.13	0.04	-0.09	-67%
Water scarcity	m^3 eq	0.93	2.21	1.28	137%
Land use	kg C deficit	159.03	-52.93	-211.96	-133%

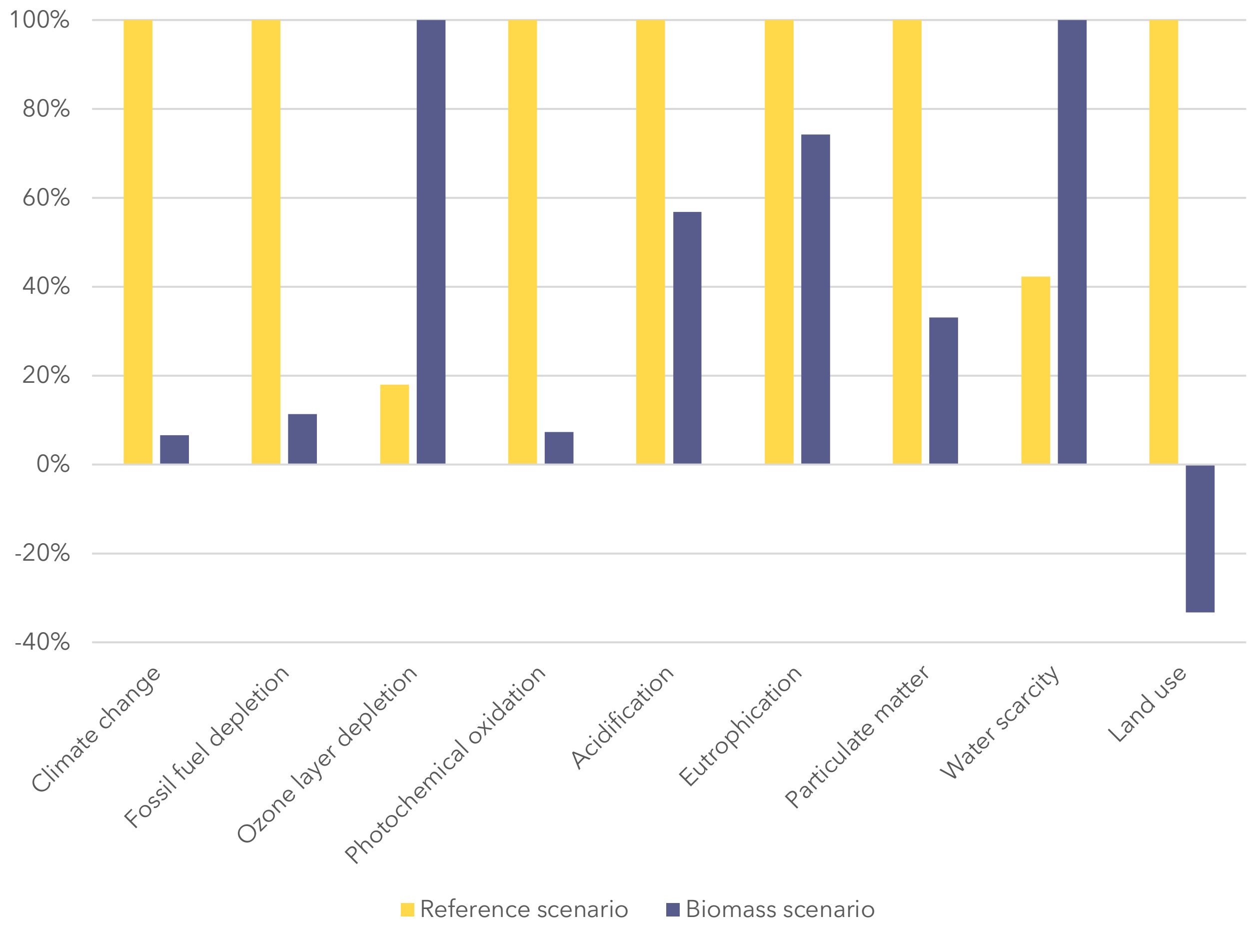

Figure 6 Relative LCA results, per MWh

4.1 Contribution analysis

In the contribution analysis, the impacts on each category are broken down into groups, in order to identify the sources of environmental burdens. The groups chosen for the contribution analysis are: coal feedstock, biomass feedstock (including current fates), transport, net emissions, and other (e.g. construction and operation of power station, waste, water consumption).

4.1.1 Climate change

The contribution analysis of the reference scenario shows that, as expected, the majority of climate change impacts are caused by the combustion of coal associated with the baseline power plant (>95%), with a smaller portion associated with the coal feedstock itself (6%) (Figure 7). The current management of potential biomass feedstock streams in the baseline scenario results in a small negative impact (i.e. a net benefit). This is because more carbon is absorbed by the residues than is released through their management. For management of invasive species control and agricultural residues, this is because of burning inefficiencies, meaning some carbon is converted to carbon monoxide, which is not a greenhouse gas. For domestic biomass fuel, not all carbon contained is emitted as greenhouse gases, some is stored in the landfill, and also methane is captured, which offsets the need for methane from fossil sources. The transport and other groups have negligible contribution to the total climate change impacts (<1% each of total).

In the biomass scenario, the climate change impacts are considerably lower, primarily due to low impacts associated with waste wood combustion at the plant. The carbon dioxide emitted was previously absorbed as the biomass was grown, resulting in lower net emissions. Approximately 36% of the climate change burdens come from the transport of feedstock to the power station, with a similar portion (36%) linked to processing the biomass feedstock. These processing impacts are driven by the combustion of diesel for wood chipping. The majority of the remaining impacts (26%) are associated with the emissions that occur at the power station such as nitrous oxide and methane.

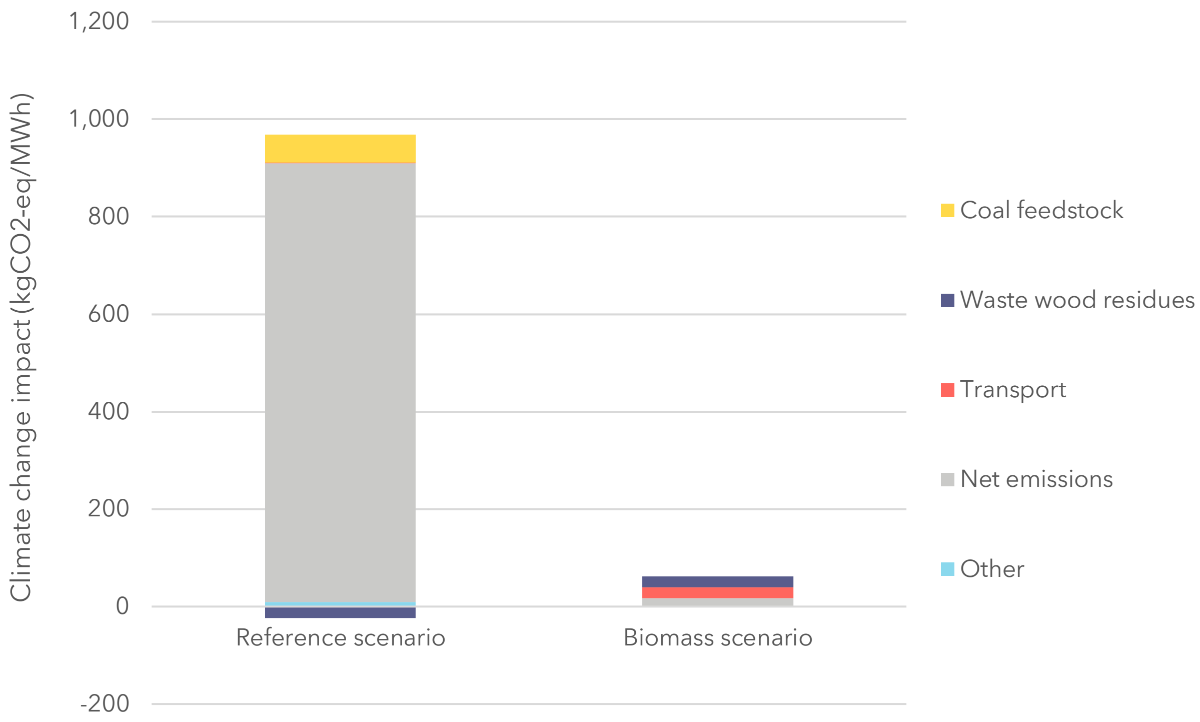

Figure 7 Climate change contribution analysis

4.1.2 Fossil fuel depletion

In the reference scenario, the depletion of fossil fuel resources is caused predominantly by the extraction of coal for electricity generation (Figure 8). The current fate whereby domestic biomass fuel goes to landfill results in a small saving of fossil fuels (0.2%) due to the collection of landfill gas. However, this is dwarfed by the fossil fuel depletion caused by the extraction of coal. In the biomass scenario, fossil fuel depletion is mainly due to the diesel consumption of the wood chipping process and transport stage. 69% of the fossil fuel depletion is linked to the fuel requirements of the residue chipping with the remaining 30% caused by the fuel requirements for transport. The overall depletion of fossil fuel in the biomass scenario is estimated to be more than 8 times lower than in the reference scenario.

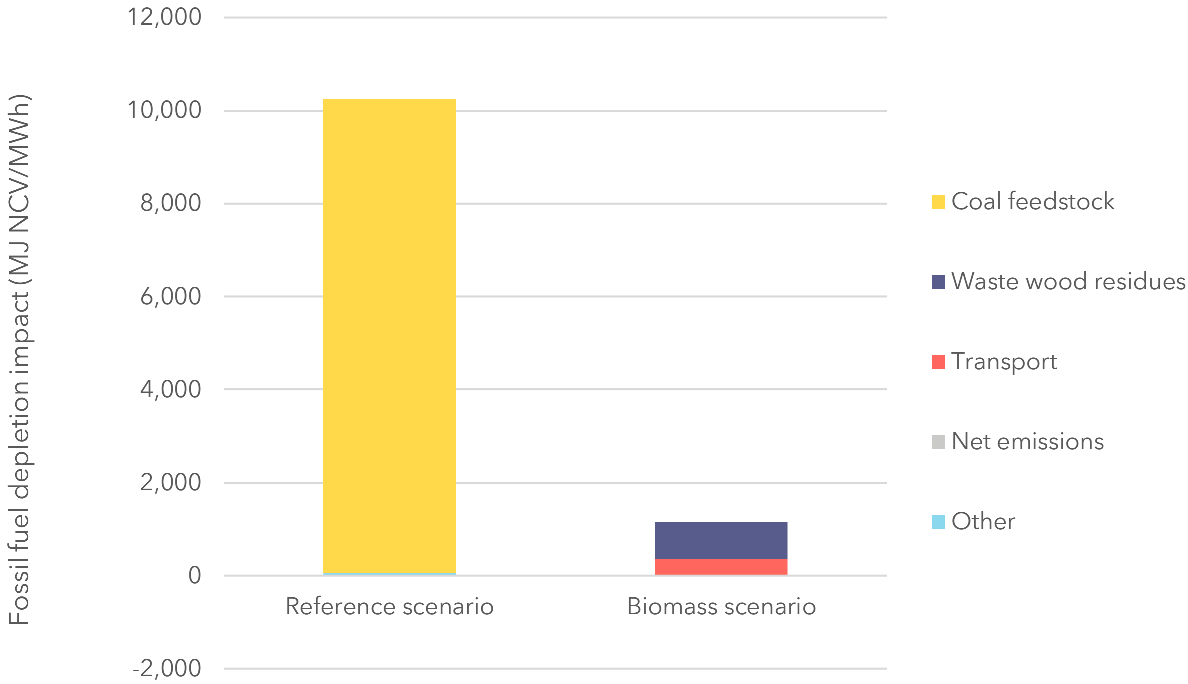

Figure 8 Fossil fuel depletion contribution analysis

4.1.3 Ozone layer depletion

Ozone layer depletion is one of only two impact categories which shows greater impacts in the biomass scenario. In the reference scenario, the impacts on ozone layer depletion are linked to the extraction of coal, chipping of residues from approved land clearing for use as mulch, and the landfill of domestic biomass fuel (Figure 9). Investigating the sources of these emissions further shows that the impacts are driven by the production of crude oil. This is linked to the diesel requirements for coal extraction and the bitumen requirements for landfill.

In the biomass scenario, the impacts on ozone layer depletion are also driven by crude oil production along the supply chain. In this case, this is required for the diesel consumption of both the transport and chipping processes.

The origins of these impacts indicate that the ozone layer depletion impacts are comparatively small overall. This is explored further in the normalisation section (Section 4.2).

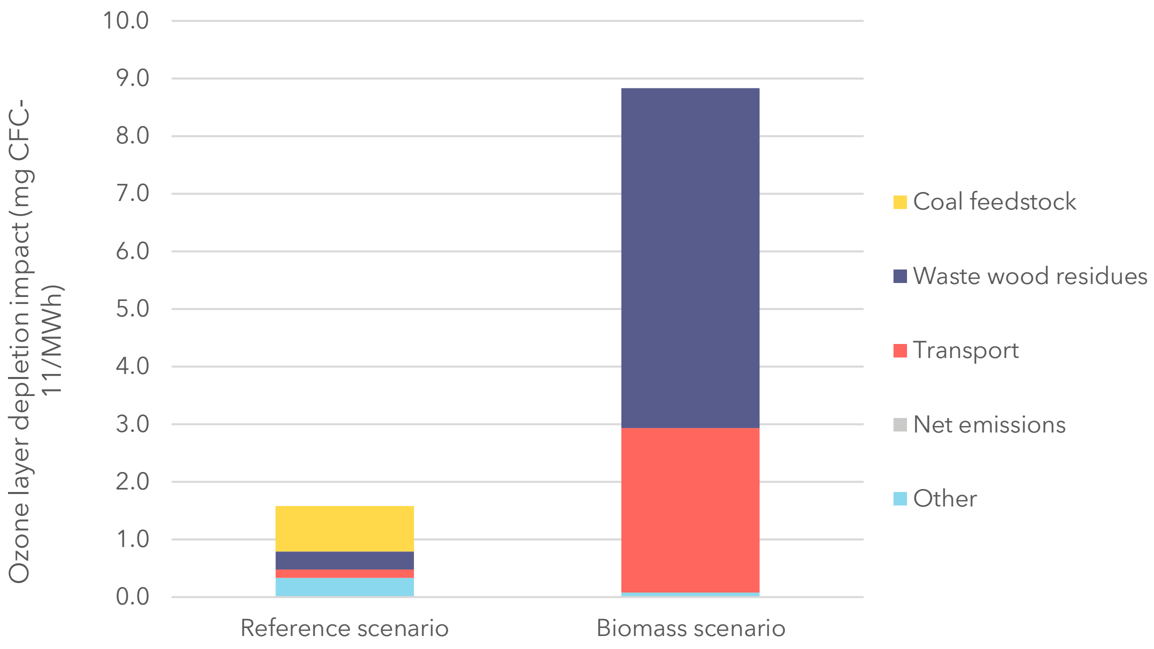

Figure 9 Ozone layer depletion contribution analysis

4.1.4 Photochemical oxidation

In the reference scenario, most of the photochemical oxidation impacts (96%) are caused by the emissions of carbon monoxide during the burning of agricultural residues and residues from invasive species control (Figure 10). This impact is reduced by over 90% with a switch to the biomass scenario. Here, the photochemical oxidation impact is caused primarily by the emissions of carbon monoxide at the power station, which are more controlled than in open burning.

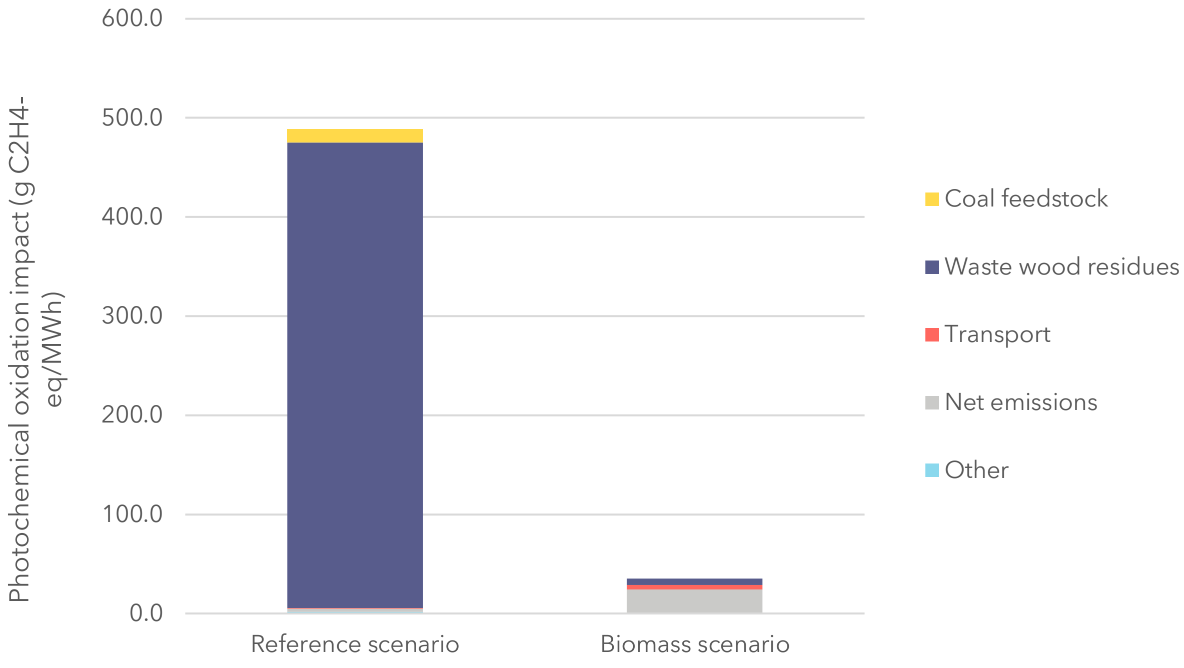

Figure 10 Photochemical oxidation contribution analysis

4.1.5 Acidification

The acidification impacts of the reference scenario are primarily linked to the emissions at the coal power station (86%), driven by the emission of nitrogen oxides during combustion (Figure 11). In the biomass scenario, the total acidification impacts are reduced by approximately 40%. In this scenario, the impacts on acidification are linked to the release of nitrogen oxides and sulphur dioxide during combustion at the power station (75%), and exhaust emissions of sulphur dioxide during the transport of the residues (9%).

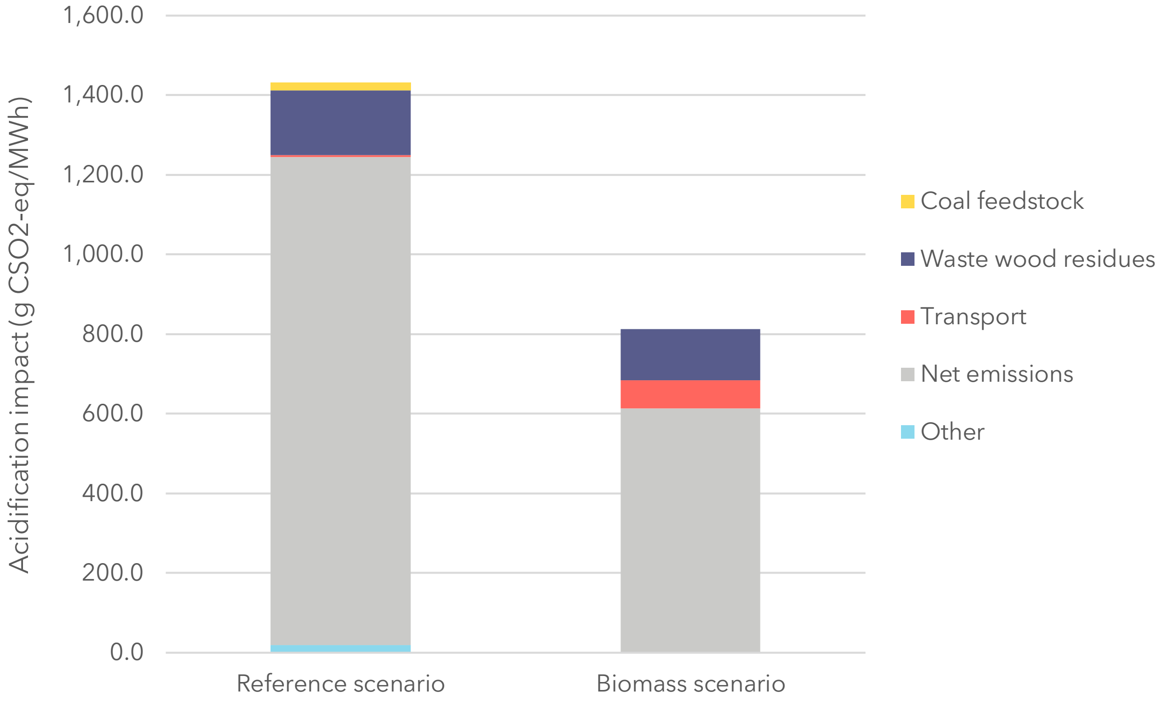

Figure 11 Acidification contribution analysis

4.1.6 Eutrophication

In the reference scenario, 74% of the eutrophication impacts are attributed to the emissions of nitrogen oxides (NOx) during the combustion of coal (Figure 12). The current practice of burning agricultural and invasive species control residues contributes 10% to this impact category, as it also emits NOx, which drives impacts on eutrophication.

In the biomass scenario, the overall eutrophication impact reduces by approximately 26%. The impacts are mainly distributed between the emissions of NOx during combustion (41%) and the 'other' category (45%), which is linked to the phosphorous leached or eroded from soil due to the use of ash as a fertiliser.

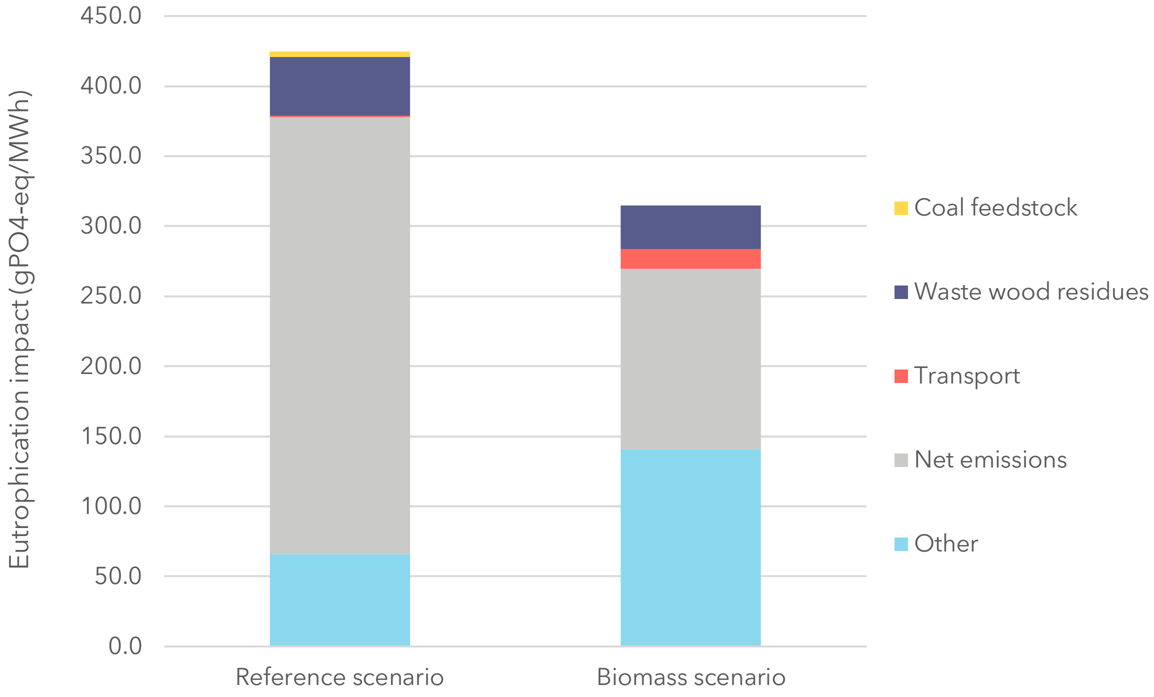

Figure 12 Eutrophication contribution analysis

4.1.7 Particulate matter

In the reference scenario, 76% of the particulate matter impacts are attributed to the current practice of burning agricultural and invasive species control residues on site (Figure 13). This practice is not a controlled burn and does not include technologies such as scrubbers to reduce emissions. Hence, the practice results in higher emissions of particulate matter than the combustion of the same residues at the power plant in the biomass scenario. The remaining particulate matter impacts are mostly linked to the particulate matter emissions occurring during coal combustion (21%).

In the biomass scenario, 62% of the particulate matter impacts occur during the combustion of the residues, with the remaining impacts linked to processing of residues (24%) and transport (13%).

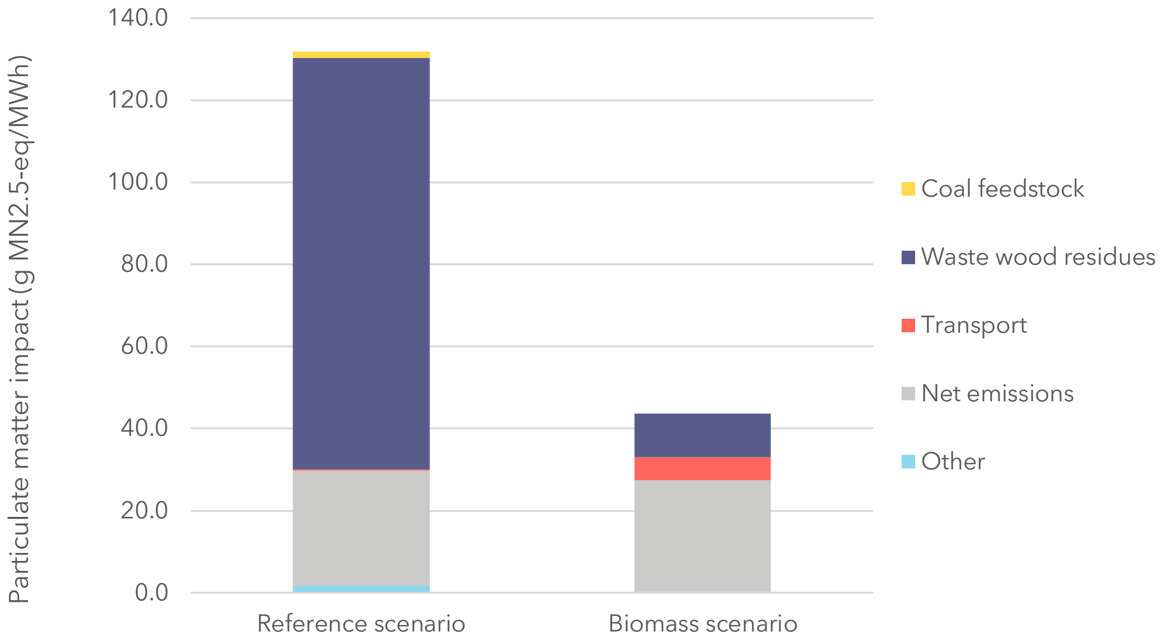

Figure 13 Particulate matter contribution analysis

4.1.8 Water scarcity

In the reference scenario, 93% of the water scarcity impacts are attributed to the 'other' category, which in this case represents the tap water consumed for cooling during the generation of electricity from black coal (Figure 14). The LCA model for the reference scenario is obtained from the AusLCI database. The water consumption value specifically is sourced from a study which investigated water consumption of electricity generators across the country [22]. For the NSW value, an average is taken across seven different coal-fired power stations. While this is the most recent data available for a collation of water consumption across power stations, since this data was collected in 2009 some power stations have since closed. The consumption of tap water per MWh across the power stations assessed varies from as little as 0.2 m3 (when cooling water obtained from the ocean), up to 2.5 m3. So while the average value used in this analysis is 1.2 m3/MWh, it contains some uncertainty.

Water at Redbank Power Station will be accessed via the existing stormwater pond, which will be supplemented with water extracted from the Hunter River. For the LCA model, the water was all modelled as river water, as the split between stormwater and river water was not known. Stormwater does not affect water scarcity, and hence if Verdant Earth were to use a fraction of stormwater to replace river water, the water scarcity impacts would be reduced. It should also be noted that the water access license is unchanged in amount from the plant's previous operation as a coal tailings facility.

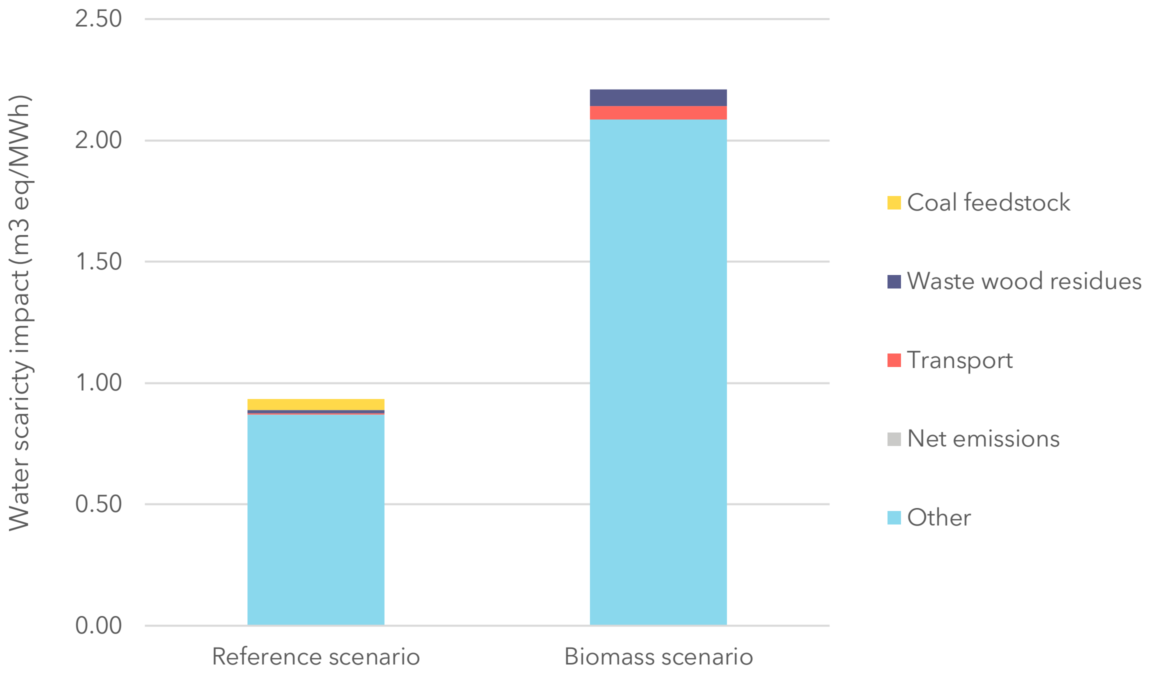

Figure 14 Water scarcity contribution analysis

4.1.9 Land use

Land use impacts are measured as a deficit of soil organic carbon. In the reference scenario, the largest impacts on land use are due to the mining of black coal for electricity generation (Figure 15), representing 81% of the total. This is caused by the transformation of land to an industrial area.

In the biomass scenario, there is a land use impact associated with the transport of feedstock. This is driven by the upstream land transformation for crude oil extraction which becomes diesel. This impact is counter balanced by the land use benefits associated with the production of energy crops, resulting in a net negative impact, i.e. an increase in soil carbon. This increase in soil carbon occurs under the assumption that land is transformed from grassland to sclerophyllous shrub land.

Land use for biomass production other than energy crops is not included as all residue fuel sources are considered waste products, and hence any land use impacts are associated with the determining product.

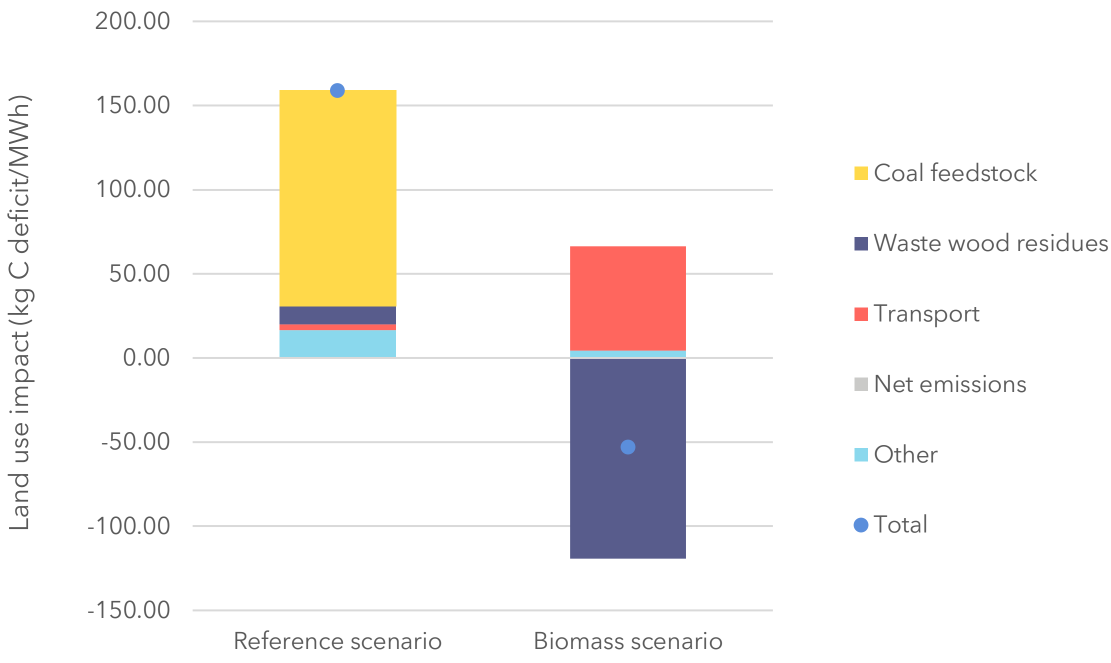

Figure 15 Land use contribution analysis

4.2 Normalisation

To understand the relative importance of different impact categories, LCA results can be normalised against total annual impacts of a region, in this case the total annual global impacts (Table 15). This involves analysing the results across impact categories with reference the annual global impact for that category, and allows for an assessment of the *scale* of the impacts, i.e., how important the impact category is when comparing scenarios. The normalisation factors used are shown below.

Table 15 Annual global impact used for normalisation

Impact category	Unit	Normalisation factor	Source	Reference year
Climate change	kg CO2 eq	4.18E+13	CML [5]	2000
Fossil fuel depletion	MJ NCV	3.80E+14	CML [5]	2000
Ozone layer depletion	kg CFC-11 eq	2.27E+08	CML [5]	2000
Photochemical oxidation	kg C_2H_4 eq	3.68E+10	CML [5]	2000
Acidification	kg SO_2 eq	2.39E+11	CML [5]	2000
Eutrophication	kg PO_4^{3-} eq	1.58E+11	CML [5]	2000
Particulate matter	kg PM2.5	3.11E+10	ILCD [23]	2000
Water scarcity	m^3 eq	4.23E+11	ILCD [23]	2000
Land use	kg C deficit	3.19E+16	ILCD [23]	2000

Figure 16 shows the normalisation results. The resulting numbers on the Y axis represent the fraction of global impact which occur as a result of 1 MWh of electricity from the two scenarios analysed. The numbers are very small because the use of 1 MWh of electricity is small compared to the entire global economy. However, it is the relative contribution under each impact category which is important.

Overall, the normalisation results reflect the relatively high contribution of fossil electricity to a range of impact categories including climate change, fossil fuel depletion and photochemical oxidation potential. It also shows that in relative terms, power generation from both scenarios contributes very little to land use and ozone depletion. This tells us that when comparing the two scenarios, climate change, fossil fuel depletion, and photochemical oxidation are the most important impact categories to consider.

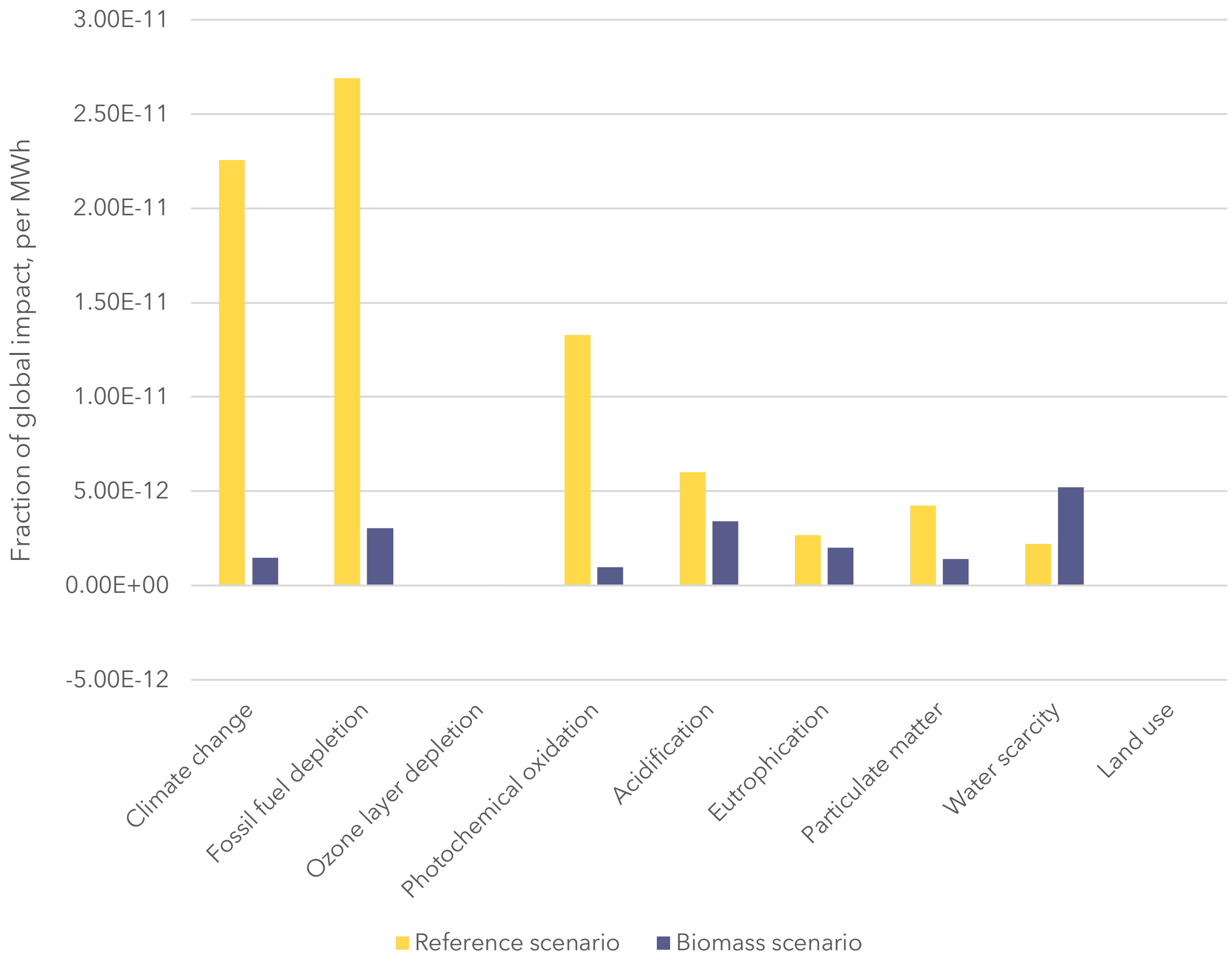

Figure 16 LCA results, normalised

The main results (Section 4) showed that the production of electricity with biomass results in environmental savings in all impact categories except for ozone layer depletion and water scarcity.

The normalisation results presented in Figure 16 show that under the assumptions used in this study, the biomass scenario results in significant environmental savings in the impact categories which hold the largest shares of global impacts (climate change, fossil fuel depletion, and photochemical oxidation). So, while the conversion of Redbank Power Station to a biomass facility may result in detrimental environmental effects in some impact categories, the magnitude of these effects is small in comparison to global impacts and other impact categories.

4.3 Sensitivity analysis

In the sensitivity analysis, the results are tested for robustness by assessing how sensitive they are to variations in key parameters, as well as investigating how impacts can be minimised through mitigation strategies. In this section, the following scenarios are examined:

Mitigation strategies:

- Effect of varying fuel type for chipping and transport
- Effect of reducing transport distance for feedstock

Modelling choices

- Effect of adjusting modelling assumptions for current fate of landfill of DBF
- Effect of altering the choice of marginal electricity supplier in reference scenario

4.3.1 Mitigation strategies

In the main results, it is assumed that the biomass feedstock travels, on average, a distance of 300km from the site of collection to Redbank Power Station, excluding the energy crops, which are assumed to be located 50km from the power station. An additional 50km is assumed for the pelletisation of agricultural residues. In this section, the results are assessed with a reduced average transport distance of 150km.

In the main results, the impacts from diesel consumption for transport and shipping are prevalent across several impact categories. In this section, a switch to biodiesel is modelled for both chipping and transport. The results for both mitigation strategies are shown in Table 16 below.

As expected, a smaller transport radius results in lower impacts in all impact categories. In terms of climate change, halving transport distance allows to reduce impacts of the biomass scenario by 12% (Figure 17). A similar trend is observed on all other indicators. Introducing biofuels for chipping and transport has a significant effect on climate change impacts, resulting in a 67% reduction. Combining these two strategies results in a 72% reduction in climate change impacts. When biofuels are introduced, the impacts of the biomass scenario reduces for climate change, fossil fuel depletion, and ozone layer depletion. However, an increase in impacts is seen in the remaining indicators. This affects the preferred scenario for eutrophication and land use, meaning that for these two categories, the use of biofuels means that the coal reference scenario performs better. However, it should be noted that the normalisation results (Section 4.2) showed that total land use impacts are insignificant on a global scale. Eutrophication was also not identified as a key impact category.

Table 16 Sensitivity analysis, transport distance and use of biofuels, per MWh

Impact category	Unit	Reference scenario	Biomass scenario (baseline) *(300km transport radius, diesel)*	Alternative biomass scenario *(150km transport radius)*	Alternative biomass scenario *(Biofuels for chipping and transport)*	Alternative biomass scenario *(150km transport radius & biofuels for chipping and transport)*
Climate change	kg CO2 eq	944	61.8	54.1	20.6	17.2
Fossil fuel depletion	MJ NCV	10,224	1,162	1,042	656	586
Ozone layer depletion	mg CFC-11 eq	1.6	8.8	7.9	4.8	4.2
Photochemical oxidation	kg C_2H_4 eq	0.489	0.036	0.034	0.050	0.047
Acidification	kg SO_2 eq	1.43	0.81	0.79	1.10	1.03
Eutrophication	kg PO_4^{3-} eq	0.42	0.31	0.31	0.46	0.44
Particulate matter	kg PM2.5	0.132	0.044	0.042	0.062	0.058
Water scarcity	m^3 eq	0.93	2.2	2.2	2.3	2.3
Land use	kg C deficit	159.0	-52.9	-74.2	2250.4	1975.4

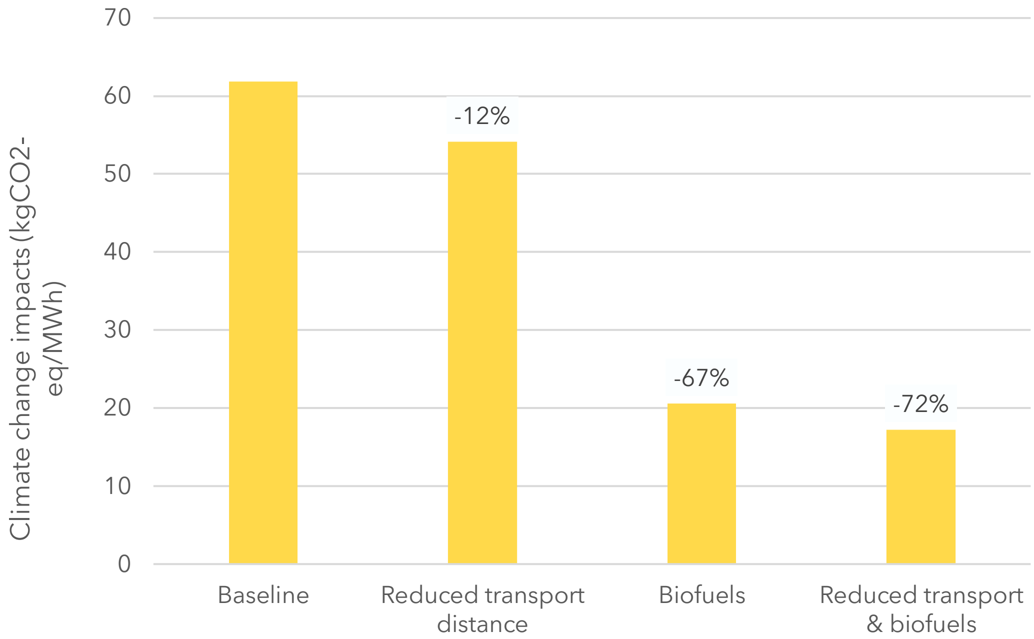

Figure 17 Sensitivity analysis, transport and biofuels in biomass scenario, climate change

4.3.2 Modelling choices

Choice of marginal supplier of electricity

In the main results, electricity from black coal was chosen as the marginal electricity supply, based on the assumption that as electricity from Redbank Power Station is generated, electricity from black coal will be displaced. The marginal electricity supplier can be difficult to determine and depends on individual markets and investments. An alternative marginal electricity supplier may be electricity from natural gas. Only the reference scenario is affected by the choice of marginal electricity supplier.

The reference scenario results with both the coal and gas marginal electricity suppliers are shown in Table 17, along with the relative difference to the biomass scenario.

Impacts of the reference scenario decrease or remain similar in all impact categories when switching to natural gas as the marginal supplier of electricity. In the case of climate change, we observed a decrease of 39%. However, the relative climate change benefits decrease only slightly when considering natural gas as the marginal supplier over black coal. This shows that even when electricity generated at Redbank Power Station displaces a lower-emitting electricity supplier such as natural gas, there is still a significant reduction in climate change impacts overall.

Since the reference scenario eutrophication impacts of natural gas are lower than in the biomass scenario, the relative impact of the biomass scenario shows an increase in eutrophication. This is in contrast to the main results, which showed a relative decrease in eutrophication impacts. Similarly, the relative acidification showed a benefit when displacing coal, but a detrimental effect when displacing natural gas. The normalisation results (Section 4.2) showed that neither eutrophication or acidification were identified as key impact categories.

Table 17 Sensitivity analysis, marginal electricity supplier, per MWh

Impact category	Unit	Reference scenario *(coal marginal electricity supply)*	Biomass scenario	Difference between scenarios (%)	Alternative reference scenario *(natural gas marginal electricity supply)*	Difference between scenarios (%)
Climate change	kg CO2 eq	944	61.8	-93%	575	-89%
Fossil fuel depletion	MJ NCV	10,224	1162	-89%	10,152	-89%
Ozone layer depletion	mg CFC-11 eq	1.6	8.8	458%	0.32	2677%
Photochemical oxidation	kg C_2H_4 eq	0.5	0.04	-93%	0.5	-93%
Acidification	kg SO_2 eq	1.4	0.8	-43%	0.42	95%
Eutrophication	kg PO_4^{3-} eq	0.4	0.3	-26%	0.09	234%
Particulate matter	kg PM2.5	0.1	0.04	-67%	0.1	-62%
Water scarcity	m^3 eq	0.9	2.2	137%	0.10	2141%
Land use	kg C deficit	159	-52.9	-133%	28.9	-283%

Landfill assumptions

In the reference scenario of the main results, the domestic biomass fuel to landfill is modelled using a standard model for wood waste in landfill obtained from AusLCI. The parameters of this model are based on the National Inventory Report, which includes values for Degradable Organic Content (DOC) and fraction of DOC which dissimilates (DOCf). An alternative model exists for the breakdown of wood in landfill, which considers a higher amount of carbon storage, i.e., less breakdown of carbon in the wood into greenhouse gases and hence lower DOCf. A sensitivity analysis is conducted using the alternative unit process 'waste treatment, wood and wood-waste, low degradation assumption, at landfill/AU U' for the treatment of DBF in landfill in the reference scenario. As with the main results, this process is modified with carbon content and moisture content consistent with feedstock modelling in this study. The results (Figure 18) show that the impacts of the reference scenario decrease slightly under the assumption of low degradation of wood in landfill, as the carbon storage is increased. However, this does not significantly affect the comparison of the reference scenario to the biomass scenario.

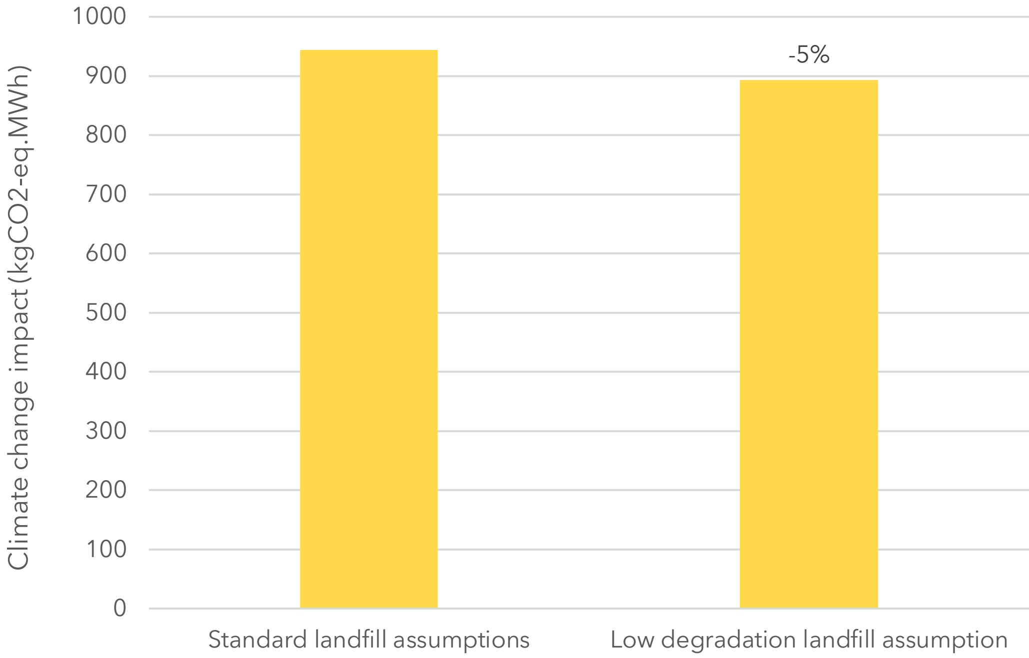

Figure 18 Sensitivity analysis, landfill assumptions for reference scenario, climate change

5 Conclusion and Recommendations

In this study, two scenarios have been compared: a reference scenario representing a 'business-as-usual' approach; and a biomass scenario, in which Redbank Power Station is converted and produces electricity for the NSW grid from 100% biomass feedstock. The difference between the two scenarios represents the impacts of a shift from the reference scenario to the biomass scenario.

The results show that this shift results in environmental savings to climate change, fossil fuel depletion, photochemical oxidation, acidification, eutrophication, particulate matter, and land use impacts. Ozone layer depletion and water scarcity are the only impact category where the impacts of a shift are increased. However, the normalisation results indicate that this increase is small relative to other impact categories' contribution to global impacts.

In quantitative terms, the production of electricity from biomass at Redbank Power Station will save 882kgCO_2-eq for every MWh generated, a reduction of 93% from the reference scenario. This equates to an annual saving of 862 ktCO_2-eq. The majority of this saving is due to the absorption of carbon during the growth phase of feedstocks - the products of which ultimately form the wastes which enter the combustion process. The physical emissions of carbon dioxide from the power station are mostly negated by this earlier absorption.

The contribution analysis showed that for the reference scenario, the majority of impacts to climate change, acidification and eutrophication are associated with the emissions occurring during coal combustion. For fossil fuel depletion and ozone layer depletion, the majority of impacts can be traced back to the extraction of coal. For photochemical oxidation and particulate matter, the impacts are mostly associated with current management of the potential biomass feedstock streams, particularly the open burning of agricultural and invasive species control residues. For water scarcity, the water use at the power station contributes the highest impacts.

For the biomass scenario, the contribution analysis showed that chipping and transport of the biomass feedstock account for the majority of climate change, fossil fuel depletion and ozone layer depletion impacts. Photochemical oxidation, acidification, particulate matter and eutrophication are primarily caused by the combustion of residues at the power plant. For water scarcity, the water use at the power station contributes the highest impacts, and for land use, the impacts are associated with upstream land use change associated with the fuel for transport. However, these are negated by the soil carbon benefits associated with the growth of energy crops.

The sensitivity analysis examined the robustness of the results by testing modelling choices (landfill assumptions, choice of marginal electricity supplier) and potential mitigation strategies (reduced transport distance and use of biofuels in chipping and transport). It was found that decreasing the transport radius from 300km to 150km reduces the impacts of the biomass scenario by 12%. The use of biofuels can reduce the impacts of the biomass scenario by 67% and the use of both biofuels and reducing transport distances can result in a 72% reduction in climate change impacts. This increases the relative benefits of the biomass scenario over the reference scenario from 93% to 98% for climate change.

The sensitivity analysis of the choice of marginal supplier showed that even when the biomass scenario is compared to a lower-emitting electricity source such as natural gas, considerable climate change savings are still made (89%). Therefore, modifying the assumption of the marginal supplier does not affect the direction of the results, and solidifies the notion that the proposed project has climate change benefits. Similarly, a more conservative assumption for degradation of wood in landfill was also shown to have little effect on the overall results.

Overall, this study has shown that the conversion of Redbank Power Station to a biomass facility will result in significant savings in climate change impacts. Savings are also seen in multiple other impact categories, with the exception of ozone layer depletion and water scarcity. Ozone layer depletion is considered irrelevant since the emissions contributions are small and come from deep within the transport supply chain. Additionally, the water consumption was modelled conservatively, without considering potential use of stormwater.

In order to maximise the environmental benefits of the production or electricity with biomass feedstock at Redbank Power Station, steps could be made to minimise transport distances and implement a switch to biodiesel for chipping and transport.

5.1.1 Limitations and opportunities for improvement

This study, like any life cycle assessment, comports limitations. It is worth pointing out that a life cycle assessment is a model, and as such it relies on assumptions and approximations. The ability to use these assumptions and approximations is what allows us to complete a life cycle assessment, and we rely on their robustness to provide the closest representation possible of the production system under study.

The limitations of this assessment are:

- Our knowledge of the future power generation mix. As shown in the sensitivity analysis, the benefits of producing power at Redbank vary depending on the type of electricity being displaced. If coal were to be removed from the grid mix or the power generated from Redbank were to displaced gas fired generation, the results would still be highly beneficial, but would not be as dramatic. It is also possible that the marginal electricity supplier will eventually be a renewable source in the future.
- Assumptions around current fates of the different feedstock types. Verdant Earth are targeting feedstocks with no higher order uses. However, the current fate of the biomass feedstock streams do have an effect on the results and could be reviewed once operation has begun and these are better understood.
- Assumptions around removal of agricultural residues from productive land. Further study could consider the implications on soil carbon.
- Assumptions surrounding transport distances. Average transport distance of biomass feedstock is assumed to be 300km. This assumption could be reviewed once operation has begun and the feedstock logistics are better understood.

The uncertainty of the results could also be minimised in the future with the inclusion of measured site-specific data for the combustion of biomass.

6 References

1. Grant, T. and J. Bengtsson, *Life Cycle Assessment (LCA) of Bioenergy Products and Projects*. 2016, ARENA: Canberra.
2. International Organization for Standardization, *International Standard, ISO/DIS14040, Environmental Management Standard- Life Cycle Assessment, Principles and Framework*. 2006: Switzerland.
3. Department of Environment and Energy, *National Inventory Report 2014 (revised) Volume 1*. 2016: Canberra.
4. IPCC, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C.U. Press, Editor. 2013: Cambridge, United Kingdom and New York, NY, USA. p. 1535.
5. Institute of Environmental Sciences (CML), *CML-IA Characterisation Factors Version 4.8*, U.o. Leiden, Editor. 2016: Leiden, NL.
6. Guinée, J.B., et al., *Handbook on life cycle assessment : operational guide to the ISO standards*. 1 ed. Eco-efficiency in industry and science. Vol. 7. 2002, Dordrecht, Netherlands: Springer Netherlands. 692.
7. Heijungs, R., et al., *Environmental Life Cycle Assessment of Products. Guide and Background*. 1992, CML: Leiden, The Netherlands.
8. Humbert, S., et al., *Intake Fraction for Particulate Matter: Recommendations for Life Cycle Impact Assessment.* Environmental Science & Technology, 2011. **45**(11): p. 4808-4816.
9. Pfister, S., A. Koehler, and S. Hellweg, *Assessing the environmental impacts of freshwater consumption in LCA.* Environ. Sci. Technol., 2009. **43**(11): p. 4098-4104.
10. European Commission, *Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods. Database and Supporting Information*. 2012, Join Research Centre Institute of Environment and Sustainability: Luxembourg.
11. Tanner, D., *Redbank Power Station – Description of Proposed Modifications for Conversion to Fire Biomass fuels*. 2021, Boiler & Power Plant Services Pty Ltd.
12. Verdant Earth, *Redbank Power Station QA/QC, Supply Chain and Material Handling*. 2021.
13. Sperandio, G., et al., *Environmental Sustainability of Heat Produced by Poplar Short-Rotation Coppice (SRC) Woody Biomass.* Forests, 2021. **12**(7).
14. Röder, M., C. Whittaker, and P. Thornley, *How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues.* Biomass and Bioenergy, 2015. **79**: p. 50-63.
15. Kellaghan, R., *Restart of Redbank Power Station and Use of Biomass (Excluding Native Forestry Residues from Logging) as a Fuel Air Quality Impact Assessment - Version 9*. 2023, EMM Consulting.
16. EMM, *Restart of Redbank Power Station and use of biomass (excluding native forestry residues from logging) as a fuel - Greenhouse Gas Mitigation Plan and Climate Change Adaptation Plan Version 2*. 2023.
17. Department of Environment and Heritage and Water. *National Pollutant Inventory Data for Year 2007/08*. 2009 [cited 2004; Available from: http://www.npi.gov.au/.
18. Rojas-Sandoval, J. and P. Acevedo-Rodriquez, *Eucalyptus camaldulensis (red gum)*. 2019, CABI Digital Library.
19. Ximenes, F., *Potential carbon abatement of growing short-rotation woody crops*. 2023, NSW Department of Primary Industries.
20. Morales, M., et al., *Cradle-to-gate life cycle assessment of Eucalyptus globulus short rotation plantations in Chile.* Journal of Cleaner Production, 2015. **99**: p. 239-249.
21. ALCAS, *Australian Life Cycle Inventory Database (AusLCI) Version 1.42*, A.L.C.A. Society, Editor. 2023: Melbourne.
22. Smart, A. and A. Aspinall, *Water and the electricity generation industry – Implications of use, Waterlines Report Series No.18,*. 2009, National Water Commission: Canberra.
23. European Commission JRC IES, *ILCD handbook - International Reference Life Cycle Data System (ILCD) - ILCD Handbook Recommendations for Life Cycle Impact Assessment in the European context*. 2011, European Commission Joint Research Centre Institute for Environment and Sustainability,: Ispra (VA) Italy.

Appendix A. Details of compliance

The compliance with ARENA requirements is demonstrated below in Table 18. Quantitative assessment of greenhouse gas emissions provided by the climate change indicator are included within the guidelines.

Table 18 Compliance with ARENA guidelines

ARENA Requirement		Compliance/Comment
2.1	**Goal**	
	The LCA shall document the goals of the study including whether it is part of an ARENA funding requirement and what TRL/CRI level the technology has currently reached.	Yes - Goal documented (Section 2.1). No TRL/CRI level provided as this is not being submitted to ARENA for funding.
2.2	**Functional unit & System Boundary**	
	The system boundary shall be based on cradle to grave with the functional unit being the production of fuel and conversion to delivered energy.	Yes. Cradle to grave system boundary is included (Section 2.2.3).
	The functional unit shall focus on the production of bioenergy so that it is comparable to the reference system	Yes. Functional unit is production of electricity from bioenergy and from a fossil-based reference system (Section 2.2.2)
	A cutoff criterion based on mass and energy flows may be used to exclude minor flows from the system boundary; however, the effect of these exclusions should be assessed.	Yes. Cut-off criterion is specified (Section 2.2.3)
	The embodied impacts of capital equipment and infrastructure may be excluded from the LCA without further justification, except for: Production systems estimated to have an economic life of less than 10 years.; Production systems requiring establishment of significant supporting physical infrastructure, such as dedicated roads, rail, pipelines and inter-modal change facilities. For systems fitting either qualifier above, capital equipment and infrastructure shall be included at a scoping level in the LCA.	Yes. New capital equipment and infrastructure are included (Section 2.2.3). Existing capital at Redbank which will be reused as part of this process has been excluded as its sunk environmental impacts expended in production of the earlier power station.
2.3	**Environmental impact**	
	Impact categories for use in the LCA are: • climate change • fossil fuels resource depletion • fossil fuel energy use (net calorific value) • particulate matter formation • eutrophication • consumptive water use • land use	Yes. All indicators has been included (Section 2.2.8).
2.4	**Temporal aspects**	
	The temporal scope of the LCA shall be documented. The timeframe for the LCA should be based on the economic timeframe for the proposed plant and equipment, which can be taken to be between 20 and 30 years The economic timeframe for the proposed plant and equipment should be based on the real, expected service life, rather than based on other criteria such as warranty time periods.	Yes. Temporal aspects are documented (Section 2.2.5)
	The LCA should be undertaken without the effects of time, such as changes outside the project's control, including technology improvements, electricity grid changes, climatic changes, etc.	Yes. No impact of time is included in GHG characterization factors
	The timing of emissions and removals shall be documented in the inventory.	No. As the majority of emissions are ongoing in both system this has not been documented

ARENA Requirement		Compliance/Comment
2.5	**Multi-functionality and allocation**	
	The allocation of impacts between individual products in multifunction processes shall follow the following hierarchy: • subdivision of processes; • allocation based on causal relationships of inputs and emission to output products; • system expansion for joint production, and • allocation based on energy content or economic value.	Yes. System expansion has been used throughout the study for coproduct allocation (Section 2.2.4)
	The effects of alternative approaches to multi-functionality should be demonstrated	No. As costs are difficult to obtain for many of the coproduct economic allocation has not been undertaken and add no value to the study.
	For waste used as a feedstock, the impacts associated with its handling and processing shall be included in the LCA. Furthermore, the alternative fate of that material (landfill, left on field) should be included in the calculation.	Yes. Alternative feedstocks are modelled with alternative fate (Section 2.2.3).
2.6	**Inventory analysis**	
	Generic data may be used for upstream processes and for any processes where site specific data are not available. The use of generic data in this second instance should be documented and justified.	Yes. Generic data from databases has been used from AusLCI (Section 3.2).
	In relation to multi-functionality – generic data that do not follow the same approach to allocation of co-products (for example AusLCI database based on economic allocation) can be used. However, where an allocation method has been used and the allocated product represents a significant contribution greater than five percent (5%) of any indicators used in the LCA, its allocation should be adjusted to be consistent with this method.	Yes. No data have been sourced outside AuslCI
2.7	**Reference system and benchmarking**	
	The results of bioenergy and biofuel studies shall be compared to a reference system, which represents a scenario where the specific bioenergy under study is not produced.	Yes. The bioenergy scenario has been compared to a non-bioenergy reference system (Section 2.2.2).
2.8	**Land Use Change**	
	The carbon dioxide emissions from direct LUC shall be calculated for land use activities in the project based on the IPCC Tier 1 approach.	Yes. Documented (Section 2.2.7).
2.9	**Treatment of fossil, biogenic and atmospheric carbon**	
	All flows of carbon between different carbon pools (atmosphere, fossil, biosphere) shall be included and documented separately in the inventory.	Yes. Documented (Section 2.2.6).
2.10	**Reporting**	
	The LCA must include an ISO 14044 compliant background report.	Yes.
2.11	**Critical review.**	
	An ISO 14044 compliant critical review of the LCA shall be undertaken by qualified person according to the ARENA guidance.	No - review is planned but not yet completed.