lifecycles.

Greenhouse gas and sustainability footprints of emerging biofuels for Queensland

Undertaken by Lifecycles

For Department of Environment and Science

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Important disclaimer

Acknowledgments

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Contents

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Shortened forms

ACRONYM	FULL NAME
ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ABS	Australian Bureau of Statistics
ACCC	Australian Competition and Consumer Commission
AIP	Australian Institute of Petroleum
APSIM	Agricultural Production System Simulator
ARENA	Australian Renewable Energy Agency
AU	Australian
AUD	Australian dollar
AusLCI	Australian National Life Cycle Inventory Database
BMP	Best management practice
BOD	Biological oxygen demand
CAD	Canadian dollar
CARB	California Air Resources Board
CCA	Copper chromium arsenic (treated timber)
CIE	Compression ignition engines
COD	Chemical oxygen demand
CSBP	Chemicals and Fertilisers Division of Wesfarmers
DAP	Diammonium Phosphate
DES	Department of Environment and Science, Queensland Government
DDGS	Dried distiller's grains and solubles
dLUC	Direct land use change
EHP	Department of Environment and Heritage Protection, Queensland Government
EPU	Equivalent passenger units
GAP	Good agricultural practice
GHG	Greenhouse gas
GJ	Gigajoule
iLUC	Indirect land use change
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilowatt hour
LCA	Life cycle assessment
LCI	Life cycle inventory
LUC	Land use change
MJ	Megajoule
ML	Megalitre
MSG	Monosodium glutamate
MSW	Municipal solid waste
MT	Megatonne
NEM	National electricity market
NMVOC	Non-methane volatile organic compounds
NREL	National Renewable Energy Laboratory
PM	Particulate matter
PULP	Premium unleaded petrol
RON	Research oxygen number
RSB	Roundtable for Sustainable Biomaterials

RSPO	Roundtable on Sustainable Palm Oil
RULP	Regular unleaded petrol
SIE	Spark ignition engines
SOM	Soil organic matter
tkm	Tonne.kilometer
UCO	Used cooking oil
USD	US dollar

Glossary

Term	Definition
Allocation	Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems (ISO 14040).
Biogenic carbon	Carbon derived from biomass (ISO/TS 14067).
Break crop effect	The benefits which occur due to the addition of a different crop in cropping rotation, such as the addition of legume and/canola in wheat cropping system
Carbon dioxide equivalent (CO_2 eq., CO_2 e)	Unit for comparing the radiative forcing of a greenhouse gas to that of carbon dioxide (ISO/TS 14067).
Carbon footprint	Sum of greenhouse gas emissions and removals in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change (ISO/TS 14067).
Characterisation factor	Factors derived from a characterisation model that are applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator (ISO 14040).
Direct land use change (dLUC)	Change in human use or management of land within the product system being assessed (ISO/TS 14067).
Eutrophication	The process by which a body of water becomes enriched in dissolved nutrients (as phosphates) that stimulate the growth of aquatic plant life usually resulting in the depletion of dissolved oxygen (Merriam-Webster.com 2016).
Fossil carbon	Carbon that is contained in fossilised material (ISO/TS 14067).
Functional unit	Quantified performance of a product system for use as a reference unit (ISO 14040).
Climate change potential (GWP)	Characterisation factor describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to that of carbon dioxide over a given period of time (ISO/TS 14067).
Glycell™	Commercially available process for conversion of plant components into biomaterials.
Greenhouse gas (GHG)	Natural or anthropogenic gaseous constituent of the atmosphere that absorbs and emits radiation at specific wavelengths within the spectrum of infrared radiation emitted by the earth's surface, the atmosphere, and clouds (ISO 13065).
Impact category	Class representing environmental issues of concern to which life cycle inventory analysis results may be assigned (ISO 14044).
Indirect land use change (iLUC)	Change in the use or management of land that is a consequence of direct land use change, but which occurs outside the product system being assessed (ISO/TS 14067).
Land use change (LUC)	A change in human use or management of land.
Life cycle assessment (LCA)	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 14040).
Life cycle impact assessment (LCIA)	Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO 14040).
Life cycle inventory (LCI)	Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle (ISO 14040).
Multi-functionality and co-products	Refers to a process that creates multiple products or functions. Products often thought of as waste can also be thought of co-products if they provide some function or value.
System boundary	Set of criteria specifying which unit processes are part of a product system (ISO 14040).
System expansion	Recommended ISO 14040 method for avoiding allocation. This is done by 'expanding the product system to include the additional functions related to the

	co-products’ (ISO 14044), note also that Annex H in 13065 gives guidance on application of system expansion.
Tonne.kilometer	Units used to describe freight task measured by the multiple of the net tonnes moved and the net distance travelled (i.e. not including return distance)

1 Executive summary

1.1 Method

This report delivers the results of a life cycle assessment identifying the greenhouse gas benefits and broader sustainability profiles for emerging biofuels from feedstocks and technologies that, have not yet been used for commercial production of biofuels in Queensland. The sustainability credentials of biofuels have become more important with the implementation of the Queensland biofuel mandate.

The mandate sets minimum sales volumes of biobased petrol and biobased diesel for liable fuel sellers. The Liquid Fuel Supply Regulation 2016 prescribes sustainability criteria that must be satisfied for the biofuel to be eligible to count towards a liable fuel sellers' obligations under the mandate. All biofuels, regardless of the type and feedstock source, must deliver greenhouse gas emissions savings of at least 20% (before blending) when compared to regular petrol or diesel. A life cycle assessment is one way of demonstrating the greenhouse gas requirement can be met. This requirement is one of the principal drivers for undertaking this report.

The report also provides insights into the potential strengths and weaknesses of different emerging feedstocks and technologies across a variety of environmental indicators. The results of the LCA could inform proponents on the types of activities or process change that could deliver further improvements the performance of proposed biofuels.

The study examined 20 fuels scenarios, including seven sources of ethanol, two sources of biodiesel and 11 sources of renewable diesel. The selection of fuels and feedstocks was based on potential production scenarios in Queensland.

In LCA, the basis for comparing alternatives is referred to as a functional unit. For this study, the functional unit is a replacement of one litre of fossil fuel with the equivalent biofuel in the Queensland market.

Greenhouse gas emissions are a focus of the Regulation and these are measured using the impact category climate change, which is calculated by weighting each of the contributing gases using global warming potentials. For example carbon dioxide is 1 and methane is 25 under the current reporting guidance for Australian GHG accounting. (Commonwealth of Australia 2017) This study also includes other relevant environmental indicators, including fossil energy, eutrophication, particulate matter, land use and water scarcity.

1.2 Results

Table 1 shows the percentage emission reduction for replacing fossil fuel with equivalent biofuel. A positive percentage represents biofuel having a lower impact than fossil fuel. The colour map shows green cells representing where biofuels have lower impacts than fossil fuels and red cells where biofuels have greater impacts than the comparable fossil fuel.

Table 1 shows that in 18 of the 20 scenarios, the net climate change result for replacing fossil fuel with equivalent biofuel is a reduction in impacts. In two scenarios, the impacts of biofuel replacing fossil fuel is an increase in climate change impacts, which is due to the impacts of removing high carbon material from landfill to make these biofuels (tyres and CCA wood waste). Both of these waste streams are problem wastes for landfill: tyres are structurally problematic for landfills and CCA wood waste has toxic materials that could potentially leach from the material. If the carbon storage in landfill is not included in the scenario, both scenarios are positive for the biofuel.

One of the drivers of the biofuel industry is to replace demand on fossil so it not surprising that all scenarios except 1, have lower fossil energy depletion. The anomaly is renewable diesel from MSW using gasification and Fischer–Tropsch. There is significant electricity use in this process as well as a loss of electricity generation at landfill from biogenic methane, which is the alternative assumed use of MSW.

For eutrophication the scenarios that involve cropping have much higher impacts than fossil fuel. This is due to agricultural emissions and the relatively low impacts of fossil fuel on this indicator.

Particulate matter impacts are from two main sources: combustion emissions from biomass and fossil fuel combustion, and ammonia emissions from agriculture.

The land use impacts are dominated by the cropping activities, Carinata and tobacco. Sugarcane and agave have less land use impact as they are perennial crops and have higher productivity per hectare. The other biofuel scenarios have little effect on land use.

Finally, for water scarcity, irrigated sugarcane has the most significant impact because it is a fully irrigated crop. For all other scenarios water use is small since it is used for biofuel production processes.

Table 1 Percentage reduction in impact of biofuel replacing fossil fuel.

	Climate change	Fossil energy depletion	Eutrophication	Particulate matter	Land use	Water scarcity
	%	%	%	%	%	%
E.agave ferm.	89	99	-75	-9	87	-285
E.sugarcane integ. bioref. ferm.	42	76	-1384	-48	79	-19979
E.agave & moll. ferm.	80	91	-259	-9	-15	-279
E.cane trash Glycell	72	76	-252	5	17	-895
E.cane trash conc. acid	84	89	46	57	92	-90
E.wood waste conc. acid	73	82	14	50	86	-100
E.cotton GT dilute acid	102	108	7	-30	59	-269
BD.Carinata transest.	52	67	-255	-36	-87	-227
BD.tobacco transest.	48	60	-325	-103	-5	-5055
RD.forestry resid. pyrolysis	76	138	0	82	161	118
RD.cane trash pyrolysis	82	143	18	88	165	126
RD.wheat straw pyrolysis	83	141	25	90	163	120
RD.prickly acacia pyrolysis	80	142	3	85	164	125
RD.tyres destruc. distill.	18	255	187	233	261	390
RD.wood waste cata. depoly.	-18	38	11	47	96	18
RD.green waste cata. depoly.	35	34	-76	5	81	-82
RD.forestry res. cata. depoly	39	40	-64	33	88	-9
RD.food waste cata. depoly	35	34	-76	5	81	-82
RD.tyres. cata. depoly.	-29	64	-7	110	103	161
RD.MSW gasification FTP	593	-28	-401	-18	135	-478

Note: The table colour gradations are from green (better for biofuel) through to red (better for fossil fuel) and orange are to close to call either way. For global warming the tipping point is set as 20% benefit while all other indicators the tipping point is set at zero.

1.3 Conclusions

The aim of this report was to determine the greenhouse gas emission profiles of the emerging biofuels for Queensland, represented by the climate change indicator. Of the 20 scenarios assessed, 17 of them had greater than 20% climate change benefit compared to conventional fossil fuel. The three fuels that do not meet the 20% requirement have substantial climate change impact contributions from removing carbon stored in landfill. This is because the study methodology counts the undegraded fraction of carbon embodied in those waste materials as a long-term store of carbon, when they are placed in landfill. If we were to follow Australia's national greenhouse accounts approach, where these waste materials are not counted as a carbon store, then the three scenarios would meet the 20% threshold.

Because most of the scenarios were based on non-commercial technologies, a robustness check was undertaken to test how the results would shift if the scenario parameters were pushed to a highly conservative (in favour of fossil fuel) position. All 17 scenarios that initially passed the 20% threshold still had more than 20% savings after applying the robustness check.

There are some generalisations that can be drawn from the 20 scenarios in relation to climate change impacts.

- Biofuels which address waste management challenges with highly degradable carbon, such as MSW, food & green waste can have dramatic benefits, especially if the biofuel helps to keep these materials from going to landfill.
- Biofuels based on highly stable carbon wastes such as tyres and wood waste need to compete with alternative treatment methods which can include landfill but also other fuel using processes such as cement kilns. In these scenarios the local supply situation will be critical to determine the alternative fate of these materials and therefore the overall environmental performance.
- Biofuels based on accessing woody wastes that are otherwise breaking down in the environment, such as forestry and agriculture residues and prickly acacia, have performed very well with the only possible concern being the effects of these removals on soil carbon.
- Biofuels based on high biomass yields that combine to produce liquid fuels and electricity perform well, however they do increase indirect land use pressure, and for some, overall water demand.
- Biofuels based on vegetable oils have the benefits of low processing impacts and valuable protein co-products. There is also benefits of using these crops between other cereal crops for beneficial break crop effects.

Other environmental indicators provide insights to the trade-offs required to address climate change impacts. Unsurprisingly, growing crops has impacts on land use indicators, and irrigated crops impact water scarcity. Sugarcane production has potential impacts on eutrophication, which are already well understood in the sugar industry and are reduced through best practice management programs such as Smartcane Best Management Practice Program (BMP). Particulate matter impacts are mostly higher from fossil fuel production; however, where biomass combustion is included in the biofuel system there is potential for significant impacts, which will ultimately be a function of the quality of the emission control technology.

Care needs to be taken in interpreting the results, with consideration of the following parameters:

- the level of energy and carbon product exports from biomass systems
- ability to extract biomass without detrimental impacts to underlying soil carbon
- in the case of waste inputs, accessing the most likely alternative fate of the waste products that should be used as the baseline for comparison.

The transport of feedstocks has a low impact on the overall biofuel production footprint. It is likely that the economic cost of transport will be the limiting factor to aggregating material before the environmental impacts become a dominant factor.

2 Introduction

On 1 January 2017, Queensland's biofuel mandate commenced. The *Liquid Fuel Supply Act 1984* requires the fuel industry to meet targets for the sale of sustainable biobased fuels.

The biobased petrol mandate requires that three percent of the total volume of regular unleaded petrol sales and ethanol blended fuel sales by liable retailers must be sustainable biobased petrol (i.e. ethanol). For example, if three out of every 10 litres of regular petrol sold by a petrol station were E10, which contains 10% ethanol, that petrol station would have met the mandate. Eighteen months after commencement, from 1 July 2018, the ethanol mandate will increase to 4%. The biobased diesel mandate requires 0.5% of all diesel fuel sold to be sustainable biobased diesel.

To be counted towards a fuel seller's obligations under the biofuels mandate, biobased petrol and biobased diesel must meet the sustainability criteria prescribed by the Liquid Fuel Supply Regulation 2016.

The Liquid Fuel Supply Regulation 2016 provides the benchmarks for environmental performance that must be met for a biofuel to be considered sustainable and therefore eligible to be counted towards Queensland's biobased petrol and biobased diesel mandates.

The sustainability criteria are intended to mitigate environmental impacts from the expected increase in demand for biofuels as a result of Queensland's biofuel mandate. The sustainability criteria include:

- a greenhouse gas (GHG) improvement of 20% compared to regular petrol or diesel; and
- certification under a relevant environmental sustainability standard, which varies depending on the feedstock used to produce the biofuel.

In 2016, the Department of Environment and Heritage Protection (now Department of Environment and Science) commissioned Life Cycle Strategies to undertake a life cycle assessment (LCA) of existing and potential biofuels (Grant, Bontinck et al. 2016), in part to inform policy and determine which would meet the GHG requirements. The 2016 study covered ethanol produced from molasses, grain sorghum, wheat and starch waste, biodiesel produced from tallow, used cooking oil and canola feedstocks.

This report presents the results of a separate study that analyses a range of emerging feedstocks for biofuels that to date have not been used for commercial biofuel production in Queensland. This analysis considers crops /feedstocks such as agave, sweet sorghum, tobacco and Carinata, and waste products such as used tyres, sugarcane biomass, cotton gin trash and wood waste. It also includes forest timber grown for biomass, prickly acacia and macro algae production.

The study has been undertaken following the ISO 14040 and ISO 14044 guidelines and in line with the draft requirements for biofuels and bioenergy assessments established by the Australian Renewable Energy Agency (ARENA). The study has also undertaken a biofuels greenhouse gas calculation based on the Roundtable for Sustainable Biomaterials Standard? (Roundtable on Sustainable Biofuels 2008).

2.1 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. LCA aims to include all important environmental impacts for the product system being studied. In doing so, LCA seeks to avoid shifting impacts from one life cycle stage to another or from one environmental impact to another.

The Liquid Fuel Supply Regulation 2016 requires LCAs to be undertaken using the framework, principles and specific requirements defined in both the international standards ISO 14040:2006 and ISO14044:2006 (International Organization for Standardization 2006). The general structure of the LCA framework is shown in Figure 1. Each stage of the LCA interacts with other stages.

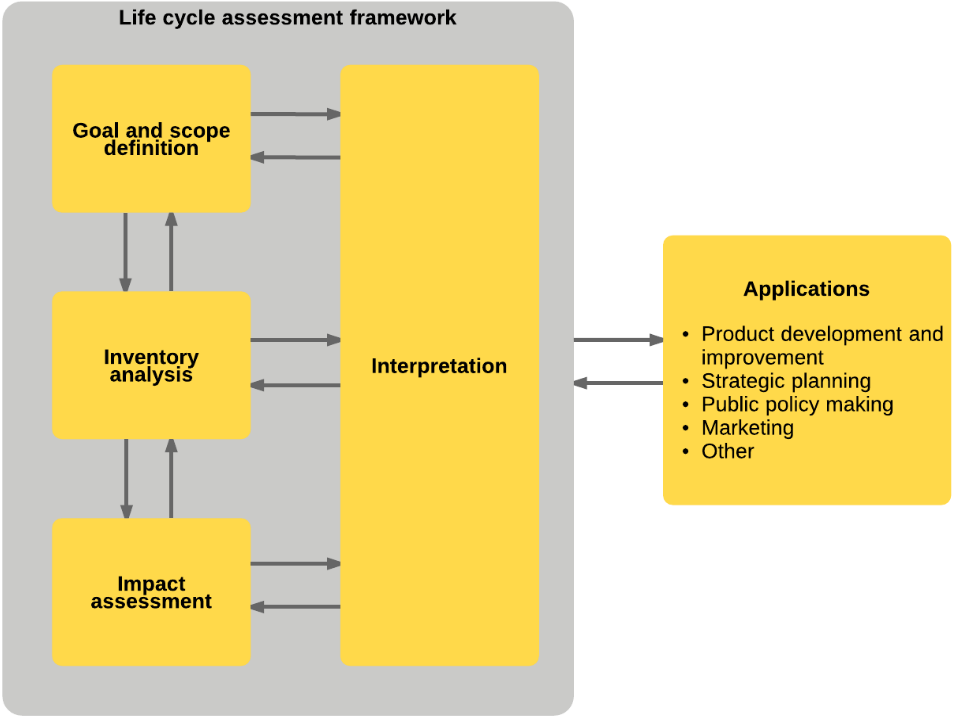

Figure 1 Framework for LCA from ISO 14040.

The first stage in the LCA framework (goal and scope definition) describes the reasons for the LCA, the scenarios, boundaries and indicators 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.

3 Goal

3.1 Reason for the study

The study is being undertaken to quantify the environmental impacts and benefits of potential biofuels that may play a role in fulfilling the biofuels mandate in Queensland.

The environmental impacts studied are limited to those that have the greatest effect on fossil and biofuel production and utilisation, and those of most relevance to government policy. These include greenhouse gas emissions represented using climate change, indicator fossil fuel depletion, impacts of phosphorus and nitrogen on eutrophication (excessive nutrient run-off), particulate matter, land use and water use.

The study calculates environmental impacts in two ways, to answer two different questions. The first is ‘What is the impact of introducing the biofuel feedstock?’, accounting for substitution effects of using or creating co-products and wastes. The second is, ‘What is the GHG emission attributable to the fuel once it is in production?’, according to the methods outlined in the Roundtable for Sustainable Biomaterials method.

3.2 Audience

The primary audience for the study is the Queensland Government and the Queensland biofuels industry. The report may also be a valuable resource for the transport sector. As the fuels analysed in the study cover a range of Australian producers, the audience may also include other government agencies and stakeholders in Australia.

4 Scope

4.1 Functional unit

The international standard on LCA describes the functional unit as defining what is being studied, and states that all analysis should be relative to the functional unit. The definition of the functional unit needs to clearly articulate functionality or service that is under investigation. In this LCA, the function was the supply of high-density liquid fuels suitable for use in the current vehicle fleet in Queensland. The role of liquid fuels is changing. In the Clean Energy Future and Government Policy Scenarios report prepared by CSIRO (Reedman and Graham 2011), biofuels were expected to be an increasing and significant part of the transport energy future, especially during the transition to electric alternatives. Liquid fuels are required for compression ignition engines (CIE), which typically use diesel fuels, and spark ignition engines (SIE), which use gasoline fuels.

The functional unit defines the common basis for comparison of alternative options being assessed. The central theme of this LCA is the replacement of conventional fuels with biofuel, the functional unit of this study is one litre of conventional fuel replacement in Queensland.

Because fuel use needs to be accounted for as actual vehicle emissions, using the most common blends of biofuel, the distance required to offset one litre of biofuel will vary by fuel type and blend.

The reference flow in an LCA is the amount of each system required to deliver the functional unit. The reference flows for replacing one litre of conventional fuels with biofuel are shown in Table 1. Using a 10% blend by volume (E10) in a petrol engine, in a standard vehicle, the car needs to travel 184 km to replace one litre of regular unleaded petrol (RULP) with ethanol. Using a 5% blend by volume (B5) in a diesel engine, in a standard vehicle, the car needs to travel 365 km to replace one litre of diesel with biodiesel (See Figure 2).

For the fuels that are produced from bio-crudes and used in diesel vehicles, the displacement of one litre of conventional fuel will be achieved through the use of one litre of fuel produced from renewable feedstock.

For transparency, the results of conventional fuels and biofuels will be calculated per km of travel and per GJ of fuel use.

Table 2 Reference flows for different fuel blends.

SCENARIO	REFERENCE FLOW
RULP replaced by E10 use	Operation of passenger vehicle with petrol (spark ignition) engine travelling 184 km in Queensland
Diesel replaced by B5 use	Operation of passenger vehicle with diesel (compression ignition) engine travelling 365 km in Queensland
Diesel from crude oil refining replaced by diesel from renewable feedstock	Operation of passenger vehicle with diesel (compression ignition) engine travelling 16.4 km in Queensland

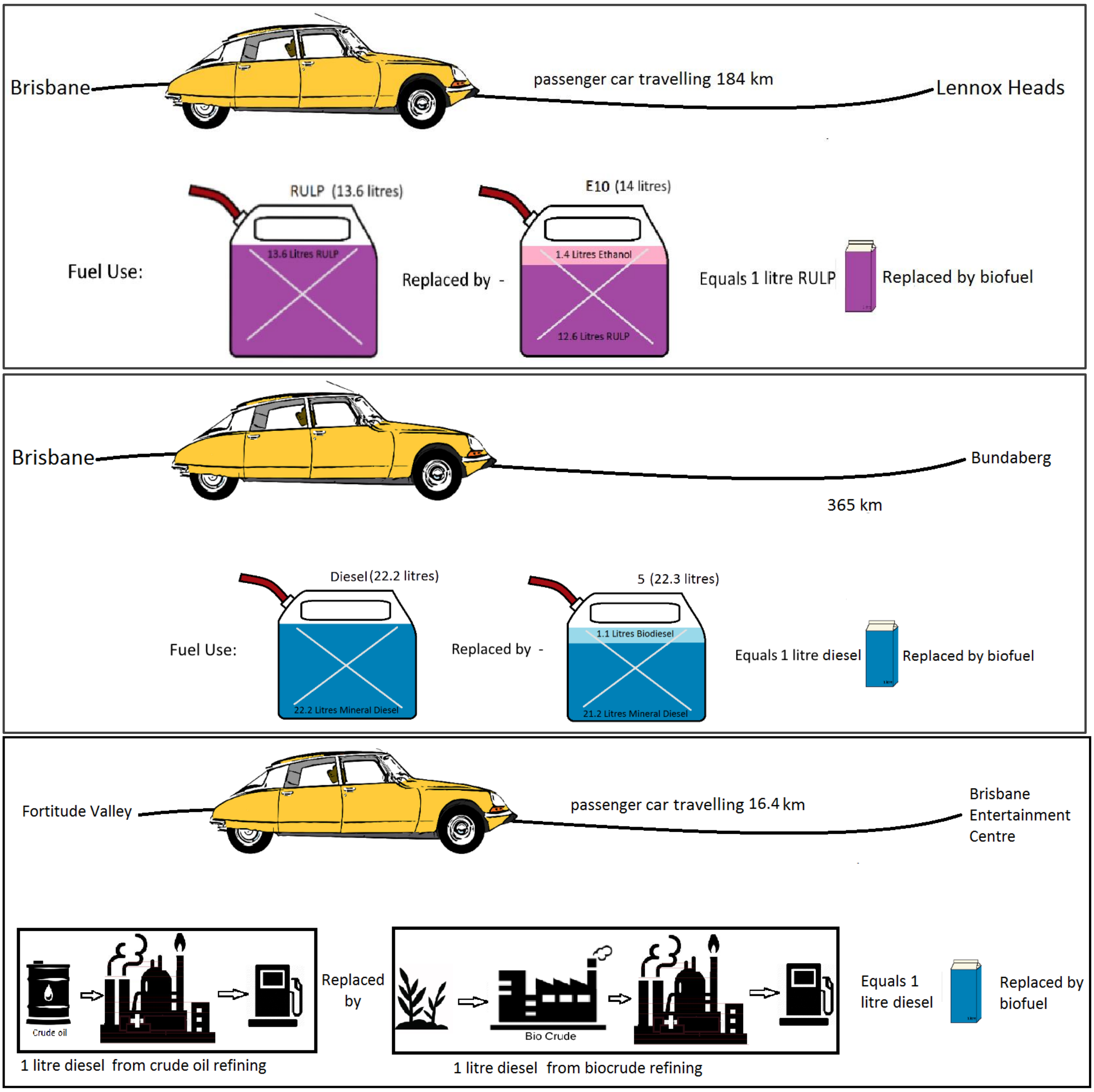

Figure 2 Reference flows for replacing one litre of conventional fuel using E10, B5 and 100% diesel.

The results are shown as the impact of replacing one litre of fossil fuel with equivalent biofuel. This was done to provide the maximum insight to the differences between fuels. In Appendix D, results are shown per km of travel, and per GJ of fuel use.

4.2 Fuel scenarios included

The fuel production scenarios were selected based on potential technology (listed in Table 2). They include seven ethanol scenarios (i.e. ethanol produced from different feedstocks), two biodiesel scenarios and 11 renewable diesel scenarios.

Table 3 List of current fuels to be assessed.

SCENARIO TYPE	SCENARIO NAME	FUEL	DESCRIPTION
Ethanol	E.agave via ferm.	Ethanol from agave	This pathway is for production of ethanol from agave. The agave is grown predominately on land not suitable for cane farming.
Ethanol	E-integrated sugar cane bioref.	Ethanol from purpose-grown sugarcane	This process involves using existing sugarcane production in a dedicated biorefinery with 100% of sugar juice used for fermentation to ethanol and the bagasse used for production of electricity.
Ethanol	E-molasses & agave via ferm.	Ethanol from molasses and agave, used as alternative feedstock six months at a time	This pathway combines feedstocks from agave and sugar production to remove the seasonality of sugarcane harvesting and utilisation. The agave is grown predominately on land not suitable for cane farming. The cane is from current sugarcane production in North Queensland.
Ethanol	E.cane trash glycell	Ethanol production from cane trash using Glycell process	This scenario involves cane trash and crude glycerine being used as a feedstock to the Glycell process, which separates the three biomass fractions – cellulose, hemicellulose and lignin – for beneficial use. Here the hemicellulose is assumed to be the input for fermentation to ethanol.
Ethanol	E.cane trash conc acid.	Ethanol production from cane trash using concentrated acid hydrolysis	This scenario involves cane trash being processed through concentrated acid hydrolysis to produce sugars for fermentation to ethanol, and lignin and other biomass for energy production.
Ethanol	E.forestry res. conc. acid.	Ethanol production from forestry residues using concentrated acid hydrolysis	This scenario involves processing forestry residue through concentrated acid hydrolysis to produce sugars for fermentation to ethanol, and lignin and other biomass for energy production.
Ethanol	E.cotton GT, dilute acid.	Ethanol from dilute acid hydrolysis and fermentation of cotton gin trash	Cotton gin trash (CGT), a waste product of cotton ginning, is treated with dilute acid and enzymes to convert cellulose components to fermentable sugars, which are then converted to ethanol.

SCENARIO TYPE	SCENARIO NAME	FUEL	DESCRIPTION
Biodiesel	BD.Carinata transest.	Biodiesel produced from Carinata grown in Australia	Based on Carinata grown in Queensland to produce oilseed, which is pressed to extract the oil and processed using a conventional transesterification process.
Biodiesel	BD.tobacco transest.	Biodiesel produced from tobacco grown in Australia	Based on a nicotine-free variety of tobacco grown in Queensland that produces oil-rich seeds, which are pressed to extract the oil and processed using a conventional transesterification process.
Renewable Diesel	RD.forestry res. pyrolysis	Wood waste is collected and processed via pyrolysis to produce bio-crude, which is refined to a renewable diesel	Based on the process proposed at Northern Oil Refinery where different feedstocks are pyrolysed to produce a bio-oil, which is then put through a distillation unit to fractionate the crude, hydrotreated and finally purified into a mix of feedstocks.
Renewable Diesel	RD.cane trash pyrolysis	Cane trash is pyrolysed to produce a bio-oil, which is refined to a renewable diesel	
Renewable Diesel	RD.wheat straw pyrolysis	Agricultural residues, such as straw, are pyrolysed to produce a bio-oil, which is refined to a renewable diesel	
Renewable Diesel	RD.prickly acacia pyrolysis	Agricultural residues, such as straw, are pyrolysed to produce a bio-oil, which is refined to a renewable diesel	
Renewable Diesel	RD.tyres destruc. distill	Tyres are used to make a bio-oil from destructive distillation, which is then refined to renewable diesel	This scenario is based on the Green Distillation Technologies approach, which processes tyres using a patented process of destructive distillation. Steel, dry carbon and a bio-oil are recovered, which are assumed to be refined by the Northern Oil Refinery in Gladstone.

Scenario Type	Scenario name	Fuel	Description
Renewable Diesel	RD.CCA wood waste cata depoly	Renewable diesel from wood waste, including CCA (copper chrome arsenic) timber, using catalytic depolymerisation	Catalytic depolymerisation breaks down organic materials including plastics and lignocellulosic material. The technology is flexible in terms of feedstock and is able to operate at small scales.
Renewable Diesel	RD.green waste cata depoly	Renewable diesel from green waste using catalytic depolymerisation	
Renewable Diesel	RD.forestry res. cata depoly	Renewable diesel from forest residues using catalytic depolymerisation	
Renewable Diesel	RD.food waste cata depoly	Renewable diesel from diverted food waste using catalytic depolymerisation	
Renewable Diesel	RD.tyres. cata depoly	Renewable diesel from tyres using catalytic depolymerisation	
Renewable Diesel	RD.MSW. Gasific. FT	Renewable diesel from municipal solid waste using gasification and Fischer–Tropsch synthesis	The gasification process is utilised on a residual organic fraction separated from municipal solid waste. It produces a synthesis gas stream, which is then converted using the Fischer–Tropsch process, into renewable diesel.

4.3 System boundary

The system boundary describes the life cycles, stages and processes included in the LCA. In this study, the function was the supply of liquid fuels to the transport sector. Typically, system boundaries should include everything that is substantially affected by demand for the fuels. This includes extraction and production processes and any additional activities required to make each option functionally equivalent. It also includes the effects of co-products along the supply chain.

4.3.1 Included processes

The LCA included fuel production activities, including extraction, storage and transport, as well as refining of fuels (Figure 3). For inputs derived from crops or other biomass, all farming and harvesting operations were included. Also included were inputs to fuel refining, dehydration, blending and transport. Infrastructure elements such as plant and construction were also included, based on general models rather than primary data collection.

4.3.2 Excluded processes

The system boundary excluded processes that are common to all options assessed and are therefore not affected by the choice of option. Excluded processes were fuel dispensing, vehicle production and vehicle maintenance (including oils and servicing), based on the assumption that all options use the same vehicles and infrastructure. Detailed system boundary diagrams are provided for each fuel scenario in Appendix A.

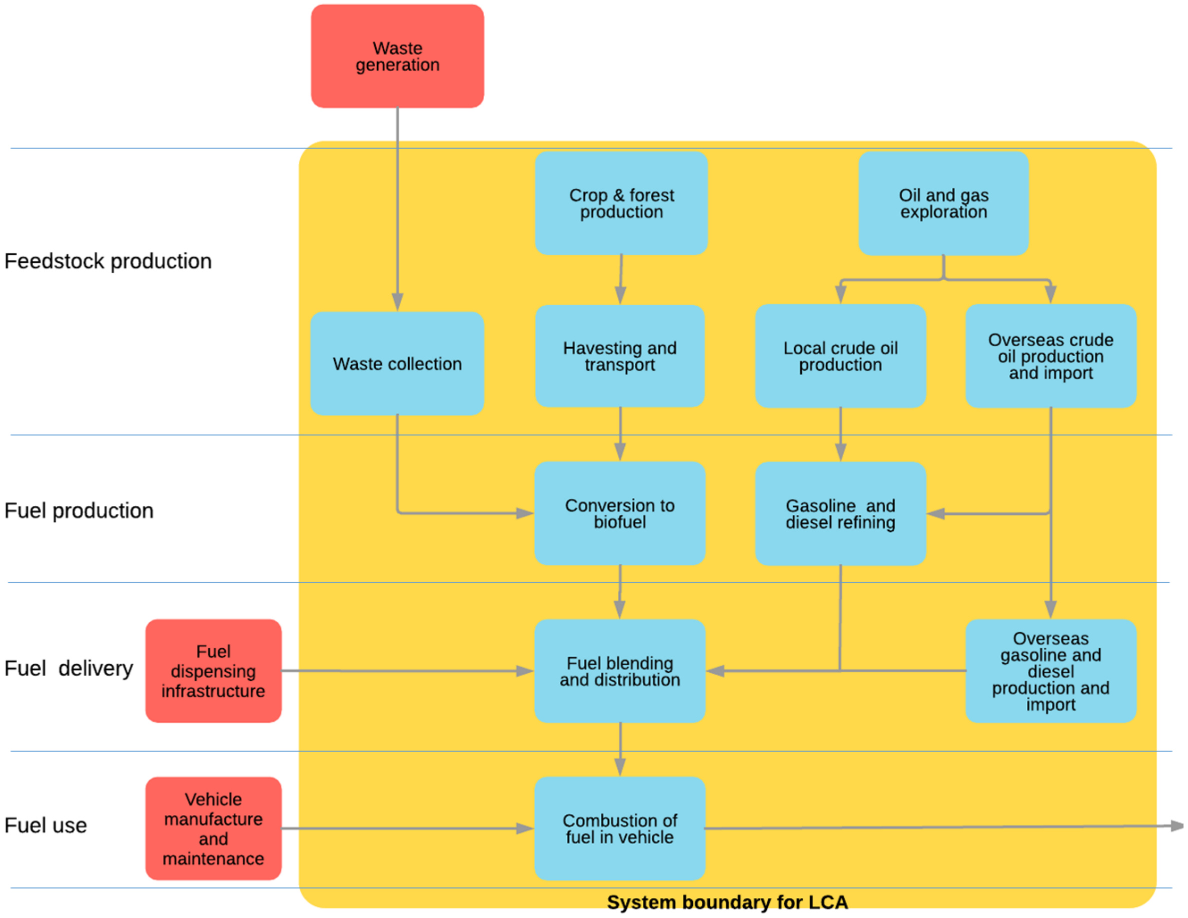

Figure 3 System boundary for the LCA

4.3.3 Cutoff criteria

The system boundary allowed for the exclusion from the inventory of any flows expected to be less than 1% of any impact category. A cutoff criterion of 1% of mass or energy flows was allowed for with the aim that not more than 5% of flows were excluded from the study. For small flows, estimates were used in preference to exclusion, where possible.

4.4 Flows included in the LCA

Figure 4 shows the characterisation of flows included in the LCA. These included flows to and from the environment as well as flows to and from other technical processes (the technosphere).

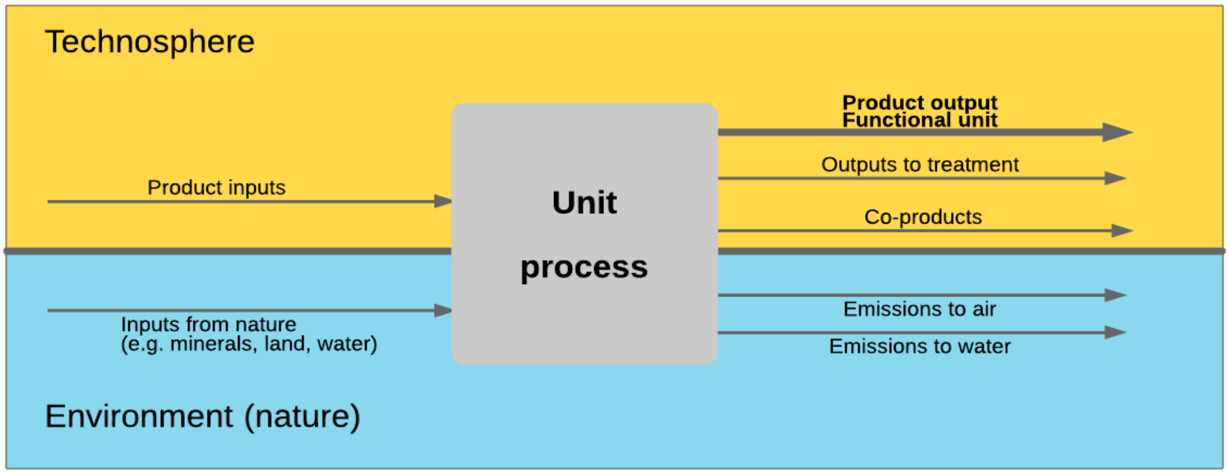

Figure 4 Inputs and outputs of a unit process in LCA.

The only water use included in the study was water extracted from groundwater, rivers, lakes and natural or man-made water storages. Rainfall onto agricultural land was not included (consistent with the impact method used in Pfister, Koehler et al. (2009)). Water use was identified within one of 36 catchments used in the Australian best practice recommended impact assessment guideline (Renouf, Grant et al. 2016).

5 Inventory analysis

Inventory analysis is the stage of the LCA in which the system being studied is broken up into unit processes. The unit processes can be categorised into foreground unit processes and background unit processes:

- **Foreground processes** are those for which specific data are collected for the study. They may include primary data collected from facilities; however, in this study it also includes secondary data from published papers and modified background processes from LCA databases.
- **Background processes** are those 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 suit the conditions of the study.

Figure 5 shows how unit processes were linked to create a system that produces the functional unit of the study. The following sections outline the sources of the background and foreground inventory data.

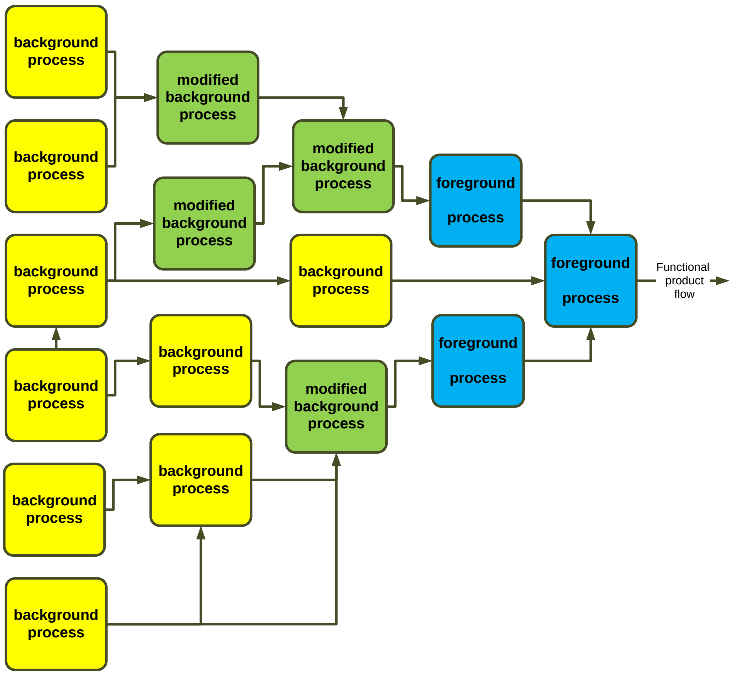

Figure 5 The linking of unit process in an LCA to produce the functional unit.

5.1 Foreground data

The description of the foreground data has been broken up into the feedstocks and the biofuel production processes. While there are some interactions between the nature of the feedstock and the fuel production process, it is more efficient to describe the assumptions around them separately.

A summary of the data sources and assumptions for the feedstocks are described in Table 4. Many feedstocks included in this assessment are waste products or co-products from other systems and it is important to understand the assumptions around the alternative uses for treatment processes for those materials.

Table 4 Summary of foreground inventory data and assumptions for biofuel feedstocks.

FEEDSTOCK	SCENARIOS USED	COMMENT
Agave	E.agave ferm. E.agave & moll	Agave is a dedicated biofuel crop, assumed to be grown without irrigation in dry areas of Queensland not suitable for sugarcane production. While test plots have been grown in Australia, data for this study was taken from agave grown in Mexico (Nunez, Rodriguez et al. 2011), which has similar soil conditions to Australia.
Sugarcane	E.sugarcane. ferm.	While it is common in Australia for molasses produced from sugar milling to be used for ethanol production, this scenario entails the use of sugarcane directly for producing ethanol without the production of raw sugar. This will increase the yield of ethanol per unit of cane and disconnect the ethanol supply from competition by other molasses users. There is also the option to optimise a cane for high biomass yields and high fibre yields, increasing energy return from the bagasse. While there are potentially different inputs to this variant of sugarcane, no data is directly available as yet, so an average of current cane grown in Queensland was used (Renouf 2011). This is assumed to be reasonable as the variation with the different cane production systems is not expected to differ dramatically.
Cane trash and tops	E.cane trash Glycell E.cane trash conc. acid RD. cane trash pyrolysis	Cane trash and tops is made up of leaves and the tops of sugarcane that is left behind in the field to break down back into the soil. This material comprises up to 1/3 of the total mass of sugarcane plants (The Biomass Producer 2017). While in some growing regions cane trash serves agronomic purposes by stabilising soil, in other regions the amount of trash is problematic for crop management. For this study, cane trash was assumed to increase from 0% to 50%, which allows for enough to be retained to support soil stability. The composition of the material was taken from an analysis of Brazilian cane trash (Franco, Pimenta et al. 2013). The change in nitrous oxide emissions from lowering the amount of residue is included.
Wheat straw	RD.wheat straw pyrolysis	Wheat and other cereal straws are a coproduct of cereal production predominantly wheat. For every tonne of wheat, there is approximately 1.5t of biomass. Average removal in Queensland is currently at 15% and this scenario increases this removal to 50% with the assumption that soil carbon will not be affected.
Forestry residue	E.forestry res. conc acid RD.forestry resid. W cata. depoly.	Forestry residue is assumed to be woody biomass that is left behind from timber harvesting operations. Like cane trash, the underlying assumption is that forestry residue can be removed at a sustainable rate that will not affect soil carbon in the forest where it is removed. This will be highly dependent on the rate of removal and the soil properties of the site. Forestry residue is typically made up of branches and tops of trees. The material is assumed to degrade naturally on the forest floor, with its CO_2 being released into the atmosphere.
Green waste	RD.green waste cata depoly	Green waste is collected from municipal and commercial sources as a pure stream of organic material with a low level of contamination. The current use of this material is mostly open composting, so this is the alternative fate used in this scenario.

FEEDSTOCK	**SCENARIOS USED**	**COMMENT**
CCA wood waste	RD.wood waste cata depoly	CCA wood waste is a problem waste due to the presence of copper and arsenic in the wood, which makes combustion highly problematic and landfill also a poor option. Landfill is, however, considered the default alternative use of the material from biofuel.
Cotton gin trash	E.cotton gin trash dilute acid hydro	Cotton gin trash is a co-product of the cotton ginning process which separates cotton lint, from cottonseed. The material presents a significant waste disposal problem that cannot be used as stock feed, with the most common disposal methods being landfill or field spreading (Knox, Rochester et al. 2006). In this study field spreading will be taken as the default management approach, and this assumes that carbon contained in the trash will break down in the field and be emitted to the atmosphere.
Waste tyres	RD.tyres destruc. distill. RD.tyres cata. depoly	Waste tyres represent a problematic waste disposal issue across Australia. Despite numerous options available for energy recovery and material recovery, most tyres at end of life are not beneficially utilised. There are three specific groups of waste tyres, which have different compositions of steel, natural rubber and synthetic rubber. These are passenger tyres, truck and bus tyres, and mining tyres. In this study, the average mix of tyres is used as a default, with a sensitivity analysis undertaken on the use of specific tyre streams. The alternative fate of tyres in the study is assumed to be landfill.
Carinata	BD.Carinata	Carinata is a similar crop to canola but it can grow in drier and hotter conditions. A dedicated crop grown specifically for the oil content of the seed, it is used as a biofuel with the added benefit of juicing animal feed from the meal left over after oiler traction. Agronomic data for producing Carinata has been supplied by Agrisoma.
Tobacco	BD.tobacco	Solaris tobacco is a nicotine-free version tobacco grown for high oil content. It also produces a valuable animal feed. Data for its production was provided by Sunchem.
Food waste	RD.food waste cata depoly	Food waste represents a highly degradable feedstock, which is currently collected in a small number of local councils in Australia, but also separated and collected from some commercial operations. The source-separated material is currently either being composted or sent to anaerobic digestion, with the former being the default alternative use for this study.
Municipal solid waste	RD.MSW gasification FTP	Municipal solid waste represents a rich organic stream with both biological material and plastics, which can be used to provide a carbon feedstock. It is assumed in this study that the material is currently being sent to landfill and this is used as the alternative fate for this material.
Prickly acacia	RD.prickly acacia pyrolysis	Prickly acacia is a noxious weed that grows extensively in Queensland's drier areas and is a major problem for grazing properties, taking over large areas and making them unproductive. The management methods are a mix of spraying and mechanical removal.

Table 5 summarises the biofuel production processes, inventory data sources and assumptions. Data was sourced directly from companies where available, with missing data derived from published company data. Where company data was not available, the study used public data, LCA datasets and external studies.

Table 5 Summary of inventory data and assumption for fuel production processes.

FUEL SCENARIO	**SCENARIO NAME**	**COMMENT**
Dilute acid hydrolysis	E.cotton GT dilute acid hyrdo	This process is a common approach used for converting lignocellulosic material into ethanol. The data for this process has been taken from ecoinvent (Weidema, Bauer et al. 2016) based on a report by (Jungbluth, Dinkel et al. 2007)

FUEL SCENARIO	SCENARIO NAME	COMMENT
Concentrated acid hydrolysis	E.cane trash conc. acid E.forestry res. conc acid	This process has been developed by EthTech Ltd over the last 10 years and involves a series of innovations for rapid conversion of lignocellulosic material to fermentable sugars and lignin. The fermentable sugars are converted to ethanol, and lignin with other unreacted material, and residue from fermentation, are used to provide the energy for the plant.
Fermentation and distillation	E.agave ferm E.cane biorefinery ferm E.agave & moll. ferm E.cane trash glycell E.cotton GT dilute acid hyrdo	Fermentation and distillation data are taken from data reported by Sarina Mill in (Grant, Bontinck et al. 2016). In all reported scenarios, the source of heat and electricity is entirely from biomass combustion, from bagasse or other waste biomass from the raw material processing.
Fermentation ethanol separation	E.cane trash conc. acid hydro E.bagasse conc acid hydro E.wood waste conc acid	EthTech provided data for an alternative ethanol separation approach, which avoids distillation as well as silage waste. The energy source for the process is assumed to be based on combustion of lignin and other waste biomass from the process.
Biodiesel production	BD.Carinata BD.tobacco	Data for biodiesel production from vegetable oils has been taken from ecoinvent (Weidema, Bauer et al. 2013), with modifications based on Australian inputs.
Pyrolysis	RD.forestry residue pyrolysis RD.cane trash pyrolysis RD.wheat straw pyrolysis RD.prickly acacia pyrolysis	This pyrolysis process is based on the plant being constructed for Northern Oil Refinery in Gladstone. It includes a pyrolysis process as well as evaporation, hydrotreating and purification processes. Data for this scenario has been provided by Southern Oil Refinery.
Glycell process	E.cane trash, Glycell	Glycell data has been provided by Leaf Resources based on process modelling. The technology has a wide range of options. For this study both the cellulose and hemicellulose will be used for ethanol fermentation, even though economics may make this unlikely.
Destructive distillation	RD.tyres destruc. distill	The destructive distillation process is particularly well suited to tyres, producing a dry carbon product, steel for recycling and a bio-oil, which is processed through the evaporation, hydrotreating and purification processes of the Northern Oil Refinery. Data for this scenario was provided by Green Distillation Technologies as well as the Northern Oil Refinery.
Catalytic depolymerisation	RD.CCA wood waste cata depoly RD.forestry res. cata depoly RD.green waste cata depoly RD.food waste cata depoly RD.tyres. cata depoly	The catalytic depolymerisation process effectively dissolves organic matter from mineral substrates enabling the organic material to be recovered for fuel production. There is potential for a wide range of substrates, which have been included in the study based on data from CDP Waste2Energy.
Gasification and Fischer–Tropsch	RD.MSW gasification FTP	The gasification process is utilised on a residual organic fraction separated from municipal solid waste. It produces a synthesis gas stream that can then be converted, using the Fischer–Tropsch process, into renewable diesel. Data for this scenario has been taken from synthesis gas processes in ecoinvent and the Fischer–Tropsch process described in Iribarren, Susmozas et al. (2013).
Fuel production	RULP	Import data from Australian Institute of Petroleum (AIP) (AIP 2013) with underlying refining data from modified ecoinvent database (ecoinvent Centre 2010, ALCAS 2016).
Diesel supply to Queensland	Diesel	Import data from AIP (AIP 2013) with underlying refining data taken from modified ecoinvent database (ecoinvent Centre 2010, ALCAS 2016).
All processes	Tailpipe emission	Emission data from passenger vehicles from the Greet model (Elgowainy, Dieffenthaler et al. 2013).

A more detailed description of the unit process data for the foreground processes is provided in Appendix A.

5.2 Background data

While hundreds of background processes contributed to the LCA, the most important processes were those that affected the results or those that were modified from the original source to better represent an input to this LCA. These background processes, data sources and modifications are summarised in Table 5. The majority of background processes are energy, chemicals and transport processes so they are not affected by local factors such as climate and soil conditions in Queensland.

Table 6 Summary of inventory data for major background processes in the LCA.

PROCESS/EMISSION	DATA SOURCE
Natural gas supply	Data is based on national statistics released by ABARE (ABARE 2011), energy industry data (Energy Supply Association Australia 2012), and the National Greenhouse Account Factors (DIICCSRTE 2013).
Electricity supply	Australian electricity supply disaggregated by state using data from Department of the Environment (2014) Electricity Supply Association of Australia (2012) and ALCAS (2017)
Process chemicals	Background chemicals which are not part of AusLCI were modelled from ecoinvent 2.2 modified with AusLCI inventory data (ALCAS 2017)
Fertiliser, pesticides, tractor emissions	ecoinvent 2.2 data (ecoinvent Centre 2010) with minor upstream flows from AusLCI where available (ALCAS 2017)
Carbon black and charcoal	ecoinvent 2.2 data (ecoinvent Centre 2010) with minor upstream flows from AusLCI where available (ALCAS 2017)
Truck transport processes	Freight transport inventories are from AusLCI database(ALCAS 2017) and were derived from freight efficiency statistic developed by Adam Pekol Consulting. (Adam Pekol Consulting Pty Ltd 2011)
Agricultural offsets sorghum, Lucerne, wheat etc	Agricultural data not specifically modelled in the foreground was taken from AusLCI database (ALCAS 2017) based on project by CSIRO and lifecycles. (Grant, Eady et al. 2015)

5.3 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[1] 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 multifunction processes.

Many co-products are used and produced when making biofuels. In fact, the drive to produce fuels from non-food sources encourages fuel producers to use waste and co-products from other sectors in their production.

The ISO 14044 LCA standard provides a four-step hierarchy for solving the issue of multi-functionality:

1a **Avoid allocation by subdividing systems** – wherever possible, allocation should be avoided by dividing the unit process into sub-processes.
1b **Avoid allocation by system expansion** – expanding the product system to include the additional functions related to the co-products.
2 **Allocation by underlying physical relationships** – the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them.
3 **Allocation between co-products** – the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, data may be allocated between co-products in proportion to the economic value of the products.
(adapted from text in (International Organization for Standardization 2006)).

Table 7 describes the four options that are available for solving allocation in multifunction systems in order of preference outlined in the ISO 14044 standard (International Organization for Standardization 2006), with a modification in line with the recommendations from UNEP/SETAC global guidance for LCA databases (UNEP/SETAC Life Cycle Initiative 2011). Option 2 has been moved ahead of system expansion as it is only applied to combined production where the production volume of different co-products can be varied.

Option 1a is only applicable when the system is not a true multifunction process, and option 2 is only applicable when the ratio of co-products can be varied, such as between diesel and petrol production in a refinery. This leaves system expansion and allocation as the two main approaches to solving multifunction systems. This study uses both approaches for all fuels, with system expansion used in the forward-looking viewpoint, to determine the impact of introducing a new fuel pathway, and economic allocation to calculate the footprint of the fuel once it is in production.

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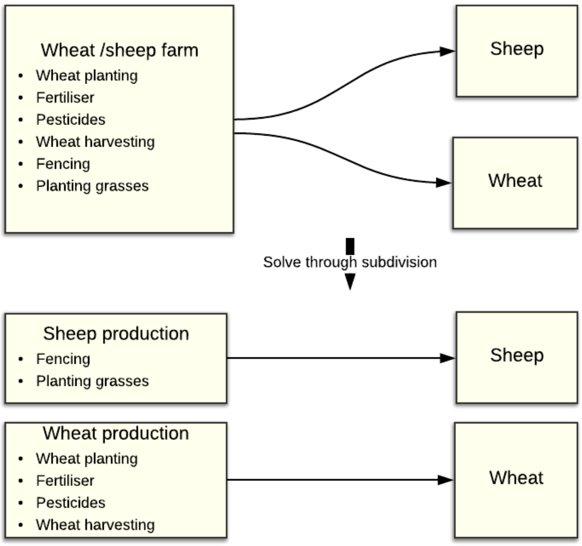
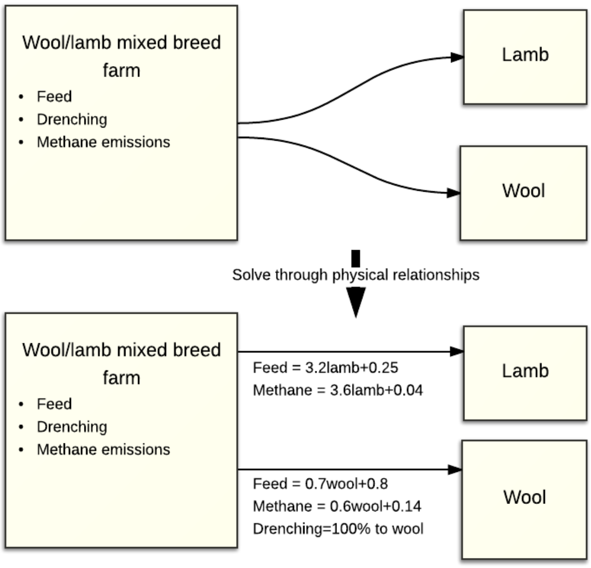
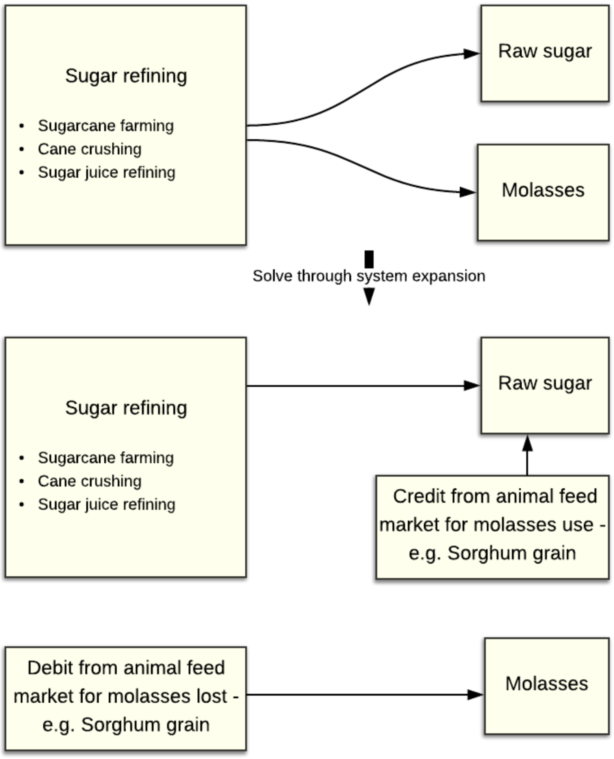
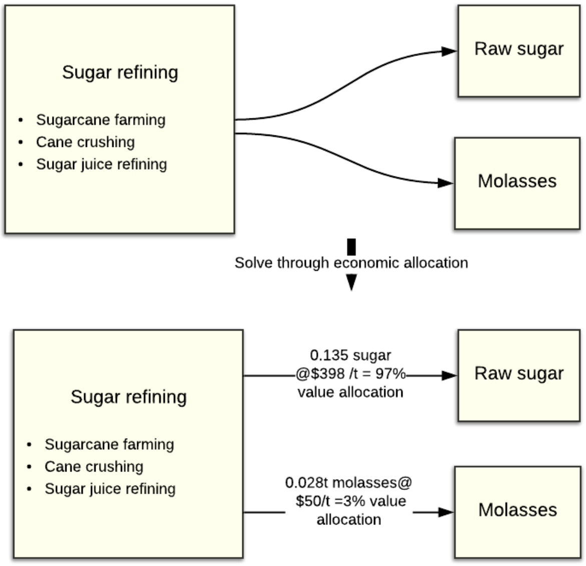
[1] While there are subtle definitions that can be found between by-products and co-products in LCA there is no distinction in this study between the co-product and a by-product.

Table 7 Description of options for solving allocation in multifunction systems.

Option	Solution description	Graphical representation
1a	Dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes. For example, for a farming establishment producing crops and sheep, subdividing and collecting data on inputs such as diesel, fertilisers etc. for energy crop production and pastoral operations separately would avoid the need for allocation.	
2	Physical relationships: For combined production, where the co-product amount is not fixed but can be changed, the impacts are allocated based on how the physical relationships between inputs and emissions change as the ratio of co-products changes. This will take the form of a mathematical relationship on how feed changes as a function of lamb production.	

Option	Solution description	Graphical representation
1b	System expansion refers to the process of including the co-product into the system boundary and then removing it by providing a credit equal to the functional value of the co-product. For example, sugar refining has the outputs of raw sugar and molasses. In system expansion the determining product (the product that determines the level of production) raw sugar has all the impacts of the upstream processes (cane growing, crushing and refining) but is given a credit (negative amount) for the animal feed function (the alternative use of molasses). For molasses, (non-determining co-product) there is a debit (positive amount) of animal feed replacement to balance what was credited to raw sugar. In this way, when the two products are added the debit and credit for animal feed cancel out.	
3	Where physical relationships alone cannot be established as the basis of allocation, the inputs and emissions should be allocated between the co-products, based on other relationships between them such as the economic value of the co-products. This is shown here using the same example as system expansion of raw sugar and molasses. The percentage allocation is a function of the value per tonne and the amount of each product produced.	

Note that all values used in the diagrams are for demonstration purposes and not actual values.

Table 8 shows the co-products in the foreground of this study and how they have been addressed. For each co-product the determining product is identified. This is the product that is the main economic driver for the production system. Co-products are then identified with the substitute that is used in the LCA and any alternative substitutes that are tested in the sensitivity section.

For biofuels that are utilising waste products there is no co-product, and the waste has no value; however, in accordance with ISO13065 the alternative fate of the waste needs to be taken into account. Table 9 shows feedstocks that are currently considered waste products and their potential alternative fate, which must be included into the LCA.

Table 8 Co-production in the LCA foreground and the replacement products used.

PROCESS	DETERMINING PRODUCT	CO-PRODUCT	SYSTEM EXPANSION SUBSTITUTED COMMODITY
Refining	Gasoline, diesel	LPG, naptha, etc.	Allocation by underlying physical relationships* substitute not used.
Agave refining	Sugar	Bagasse	Queensland coal-fired electricity as a substitute.
Fischer–Tropsch diesel production	Renewable diesel	Electricity	Queensland coal-fired electricity as a substitute.
Fischer–Tropsch diesel production	Renewable diesel	Hydrogen	Hydrogen from chlor-alkali process as substitute.
Fischer–Tropsch diesel production	Renewable diesel	Renewable gasoline	Production and use of conventional gasoline offsetting the use of renewable gasoline.
Ethanol from sweet sorghum	Ethanol	Dunder product from distillation	System expansion substitutable with fertiliser product.
Cropping	Grains	Agricultural residues	Depending on cropping, may be substituted with cereal hay. Some may be left on field as alternative fate.
Tobacco seed crushing	Tobacco oil	Tobacco seed cake	Used as animal feed for pigs. Offset with high protein feed.
Carinata seed crushing	Carinata oil	Carinata seed cake	Used as animal feed for pigs. Offset with high protein feed.
Glycell process	Sugars	Lignin	Can be used for chemical processes. No substitute had been identified so alternative use is considered energy production. Offset is Queensland black coal electricity.

Table 9 Waste products utilised in LCA and alternative disposal pathways.

PROCESS	DETERMINING PRODUCT	WASTE PRODUCT	ALTERNATIVE FATE OR WASTE PRODUCT
Sugar refining	Sugar	Trash and tops	Trash and tops left are assumed to be left on the field to degrade, if they are not removed for use in biofuel system.
Timber production	Logs	Residues from timber production	Residues left in coup to degrade if they are not removed for use in a biofuel system.
Road tyres	Use on vehicle	Waste types	Landfill is the default destination used for road tyres based on (Mountjoy, Hasthanayake et al. 2015).
Mining tyres	Use on vehicle	Waste types	The default fate for mining tyres is assumed to be abandonment at the mine site.
Cotton ginning	Lint	Cotton trash	Distribution on field where material degrades. Alternative potential fate is landfill.
Prickly acacia removal process	Prickly acacia removal	Prickly acacia plants	Assumed to be cut and poisoned and left to degrade where it is removed.
Food waste disposal	Food waste management	Food waste	Composting is the default assumption, with landfill the potential alternative.
Green waste disposal	Green waste management	Green waste	Composting is the default assumption, with landfill the potential alternative.
CCA wood waste disposal	CCA wood waste management	CCA wood waste	Landfill is the default assumption.
Municipal waste disposal	Municipal waste management	Municipal solid waste	Landfill is the default assumption, with aerobic stabilisation the potential alternative.

5.4 Carbon modelling

Special attention is given to the sources and fate of carbon in the LCA. When inventorying 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.

For the consequential LCA modelling the original source of the carbon has no effect on the results, because it is the fate of the carbon that drives the emission result, and not where it came from in the tyre production process. Fossil and biogenic carbon emissions are compared to each other, for example, storing fossil and biogenic carbon in a landfill. The type of carbon is of no consequence.

For calculation under the Roundtable for Sustainable Biomaterials (RSB), the GHG calculation approach states that biogenic carbon emissions will be treated as greenhouse neutral while fossil-based carbon will be counted as contributing to GHG. For this method the source of input feedstocks for the fraction which is biogenic and that which is fossil based are discerned.

5.5 Land use and land use change (LUC)

Impacts of land occupation and land transformation are complex to model in an LCA and are exacerbated in this study as most production systems proposed are not currently operating on a commercial scale. Table 10 outlines potential land use and land transformation consequences of each of the feedstocks. There are three situations described. The first situation is where perennial crops, new sugarcane and agave, are planted on pasture. Using IPCC land use methodology via the LUC tool developed by Blonk consultants (Blonk Consultants 2017), this led to no emissions from direct land use change (dLUC). This is because the sugar and agave are perennial systems with high biomass inputs so are unlikely to lead to a soil carbon change.

The second situation is where tobacco and Carinata are planted on existing cropland. Carinata in particular would be a break crop in cereal growing systems, and due to its better heat tolerance it can be used in hotter drier regions where canola, which is also used as break crop, cannot be used. It is not clear at this point where the tobacco might grow as it is a different variety to the traditional tobacco that was grown at the base of the Victorian Alps in north-eastern Victoria.

The third situation is where additional biomass is removed from an existing production system in the form of residues, which included cane trash and tops, cereal residues and forestry residues. These do not represent LUC but more a change in land management practice. There is a positive correlation in the soil carbon models between biomass inputs to land and increasing soil carbon (or possibly a reduction in soil carbon loss). However, this is not a simple correlation, other contributing factors will affect this. A sensitivity analysis is undertaken in Section 7.2.5 on the effect of potential soil carbon shifts.

Separate but connected to the dLUC effects are the indirect land use change (iLUC) impacts. iLUC are the potential impacts on areas outside the area under study. For example, if Carinata is grown in place of export canola or export wheat grain, there is potential for expansion of cropping land to fill this gap somewhere else in the world. A sensitivity analysis is undertaken in Section 7.2.6 on the effects of iLUC.

Table 10 Land use impacts from feedstock.

FEEDSTOCK	LAND USE OF BIOENERGY SYSTEM	LAND USE WITHOUT BIOENERGY SYSTEM	DISPLACEMENT EFFECTS
Agave	Occupation as perennial crop	Occupation as pasture	The displacement of beef production to other regions, countries or to feedlots
Sugarcane	Occupation as perennial crop	Occupation as pasture	The displacement of beef production to other regions, countries or to feedlots
Cane trash and tops	Occupation as perennial crop	Occupation as perennial crop	Potential change in soil carbon due to removal of biomass
Forestry residue	Occupation as production forest	Occupation as production forest	Potential change in soil carbon due to removal of biomass
Green waste	No direct land use	Land use for landfill disposal	Small effect on land use
Wood waste	No direct land use	Land use for landfill disposal	Small effect on land use
Cotton gin trash	Annual crop land	Annual crop land	Potential change in soil carbon due to removal of biomass
Waste tyres	No direct land use	Land use for landfill disposal	Small effect on land use
Carinata	Cropping land	Cropping land	Increased rotations of Carinata in wheat system will lead to expansion in wheat crop elsewhere in the world
Tobacco	Cropping land	Cropping land	Tobacco would displace cereal crop elsewhere in the world
Food waste	No direct land use	Land use for landfill disposal	Small effect on land use
Municipal solid waste	No direct land use	Land use for landfill disposal	Small effect on land use
Prickly acacia	Pasture land recovered	Possible pasture land increasingly lost	Increased availability and productivity of pasture land

5.6 Life cycle inventory model

The foreground and background data described in the prior two sections were modelled in SimaPro LCA software version 8.5. The inventory was calculated with 200 foreground processes which are either developed entirely for the study or modified from background data, and 8,000 background processes from the AusLCI and ecoinvent libraries. There was a total of 2,273 flows included in the inventory, of which 1,617 were not used in any of the indicators examined in the study. This is typical practice, with many flows in the LCA tracked for overall balance reasons and for indicators not relevant to this study.

6 Impact assessment

6.1 Impact assessment indicators and characterisation models

The impact assessment stage relates the inventory flows to the indicators chosen for the LCA. This was done by classifying which flows relate to which impact indicator and then selecting a characterisation model that quantifies the relationship of each inventory type to the indicator in question. For example, flows of carbon dioxide and methane are both known to contribute to the climate change indicator. The characterisation model chosen for the study was the 2013 Intergovernmental Panel on Climate Change 100-year model. This uses carbon dioxide as the reference substance with a characterisation factor of 1 and methane with a characterisation factor of 25 carbon dioxide equivalents. The same approach was taken across all indicators. The calculation of the indicator results was the summation of all inventory flows multiplied by their relevant characterisation factors. This step is referred to as characterisation. The results are in equivalent units, such as kg CO_2 eq., for each indicator. Table 10 describes each of the indicators chosen for LCA and the source of the characterisation factors.

Table 11 Impact assessment categories and characterisation models used in this LCA.

INDICATOR	DESCRIPTION	CHARACTERISATION MODEL
Climate change	Measured in kg CO_2 eq. This is governed by the increased concentrations of gases in the atmosphere that trap heat and lead to higher global temperatures. Gases are principally carbon dioxide, methane and nitrous oxide.	IPCC model based on 100-year timeframe (IPCC 2013).
Fossil energy	Measured in MJ lower heating value. It includes all energy resources extracted and used in any way. It does not include renewable energy, energy from waste or nuclear energy.	All fossil energy carriers based on lower heating values.
Eutrophication	Measured in g PO_4^{-3} eq. Algal growth from nutrient enrichment in freshwater and marine environments. Emission of nitrogen and phosphorus contribute with the model being based on the relative nutrient.	CML method based on redfield ratio (Institute of Environmental Sciences (CML) 2016).
Particulate matter	Measured in g $PM_{2.5}$. 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 plus method (Humbert, Marshall et al. 2011).
Land use	Measured in kg C deficit. The method is based on the increase or decrease in soil organic matter (SOM) as a function of LUC and land use occupation. It is based on the difference in the SOM from a natural reference state.	ILCD method (European Commission JRC IES 2011) based on Mila-i-Canals (i Canals, Romanya et al. 2007).

Consumptive water use	Measured in litres of water. Water extracted directly from the environment, thereby competing with environmental and other human requirements for water.	The impacts of water use based on water scarcity footprint by Psfister (Pfister, Koehler et al. 2009).

In addition to the characterisation process, the study used normalisation in the impact assessment stage. Normalised results were calculated by dividing results using characterisation models by an independent reference value, which for this study was the total annual emissions in Australia for each impact category. This provided an indication of the relative impact the product system had on each of the impact categories. Other impact assessment processes, such as grouping and weighting of indicators, were not undertaken in this study as the ISO standard (International Organization for Standardization 2006) forbids weighting when undertaking comparative assertions.

6.2 Results

This section presents the results of replacing one litre of fossil fuel with the functionally equivalent amount of biofuel. For the ethanol-based scenarios this is done by replacing 12.6 litres of RULP with 14 litres of E10. For the biodiesel scenarios this is done by replacing 22.2 litres of diesel with 22.3 litres of B5 and for renewable diesel the substitute is a direct 1 for 1 replacement of diesel with renewable diesel.

6.2.1 Fossil fuel baseline

Table 12 shows the impacts of production and use of RULP and diesel in Queensland. The climate change impacts for diesel were higher per litre that RULP, as it is a denser fuel and will drive an equivalent sized vehicle further. Diesel also has a slightly higher carbon content than RULP. The fossil energy depletion indicator represents all fossil fuels used in the production of RULP and diesel as well as the feedstock in the fuel itself.

Impacts on eutrophication are linked to NOx emissions and particulate matter impacts are linked to PM2.5 emissions – with both of these being produced during crude oil production, fuel transport and refinery operations. Land use for RULP and diesel is low, as the amount of fuel yielded from wells is very high compared to the overall land occupation. Fossil fuel production and use has a relatively low impact on water scarcity.

Table 12 Results for production and use of one litre of fossil fuel.

INDICATOR	CLIMATE CHANGE	FOSSIL ENERGY DEPLETION	EUTROPHI-CATION	PARTICULATE MATTER	LAND USE	WATER SCARCITY
Unit	kg CO_2 eq.	MJ NCV	g PO_4^{-3} eq.	g $PM_{2.5}$	kg C deficit	litre eq.
RULP	2.97	42	0.676	0.614	7.7	6.72
Diesel	3.35	45.9	0.737	0.568	8.6	7.07

6.2.2 Results for biofuel substitution using system expansion method

Table 13 shows the impacts and benefits of replacing one litre of fossil fuel with equivalent biofuel using the system expansion method. The equation below describes how these values are calculated. Negative values represent a benefit as the impact of biofuel is lower than that of fossil fuel. When the number is positive the impact of biofuel is higher than current fossil fuel.

$$+\,number \rightarrow fossil\ fuel\ is\ preferable$$

$$Fossil\ fuel\ prod.\,\&\ use - biofuel\ prod.\,\&\ use = net\ impact\ of\ replacement$$

$$-\ number \rightarrow biofuel\ is\ preferable$$

Table 14 shows the percentage emission reduction for replacing fossil fuel with biofuel according to the equation below.

$$\frac{Fossil\ fuel\ prod.\,\&\ use - biofuel\ prod.\,\&\ use}{fossil\ fuel\ prod.\,\&use} * 100 \qquad \begin{matrix} +\,percentage \rightarrow biofuel\ is\ preferable \\ -\ percentage \rightarrow fossil\ fuel\ is\ preferable \end{matrix}$$

The results are interpreted in detail in Section 7.1 but in summary the biofuels all perform better on climate change than the fossil fuel counterparts. Aside from the scenarios involving waste types, all scenarios have a savings of 40% with eight scenarios having savings above 80%. Waste tyres, and to a lesser extent waste, would present an anomaly whereby the alternative fate in landfill represents a carbon store, which reduces the overall benefit of utilisation as a biofuel. This is anomalous as these materials represent problems for landfills; tyres present a structural issue and CCA treated waste wood is a potential source of toxic emissions.

All biofuels have lower fossil fuel depletion that fossil fuels, which is to be expected as a central theme of biofuels is to replace the use of fossil-based fuels using biogenic material.

The remaining indicators vary substantially depending on the scenario. Cropping systems have impacts on eutrophication and land use, and when irrigation is used, on water scarcity. Particulate matter emissions depend more on the combustion processes and in reality will be highly dependent the quality of technology developed and associated emissions controls.

Table 13 Impact assessment results for replacement of one fossil fuel with equivalent biofuel

INDICATOR	CLIMATE CHANGE	FOSSIL ENERGY DEPLETION	EUTROPHICATION	PARTICULATE MATTER	LAND USE	WATER SCARCITY
Unit	kg CO_2 eq.	MJ NCV	g PO_4^{-3} eq.	g $PM_{2.5}$	kg C deficit	litre eq.
E.agave ferm.	-2.65	-41.6	0.508	0.0535	-6.66	8.23
E.sugarcane integ. bioref. ferm.	-1.25	-31.8	9.36	0.293	-6.11	577
E.agave & moll. ferm.	-2.38	-38.1	1.75	0.0525	1.13	8.08
E.cane trash Glycell	-2.13	-31.8	1.71	-0.0327	-1.34	25.9
E.cane trash conc. acid	-2.48	-37.3	-0.308	-0.351	-7.11	2.59
E.forestry res. conc. acid	-2.17	-34.3	-0.0914	-0.306	-6.62	2.89
E.cotton GT dilute acid	-3.04	-45.3	-0.0476	0.187	-4.57	7.79
BD.Carinata transest.	-1.75	-30.8	1.88	0.206	7.45	7.17
BD.tobacco transest.	-1.62	-27.4	2.4	0.58	0.431	160
RD.forestry resid. pyrolysis	-2.55	-63.5	0.00198	-0.466	-13.8	-3.72
RD.cane trash pyrolysis	-2.75	-65.7	-0.134	-0.501	-14.2	-3.98
RD.wheat straw pyrolysis	-2.77	-64.9	-0.186	-0.512	-14	-3.79
RD.prickly acacia pyrolysis	-2.67	-65.3	-0.0224	-0.482	-14.1	-3.95
RD.tyres destruc. distill.	-0.598	-117	-1.38	-1.32	-22.4	-12.3
RD.CCA wood waste cata. depoly.	0.592	-17.5	-0.082	-0.269	-8.28	-0.576
RD.green waste cata. depoly.	-1.17	-15.6	0.557	-0.0261	-6.94	2.6
RD.forestry res. cata. depoly	-1.32	-18.3	0.473	-0.186	-7.55	0.291
RD.food waste cata. depoly	-1.17	-15.6	0.557	-0.0261	-6.94	2.6
RD.tyres. cata. depoly.	0.956	-29.2	0.0518	-0.623	-8.86	-5.1
RD.MSW gasification FTP	-19.9	13.1	2.95	0.1	-11.6	15.1

Table 14 Percentage reduction in impact of biofuel replacing fossil fuel

	Climate change	Fossil energy depletion	Eutrophication	Particulate matter	Land use	Water scarcity
	%	%	%	%	%	%
E.agave ferm.	89	99	-75	-9	87	-285
E.sugarcane integ. bioref. ferm.	42	76	-1384	-48	79	-19979
E.agave & moll. ferm.	80	91	-259	-9	-15	-279
E.cane trash Glycell	72	76	-252	5	17	-895
E.cane trash conc. acid	84	89	46	57	92	-90
E.wood waste conc. acid	73	82	14	50	86	-100
E.cotton GT dilute acid	102	108	7	-30	59	-269
BD.Carinata transest.	52	67	-255	-36	-87	-227
BD.tobacco transest.	48	60	-325	-103	-5	-5055
RD.forestry resid. pyrolysis	76	138	0	82	161	118
RD.cane trash pyrolysis	82	143	18	88	165	126
RD.wheat straw pyrolysis	83	141	25	90	163	120
RD.prickly acacia pyrolysis	80	142	3	85	164	125
RD.tyres destruc. distill.	18	255	187	233	261	390
RD.wood waste cata. depoly.	-18	38	11	47	96	18
RD.green waste cata. depoly.	35	34	-76	5	81	-82
RD.forestry res. cata. depoly	39	40	-64	33	88	-9
RD.food waste cata. depoly	35	34	-76	5	81	-82
RD.tyres. cata. depoly.	-29	64	-7	110	103	161
RD.MSW gasification FTP	593	-28	-401	-18	135	-478

Note: The table colour gradations are from green (better for biofuel) through to red (better for fossil fuel) and orange are to close to call either way. For global warming the tipping point is set as 20% benefit while all other indicators the tipping point is set at zero.

6.2.3 Normalisation to national impact loads

To try and understand the relative importance of the different impact categories LCA results can be normalised against total annual impacts of a region, in this case Australia as estimated for 2008 in Table 14. Figure 6 shows the results from Table 13 divided by the total annual impacts in Table 15. The resulting numbers are very small because the use of one litre of fuel is small compared to the entire economy, but what is important is the relative contribution under each impact category. The results reflect the relatively high contribution of transport on climate change compared with other indicator endpoints (Eutrophication has a small effect in a small number of scenarios. It is important to note that low scores in normalisation do not mean the impacts are not relevant, but simply that the relative contribution is lower than impact categories with a high normalisation score.

Table 15 Estimate and annual impacts results for Australia in 2008.

IMPACT CATEGORY	UNIT	ANNUAL IMPACT	ANNUAL IMPACT PER CAPITA	DATA SOURCES
Climate change	kg CO_2 eq.	573,329,980,000	550471	(Department of Climate Change and Energy Efficiency 2010)
Fossil energy depletion	MJ NCV	11,697,515,000,000	12201	(Geoff Armitage 2007)
Eutrophication	g PO_4^{-3} eq.	259,272,380,000	10397	(Department of Environment and Heritage and Water 2011)
Particulate matter	g $PM_{2.5}$	220,931,960,000	208207	(Department of Environment and Heritage and Water 2011)
Land use	kg C deficit	4,424,406,700,000	2847468	(ABARE-BRS 2010)
Water scarcity	litre eq.	60,508,705,000,000	550471	(Australian Bureau of Statistics 2015)

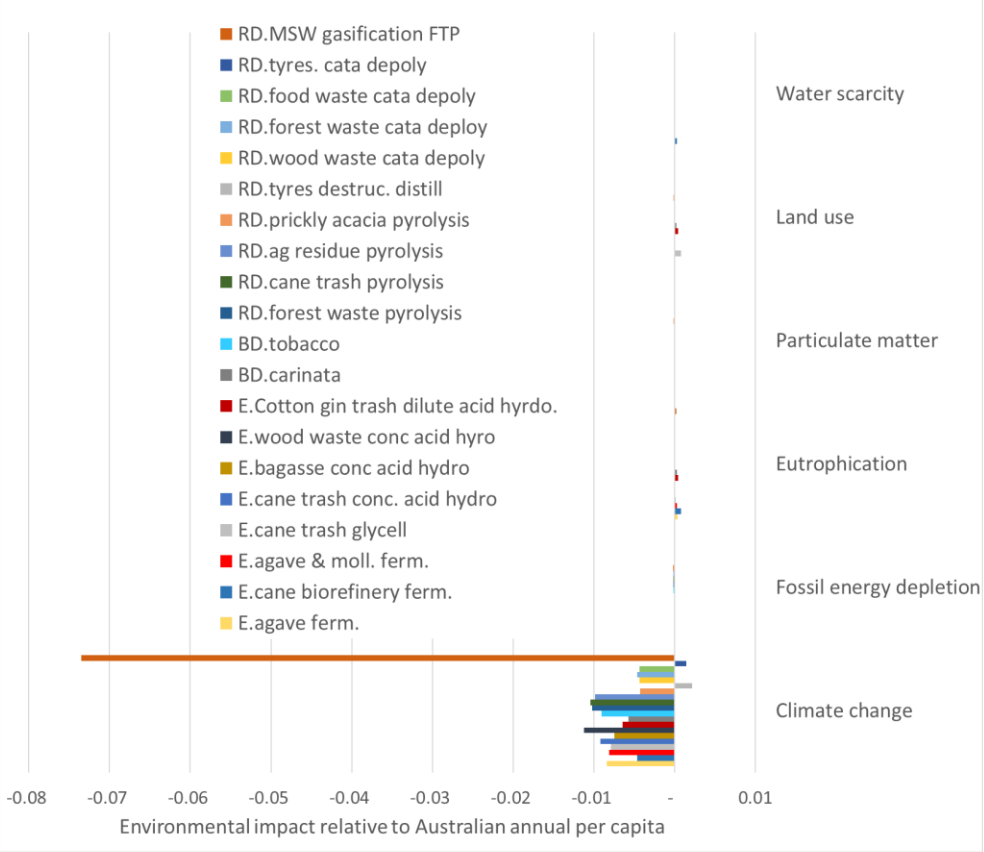
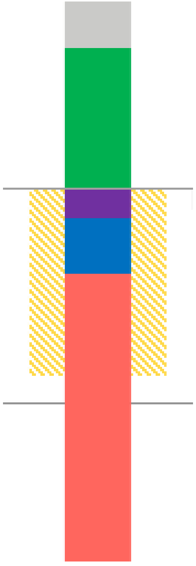


Figure 6 Comparative impact assessment results for replacing one litre fossil fuel with biofuel as a fraction of total Australian per capita impact (normalisation).

7 Interpretation

The interpretation step examined the results through a series of checks and analyses to ensure any conclusions drawn from the LCA were robust and well-supported by the data.

7.1 Contribution analyses



The results for the contribution analysis have been grouped into six categories:

- Feedstock production (grey) – production of agricultural and waste feedstocks including impacts from competition for co-product use and inputs to the biofuel process
- Biofuel production (green) – conversion of feedstocks into biofuel
- Co-products (purple) – the contribution of co-products from biofuel production
- Avoided fossil fuel production (blue) – production of fossil fuels displaced by the biofuel.
- Avoided fossil fuel emission (red) – this is the difference between the fossil fuel emissions compared with the biogenic carbon dioxide from biofuels
- Net results – (yellow hashed) this shows the results of the positive and negative contributions.

A more detailed breakdown and discussion of the impact of each fuel has been included in Appendix A.

7.1.1 Climate change

Figure 7 shows climate change impacts and benefits from replacing one litre of fossil fuel with biofuel.

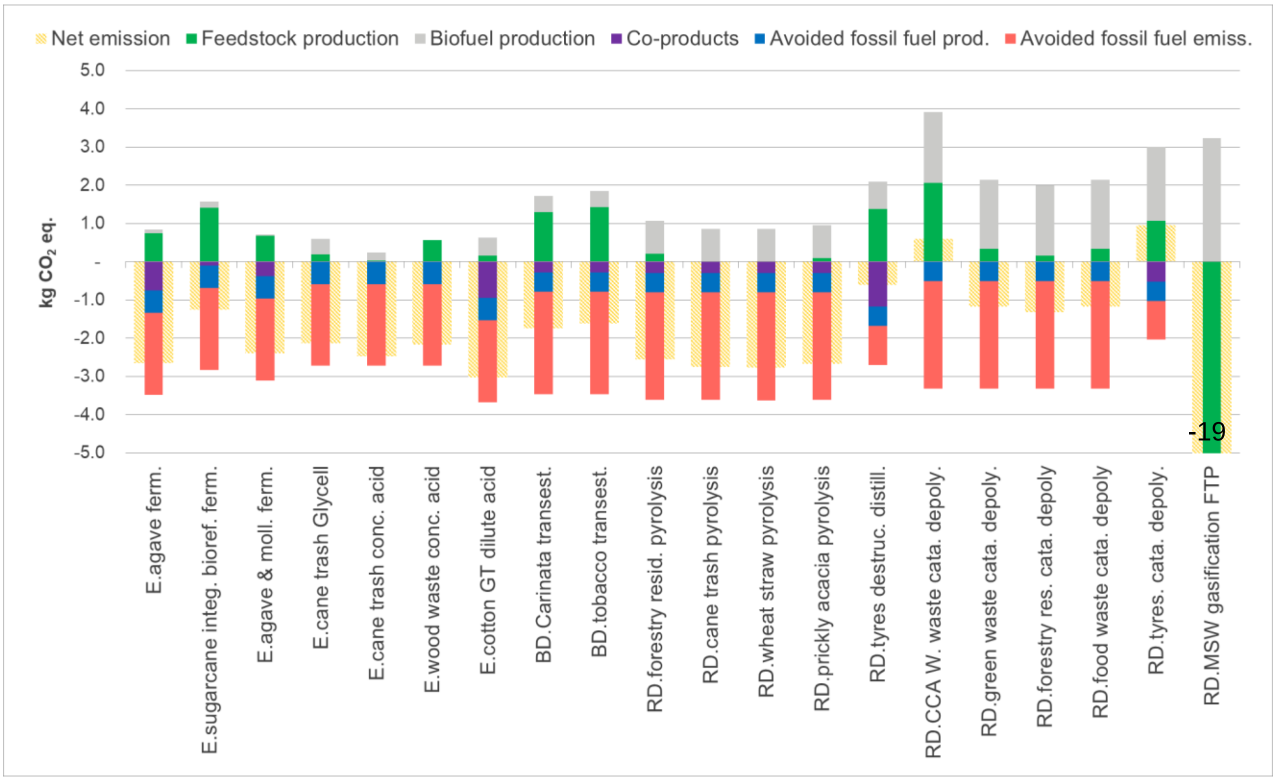


Figure 7 Climate change impact for replacement of one litre of fossil fuel with equivalent biofuel.

The two scenarios involving agave (E.agave ferm. and E.agave & moll. ferm.) have similar results with the main impacts (above the line) being in feedstock production and the main savings (below the line) in avoiding fossil fuel emissions, avoided fossil fuel production and co-products. The coproduct credit is mainly from electricity exports.

The scenario using dedicated sugarcane to produce ethanol (E.sugarcane integ. bioref. ferm.) is similar to the agave scenarios, except that there is no electricity exports and the impacts from feedstock are slightly larger.

Ethanol from the Glycell process using cane trash and tops (*E.cane trash Glycell*) has very low feedstock impacts as it's sourced from a waste material. The scenario also has low processing energy because of the use of lignin as an energy source within the process.

Concentrated acid hydrolysis of cane trash (E.cane trash conc. Acid) has very low feedstock impacts from cane trash but higher impacts from wood waste (E.forestry res. conc. acid), which has some benefits in its alternative fate which is in compost feedstock.

Cotton trash processing using dilute acid hydrolysis has impacts from the supply of enzymes used after the pre-treatment with dilute acid.

Biodiesel from Carinata and tobacco are similar in their GHG contributions with substantial impacts in feedstock production offset by the production of valuable co-products, and relatively low impacts in the biodiesel production process.

Four different pyrolysis feedstocks (show very similar results for different feedstocks, which are all lignocellulosic-based and assumed to be processed in a similar way. Forestry residue has a longer assumption than other feedstock which means the feedstock impact is higher.

The use of tyres in destructive distillation has high impacts for feedstock from the impact of the alternative fate of tyres in landfill representing a carbon store. This is because tyres do not degrade in landfill, so the carbon contained in these is kept out of the atmosphere, despite the other issues tyres in landfill represent.

Finally use of municipal solid waste for production of renewable diesel (RD.MSW gasification FTP) is off the scale of the graph as the benefits of avoiding landfill of mixed organic waste fraction is so high, due to avoided landfill methane emissions. Full detail of the breakdown for this scenario can be see in Appendix A 12.

7.1.2 Fossil fuel use

Figure 8 shows the impacts on fossil fuel depletion of replacing one litre of fossil fuel with biofuel. For all scenarios the displacement of one litre of fossil fuel represents the largest benefit for fossil fuel use.

For the first eight ethanol scenarios the biofuel production system adds almost no fossil fuel depletion because the process energy is sourced from biomass within the biofuel system. For Carinata and tobacco there is significant fossil fuel use both in the cropping system, from tractors and fertiliser manufacture, and in the biofuel system, which is predominately from the methanol used in transesterification.

The pyrolysis process and catalytic depolymerisation involves significant fossil energy inputs in both gas and electricity, and hence the high impact in the red bar of the graph. Gasification with Fischer–Tropsch has -19 higher impacts from feedstock and biofuel production than the fossil fuel life cycle. This is due in part to diversion of MSW from landfill where it generated methane – some of which (46%) is captured and used to generate electricity.

The largest fossil fuel offset for destructive distillation is from petroleum coke and steel recycling credits, which are co-products of destructive distillation. The availability of bioenergy for biofuel production processes has reduced the impacts of fossil fuel depletion for most fuels. For catalytic depolymerisation, fossil fuel use is due mostly to electricity and natural gas used in the production process.

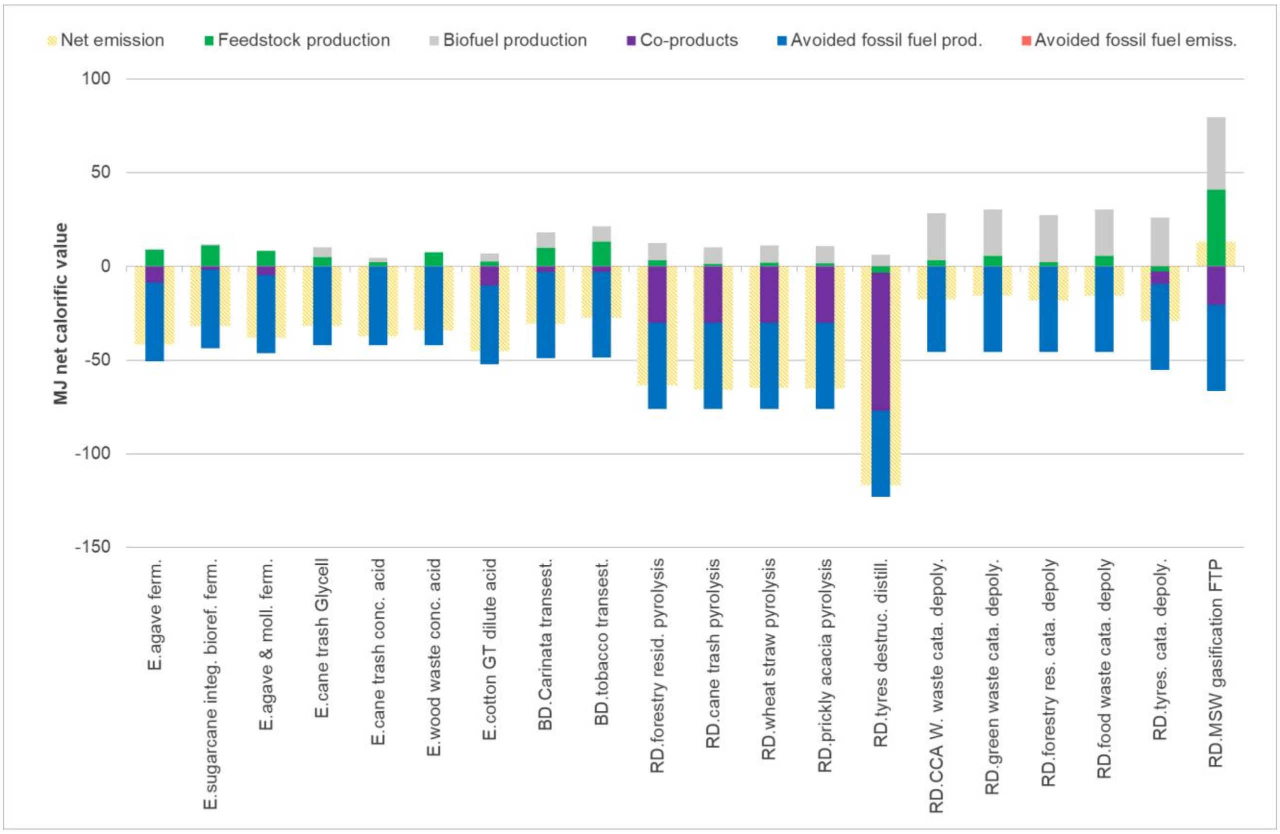


Figure 8 Fossil fuel use for replacement of one litre of fossil fuel with biofuel.

7.1.3 Eutrophication

Figure 9 shows the impacts on eutrophication from replacing one litre of fossil fuel with equivalent biofuel by life cycle stage and Figure 10 shows same data but by emission type.

The highest net impacts from eutrophication come from dedicated crop systems including agave, cane sugar, Carinata and tobacco production. These impacts are predominantly from ammonia to air, except for sugar production where nitrogen and phosphorus to water are the dominant emissions. Ammonia is released where fertilisers are applied to crops while nitrogen and phosphorus emissions to water are from leaching and runoff from cropping land.

The impacts from biofuel production in the pyrolysis and gasification scenarios are due to nitrogen oxide emissions from combustion processes. The chemical oxygen demand to water is mostly from crude oil production.

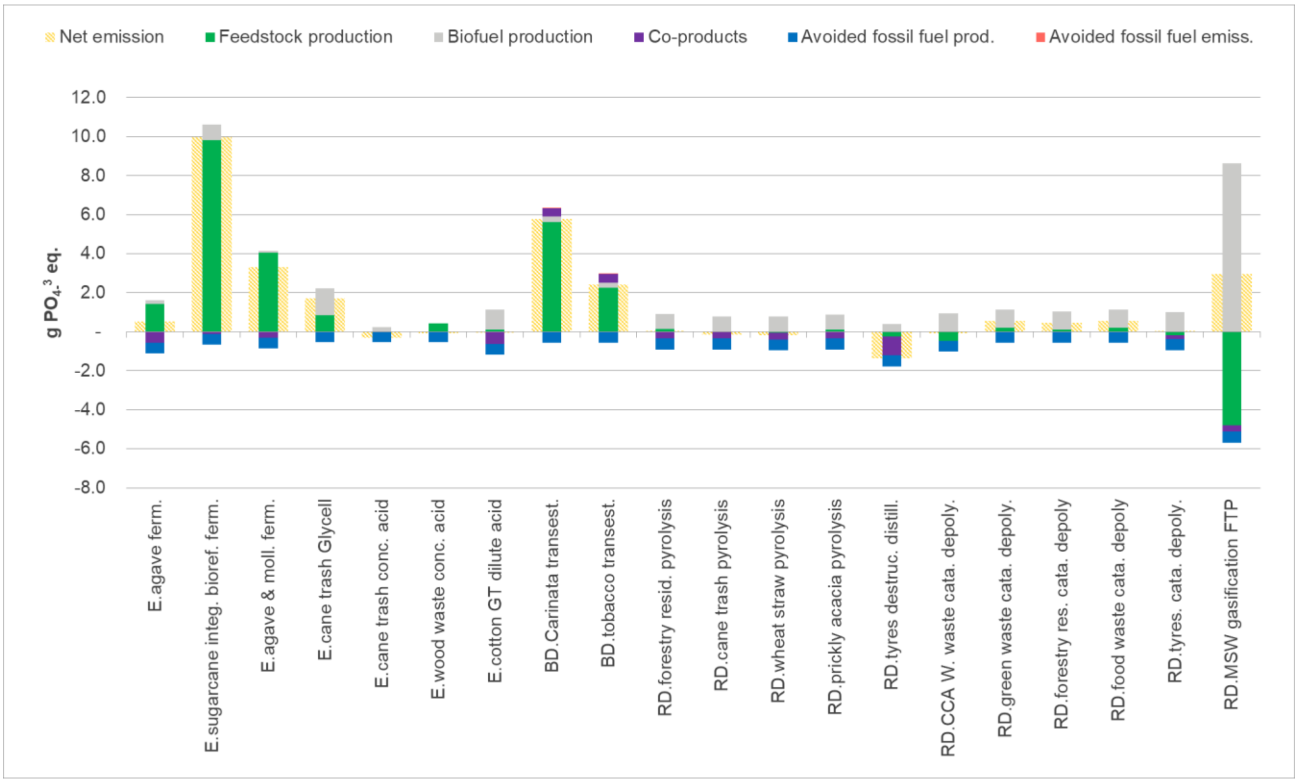


Figure 9 Eutrophication for replacement of one litre of fossil fuel with biofuel, by life cycle stage.

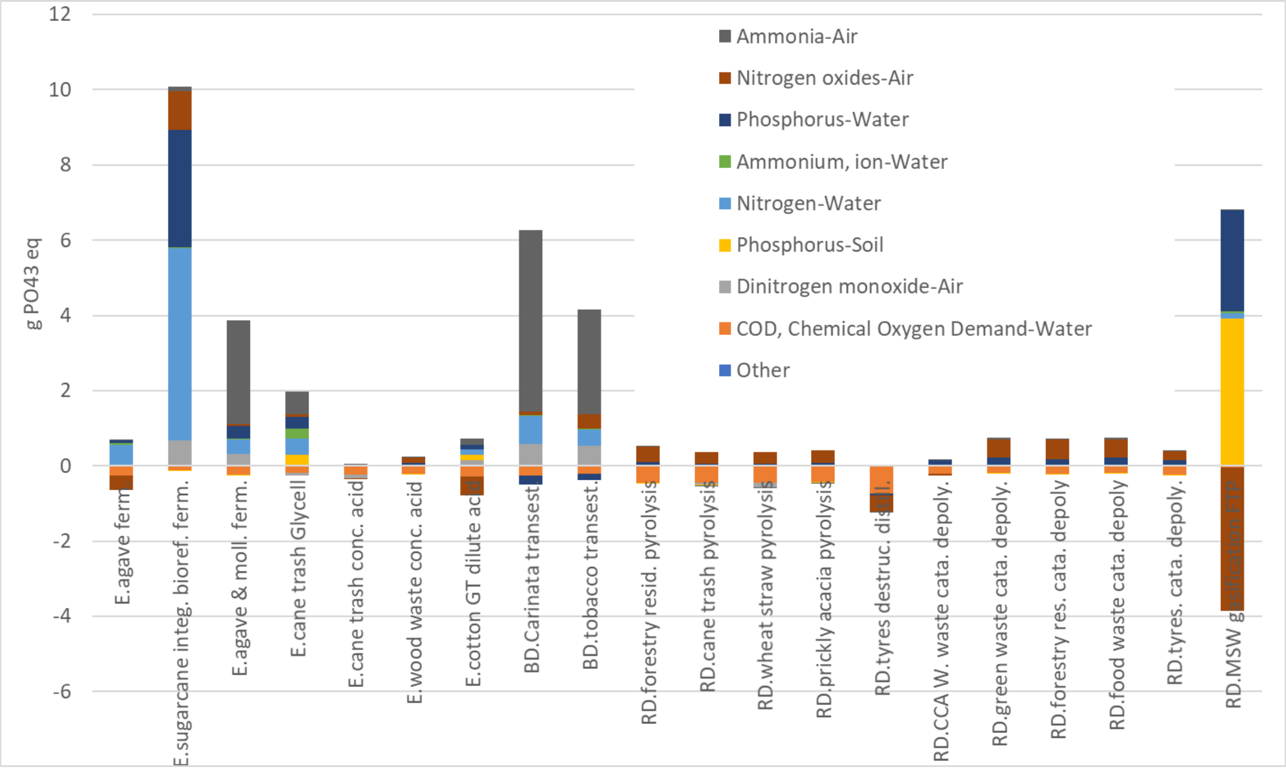


Figure 10 Eutrophication for replacement of one litre of fossil fuel with biofuel, by major emission source.

7.1.4 Particulate matter

Figure 11 shows the impacts on particulate matter from replacing one litre of fossil fuel with biofuel. Figure 12 shows the contributions by substance to the particulate matter impacts. Combustion of biomass in both bagasse (in sugar and agave) and lignin (in acid hydrolysis) contribute to particulate matter emissions. The second major contributor is ammonia from feedstock production.

Ammonia is an emission from fertiliser application and acts as a secondary particulate. Fossil fuel production does produce significant particulate matter (shown in blue below), which provides a credit to each biofuel scenario. Note that for all tailpipe emissions there has been no change of particulate matter from vehicles.

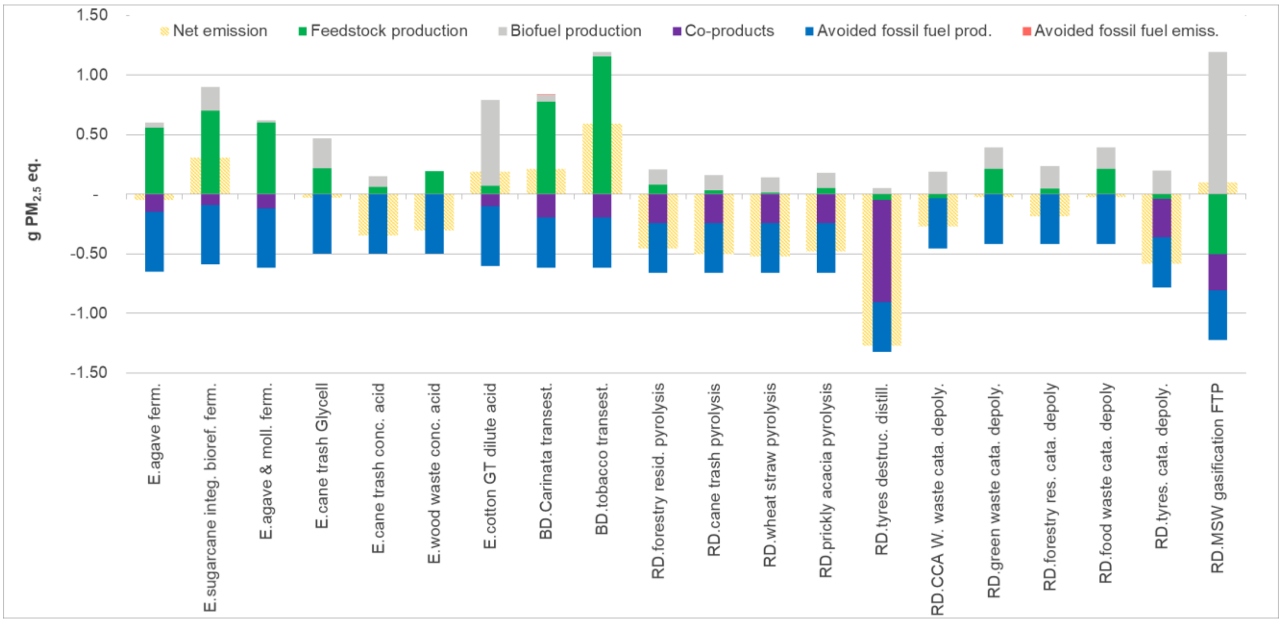


Figure 11 Particulate matter results for one litre fossil fuel replaced by equivalent biofuel.

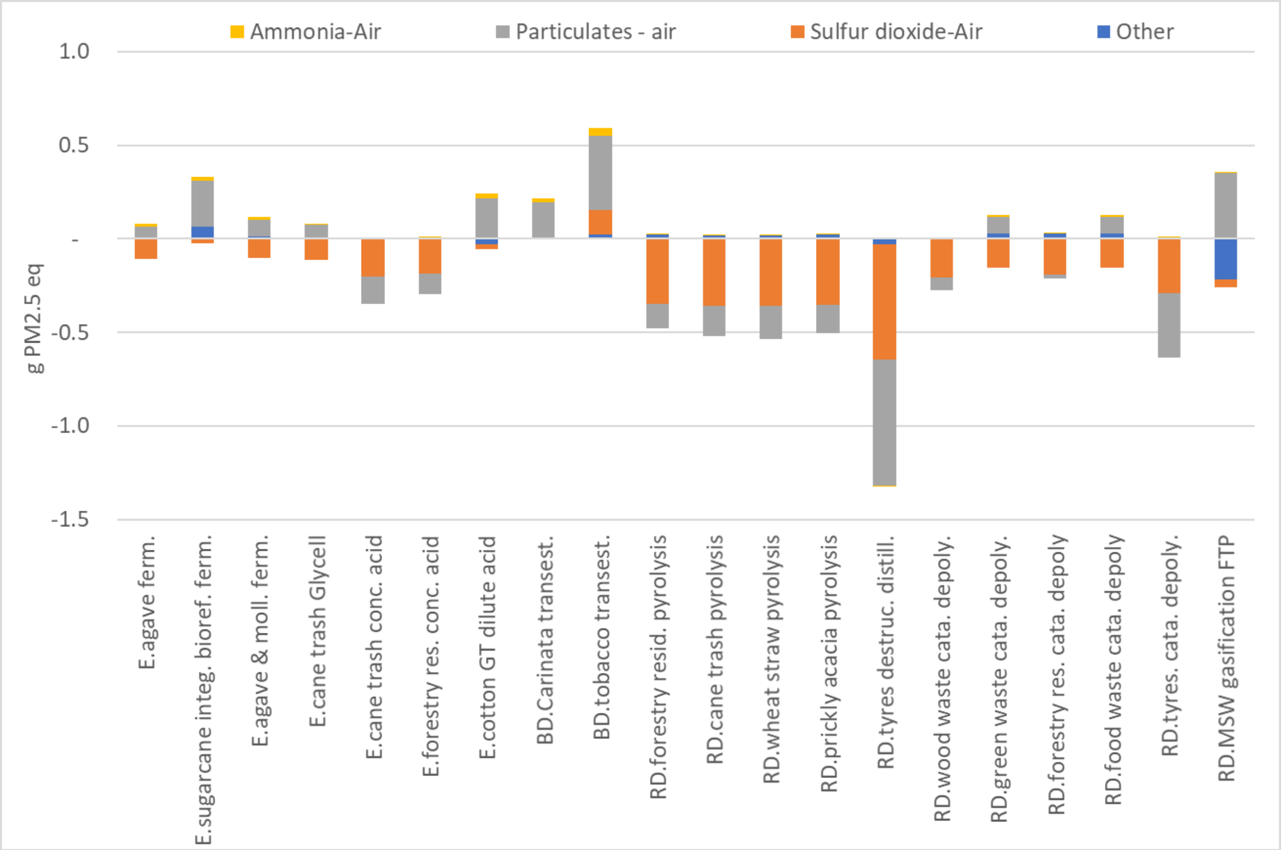


Figure 12 Particulate matter contribution by substance for one litre fossil fuel replaced by equivalent biofuel.

7.1.5 Land use

The land use results represent the impacts of occupying land and the effect of this on overall bio-productivity of the Earth's productive landscape. In these results any land transformation is not included for the biofuel systems since that is treated in the sensitivity analysis in Section 7.2.6. Figure 13 shows impacts on land use from replacing one litre of fossil fuel with biofuel. Carinata has the highest land use impact, being a dedicated crop with lower yield relative to other crops analysed, such as tobacco and sugar, which are irrigated. Land use within the other biofuel system based on waste products is very low. This does not suggest Carinata is unsustainable, simply that it utilizes part of the available resource.

The results here demonstrate that occupying land for agriculture has an impact on the bio-productivity of the planet and that utilising waste products and co-product where possible will lower this impact.

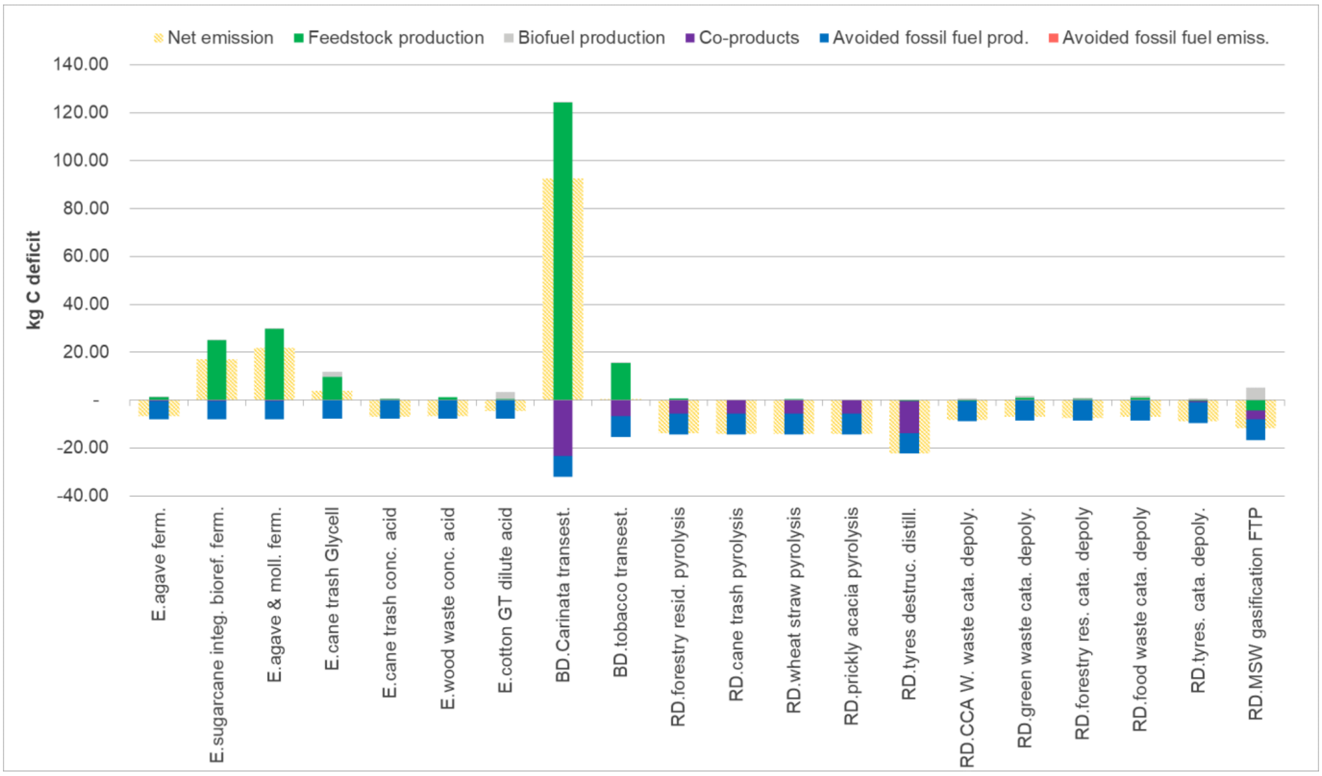


Figure 13 Land use results for replacement of one litre of fossil fuel with equivalent biofuel.

7.1.6 Water scarcity

Figure 14 shows the impacts on water from replacing one litre of fossil fuel with biofuel. The irrigation of sugarcane and tobacco dominated the water footprint as they were the only irrigated crops included in the analysis. Water use across the rest of the life cycle is not important compared to agriculture inputs.

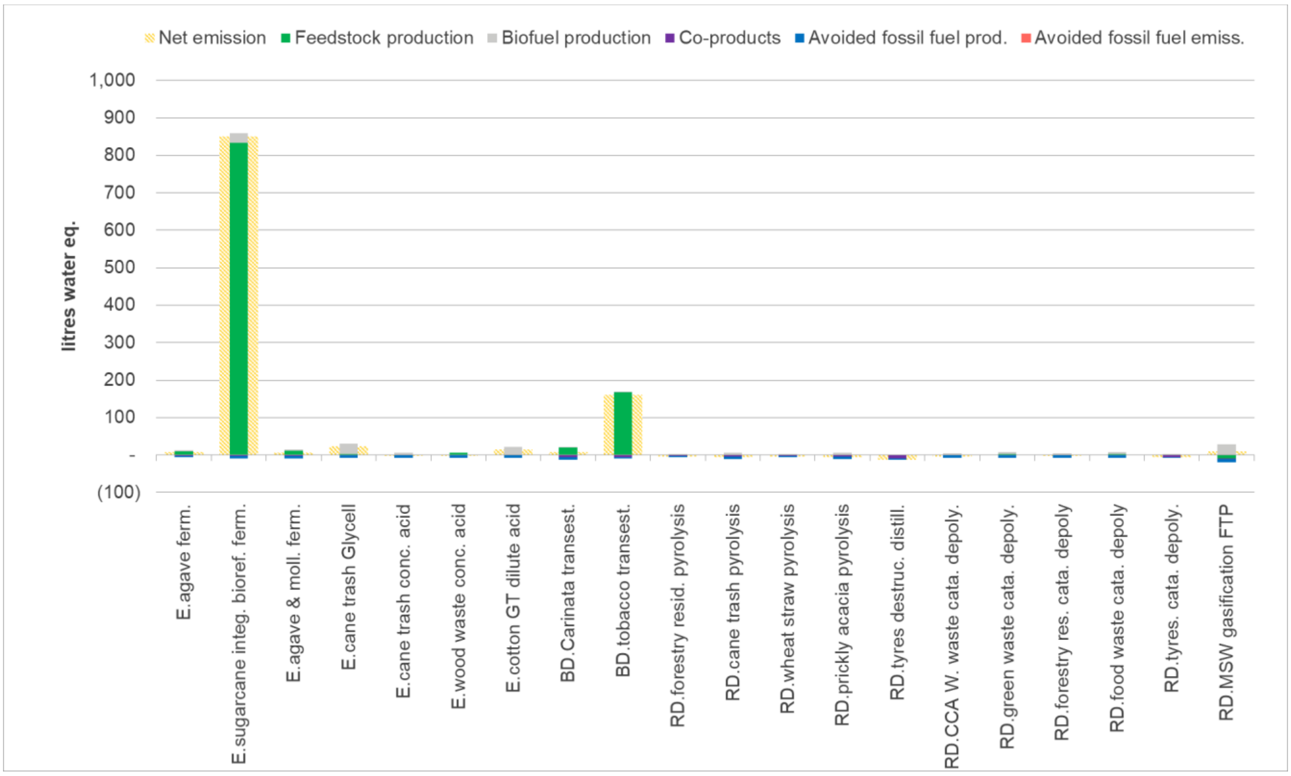


Figure 14 Water scarcity results for replacement of one litre of fossil fuel with equivalent biofuel.

7.2 Sensitivity analyses

Sensitivity analyses were used to increase the robustness of conclusions from the LCA and provide further insights into the observed environmental impacts. The following were included in the sensitivity analyses:

- The effects of alternative allocation approaches for co-products
- The effects of tyre source and alternative assumptions on fate
- Landfill as an alternative fate instead of aerobic stabilisation of waste as alternative fate for food waste and municipal solid waste (MSW) feedstocks
- Exclusion of landfill store of carbon for tyres, solid waste, and timber wastes.
- Soil carbon changes from biomass removal with sugar and cereal residues and forestry residues
- The inclusion of indirect land use change (iLUC)
- Alternative markets for carbon products from pyrolysis.

7.2.1 The effects of alternative allocation approaches for co-products

The default allocation approach to dealing with co-products and wastes was system expansion, in line with ISO 14044 standards and the draft ARENA guidelines for undertaking LCA for bioenergy and biofuel projects. However, both of these documents also require the effect of possible alternative approaches to be tested in the LCA to determine if they change the results. This sensitivity analysis examined the effect of economic allocation on the LCA results. Economic values were collected from the best available sources in the public domain. Ideally a price average of price trend data from the last five years was used, but in some cases, it was limited to a single quoted price. Wherever possible, the same price data were used in a single allocation. In some instances, industry price ratios were used rather than absolute values.

Figure 15 shows the results for the scenarios using economic allocation. In all scenarios the climate change impacts are lower for biofuel than the fossil fuels they replace.

Figure 16 shows the direct comparison of economic allocation with the study results based on system expansion. The variation in the results are greatest when comparing scenarios with waste products such as tyres, wood waste. For most other scenarios the variation is not so significant between the two calculation approaches.

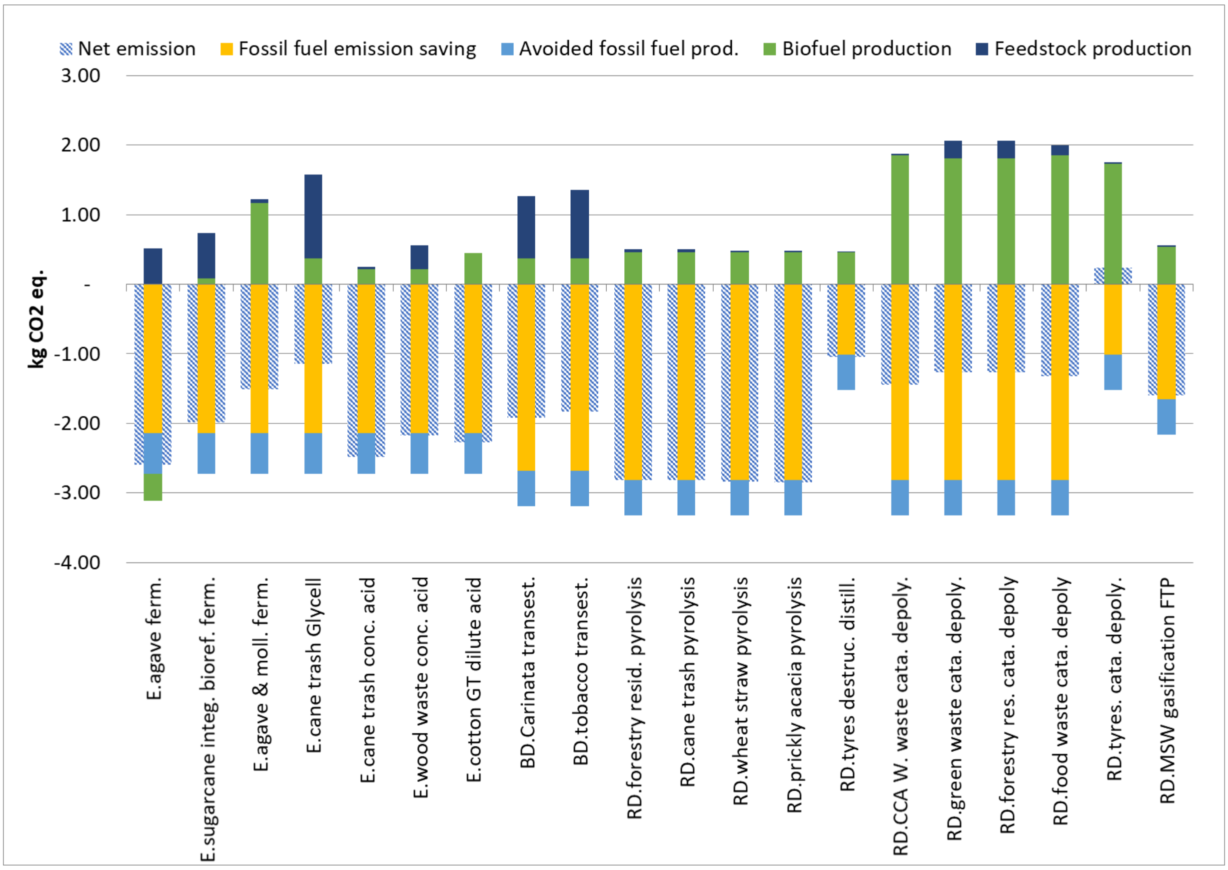


Figure 15 Climate change impact using economic allocation for 1 litre of fossil fuel replaced by equivalent biofuel

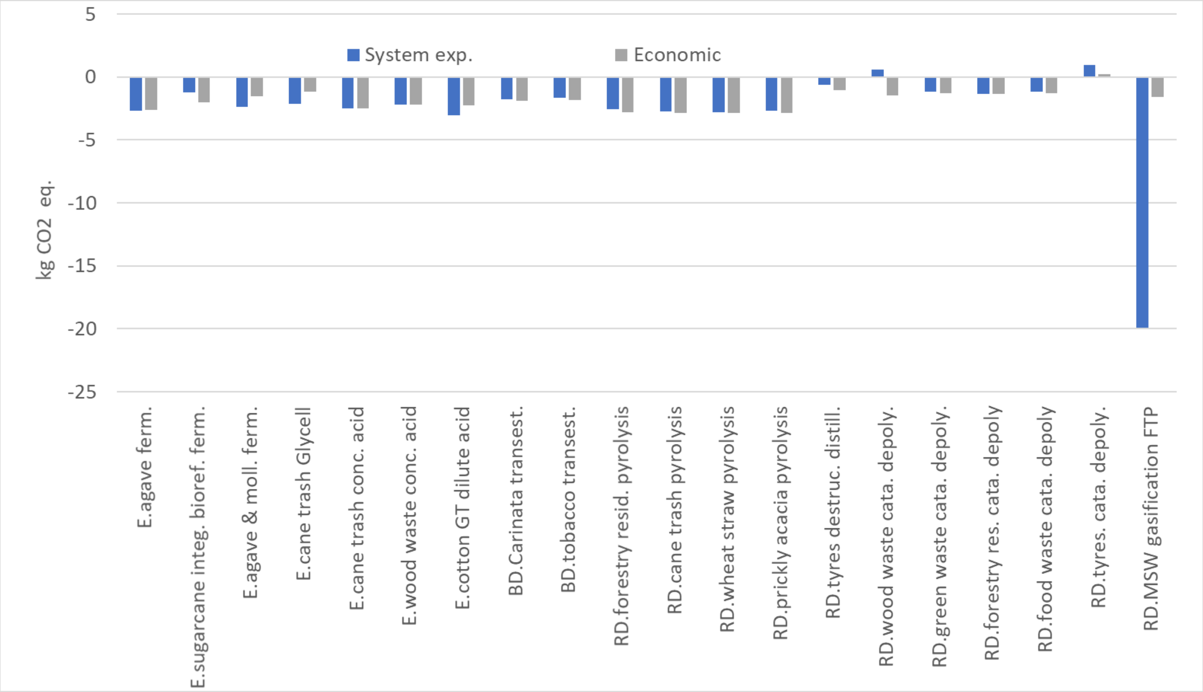


Figure 16 Comparison climate change results (using system expansion) to economic allocation

7.2.2 The effects of tyre source and alternative assumptions on fate

The results for the beneficial uses of tyres for biofuel production produce counter-intuitive results. While tyres represent a problematic disposal problem in landfill or dumping at mine sites, this disposal does keep carbon in the tyres out of the atmosphere. If tyres are utilised in biofuel the carbon stored in the tyres, or some fraction of it, is released to the atmosphere.

This sensitivity analysis looks at the different assumptions of what will happen to tyres if they are not utilised in biofuel. These options include:

- Landfill – all tyres are assumed to be stored in landfill where they do not degrade (study default)
- Cement kiln – tyres are combusted in a cement kiln where they replace coal.
- No fate – no prior destination is assumed and no credit for carbon storage is provided to waste tyres
- Economic allocation – under economic allocation the prior fate of tyres is ignored, fossil carbon emissions from the tyres are counted as GHG emissions while biogenic carbon emissions are ignored.

The sensitivity analysis also looks at the effects of different types of tyres, such as truck and bus tyres, passenger tyres or mining tyres taking into account the different composition of tyres shown in Appendix A.1.3.

Figure 17 and Figure 18 show how the climate change results vary depending of the assumptions of both the alternative fate for tyres and the source of tyres for destructive distillation and catalytic depolymerisation respectively.

Landfill and cement kilns present similar results with both beneficially avoiding the emission of fossil carbon to the atmosphere either through its storage in landfill or its replacement of coal emissions in a cement kiln. If the prior fate is ignored, the benefits are greater from the use tyres in the biofuel scenario. The economic allocation approach based on the RSB calculation approach ignores prior fate of the waste, as the tyres typically have no value, but also only credits emission offset from biogenically (via plants) derived carbon. So, in this instance, the emissions from synthetic rubber produced into biofuel are counted as climate change contributors. This is highest for the passenger tyres, which have the greatest amount of synthetic rubber.

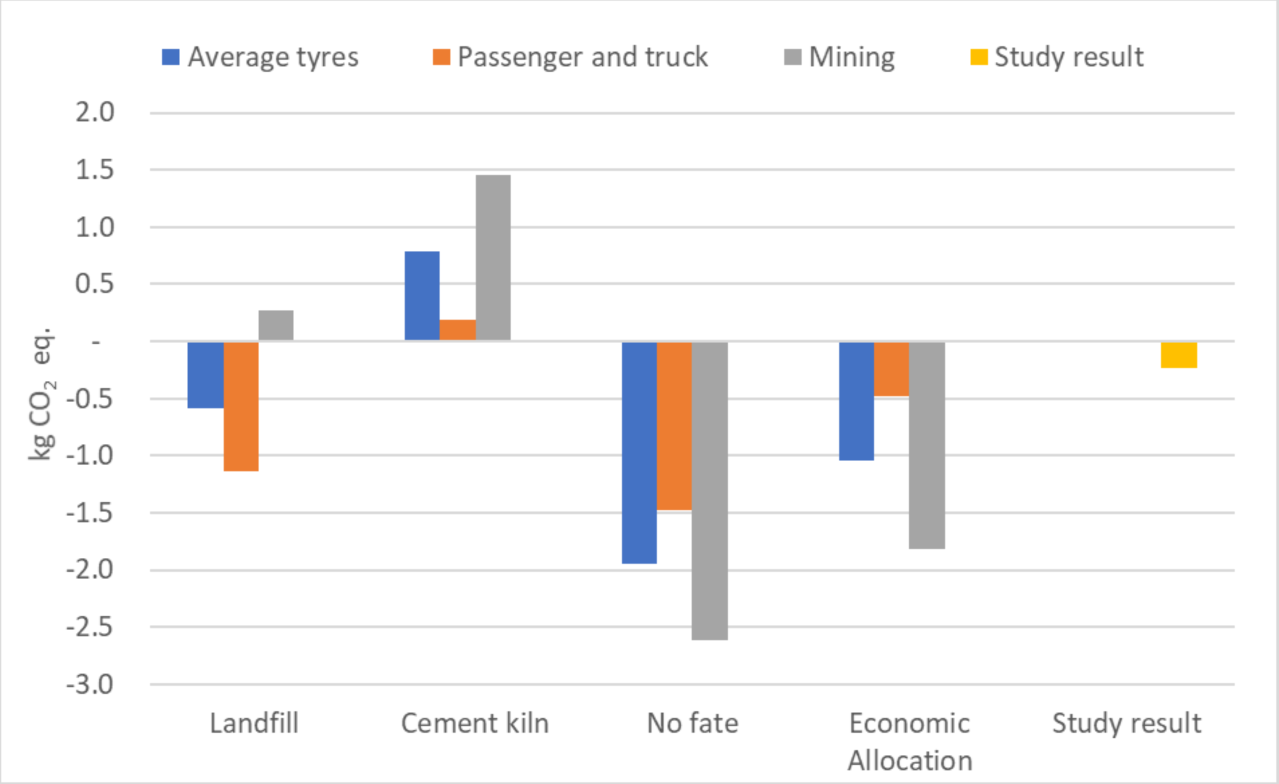


Figure 17 Sensitivity of tyre source and alternative fate for destructive distillation of tyres.

For renewable diesel produced through catalytic depolymerisation, the alternative fate of landfill storage or cement kilns represent a more favourable pathway for tyres in terms of climate change impacts. This is because the carbon offset is achieved in these scenarios with a minimum amount of additional processing. Even ignoring the prior fate in the no fate scenario, the benefits of passenger tyres offsets are not sufficient to offset the biofuel processing emissions. This is because of the high proportion of fossil-based carbon in the passenger tyres. For mining tyres, which are all-natural rubber, the biofuel option is preferable under the no alternative fate scenario and similarly under the economic allocation scenario.

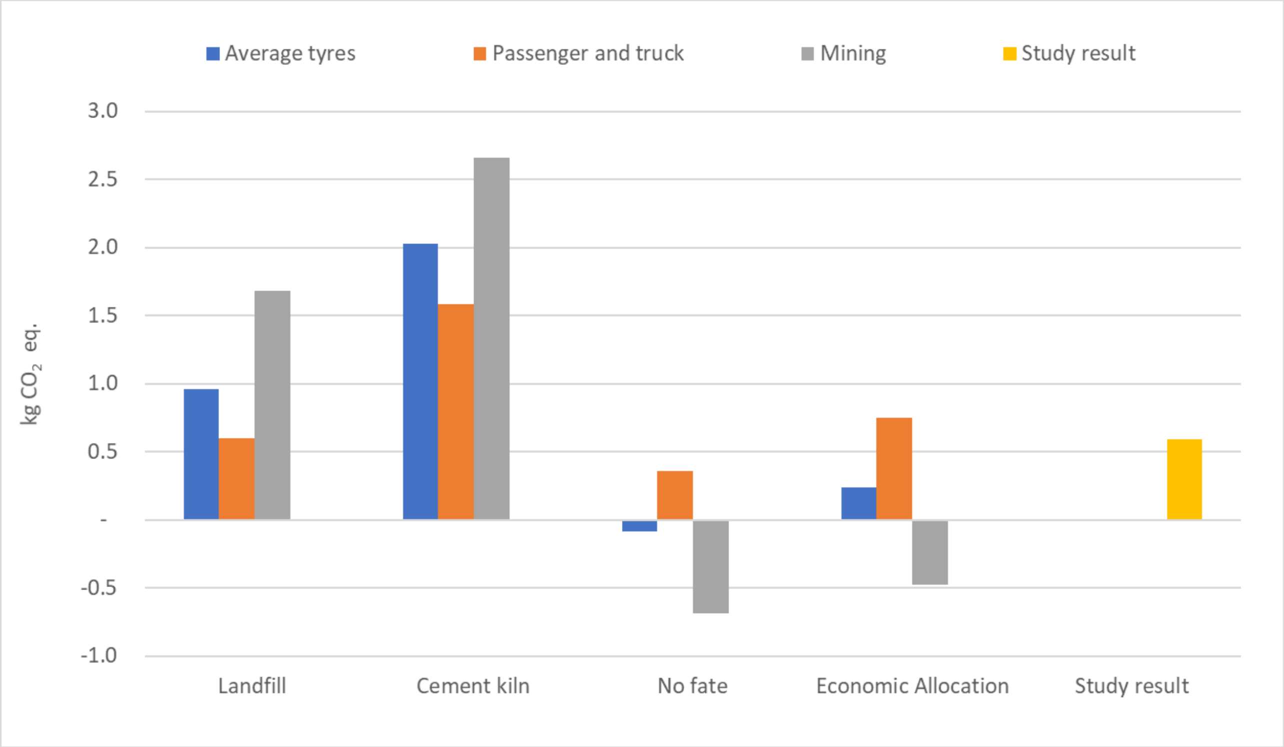


Figure 18 Sensitivity of tyre source and alternative fate for catalytic depolymerisation of tyres.

7.2.3 Landfill instead of composting waste as alternative fate for food waste garden waste and timber waste feedstocks.

For source separated organics waste streams the default assumption is that the alternative fate of these is composting. This is currently common for food, green waste and timber waste however there is potential for the biofuel industry to divert material from landfill. This scenario examines the impact if the alternative fate for food waste, green waste and wood waste is landfill rather than composting. It includes two landfill options – the average Australian landfill which is assumed to capture 46% of methane ((Commonwealth of Australia 2017) and the second where there is no gas capture - which may represent smaller regional landfills.

Note that CCA wood waste and MSW to gasification are not included in this sensitivity as they are already assumed to be diverted from landfill.

Wood waste used in catalytic depolymerisation changes little with alternative waste treatment due to the low level of degradable organic carbon released in landfill or aerobic stabilisation (Figure 19). For food waste and MSW the conventional life difference between aerobic stabilisation and landfill with or without gas capture is very large. This is principally due to methane emissions from landfill which, if avoided, lead to very large benefits, in this case allocated to the production of biofuel.

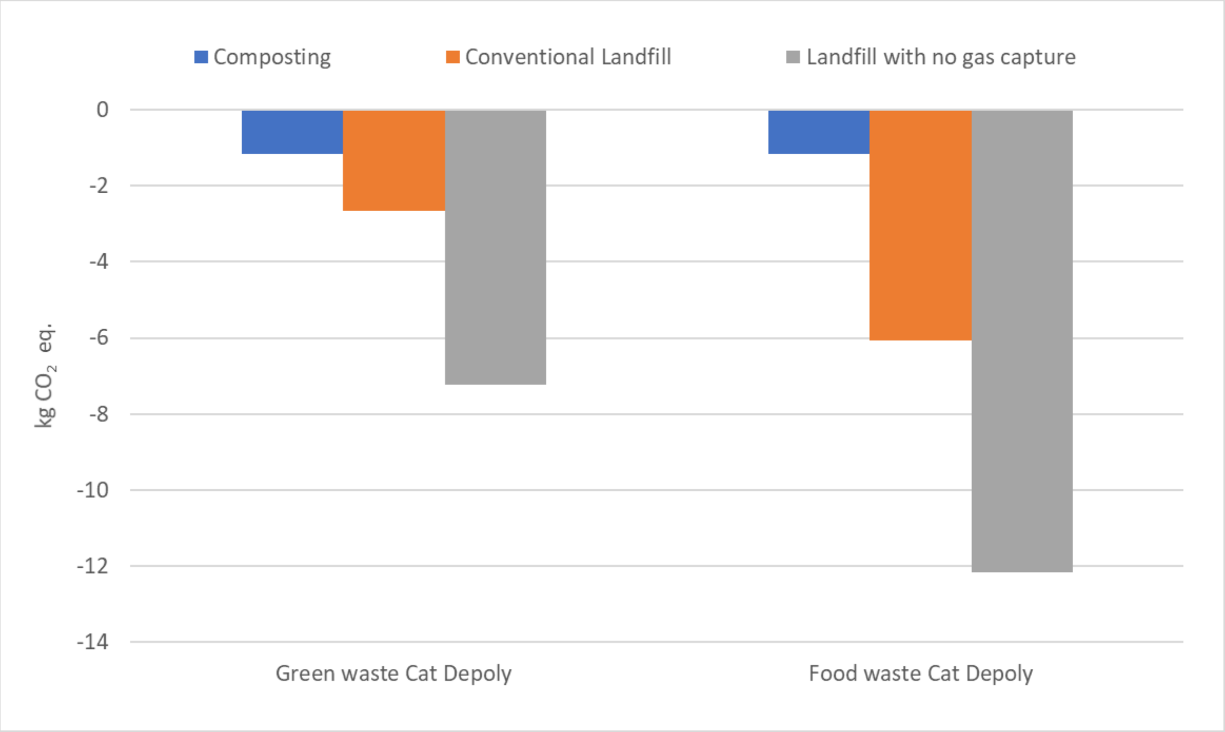


Figure 19 Sensitivity of alternative fate for organic materials for replacing one litre of fossil fuels with biofuel.

7.2.4 Exclusion of landfill store of carbon for tyres, solid waste, and CCA wood waste.

The decision to count the carbon in waste disposal to landfill as a carbon sequestration can be challenged on several grounds. Firstly, the national greenhouse gas account for Australia (Commonwealth of Australia 2017) do not count these materials entering landfill as a store in our national accounts. The international standard on carbon footprinting of products (International Organization for Standardization 2013) does not explicitly mention landfill carbon, but does require carbon storage in products to be reported separate to the carbon footprint. Carbon content and degradability of waste is estimated in the national accounts to develop emission factors for methane from landfills, but the actual storage of biogenic carbon in landfill is not included. Secondly, there is no specific management of waste at landfills aimed at storing carbon and there is a high level of uncertainty about the permanence of the carbon store. Finally, there are the other impacts of landfill, including leachate and resource loss which make it difficult to prioritise this technology as a treatment option in the future.

This sensitivity analysis excludes carbon storage in landfill and other disposal options such as abandonment of mining tyres. Figure 20 shows how the climate change results change from the study results when the landfill carbon storage is excluded. Table 16 shows that the three scenarios which previously do not meet the 20% climate change saving threshold will more than meet this threshold if landfill carbon storage is not included.

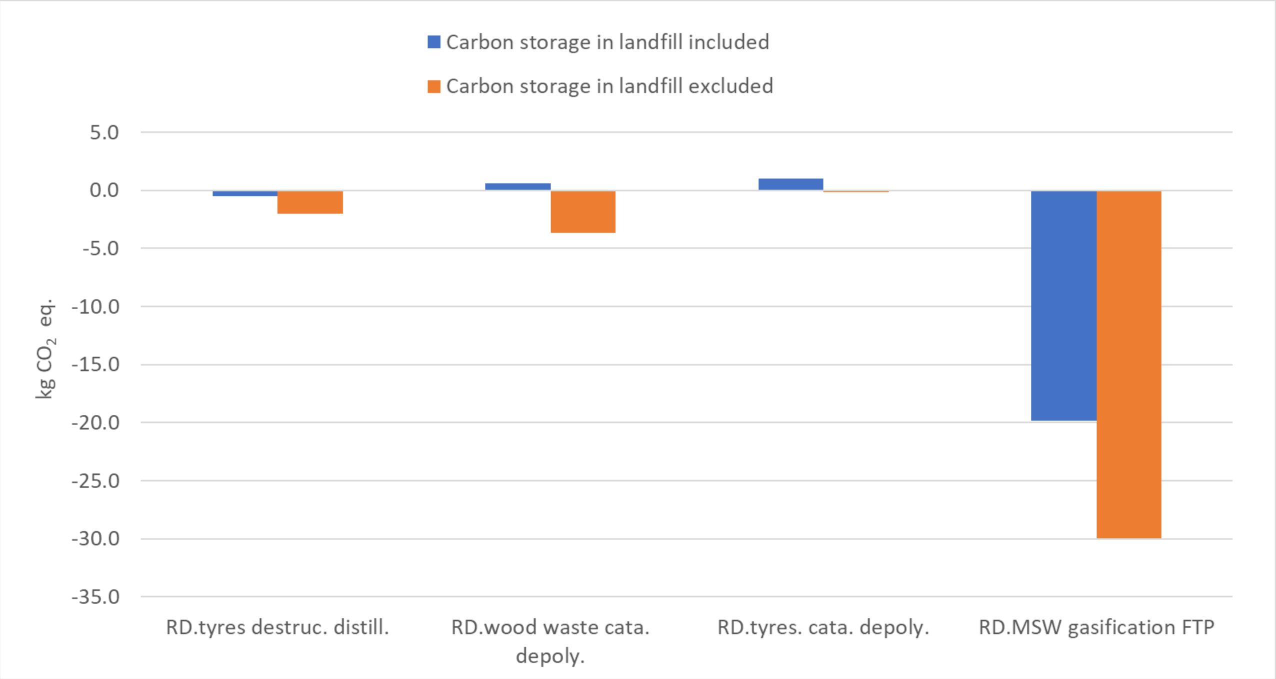


Figure 20 Sensitivity of excluding carbon storage in landfills.

Table 16: Change in percentage improvement climate change results when replacing fossil fuel with equivalent biofuel

Robustness Check	Study result %	Result when excluding landfill carbon storage.
	%	%
RD.tyres destruc. distill.	18	76
RD.CCA wood waste cata. depoly.	-18	124
RD.tyres. cata. depoly.	-29	11
RD.MSW gasification FTP	593	1008

7.2.5 Soil carbon changes from biomass removal

There are fuel pathways that have the potential to change soil carbon due to biomass removal, which would affect the results for climate change. These are those involving cane trash, wheat straw and forestry residues. Table 17 outlines the assumptions used for this sensitivity analysis. Soil carbon changes are complex and site specific and have high levels of uncertainty. A detailed calculation of these carbon changes is beyond the scope of this report, so some typical estimates of potential soil carbon changes have been used.

Table 17 Assumptions used for sensitivity analysis of including potential soil carbon change from removing biomass from cane, wheat and forest systems.

Feedstock	Change in C	Source/comment
Cane trash	500 kg/ha/year	Estimate from changes in burnt cane to green cane harvesting described in (Robertson and Thorburn 2007). Proposal is to remove 50% of residues.
Wheat straw	130 kg/ha/year	Unpublished data from CSIRO using the Agricultural Production Systems sIMulator (APSIM) in AER 22 to look at soil carbon accumulation. Assumption is that shifting from average to 15% removal of residue to 50% removal will change soil carbon accumulation from 218 kg/ha/year. With 35% less biomass being retained soil carbon changes to 76 kg/ha/year.
Forestry residues	5,000 kg/ha/35 years.	Author estimate based on directional suggestion from (Achat, Fortin et al. 2015).

Figure 21 shows the results for possible carbon changes from soil carbon change. For sugarcane trash the changes in results are small. This is due to the high yields of biomass per ha, so any potential change in soil carbon is spread across a significant volume of biofuel. By contrast, with the impacts for potential changes for wheat straw, the impacts are significant because the yield of straw is much lower, and the carbon loss is concentrated in a smaller volume of fuel.

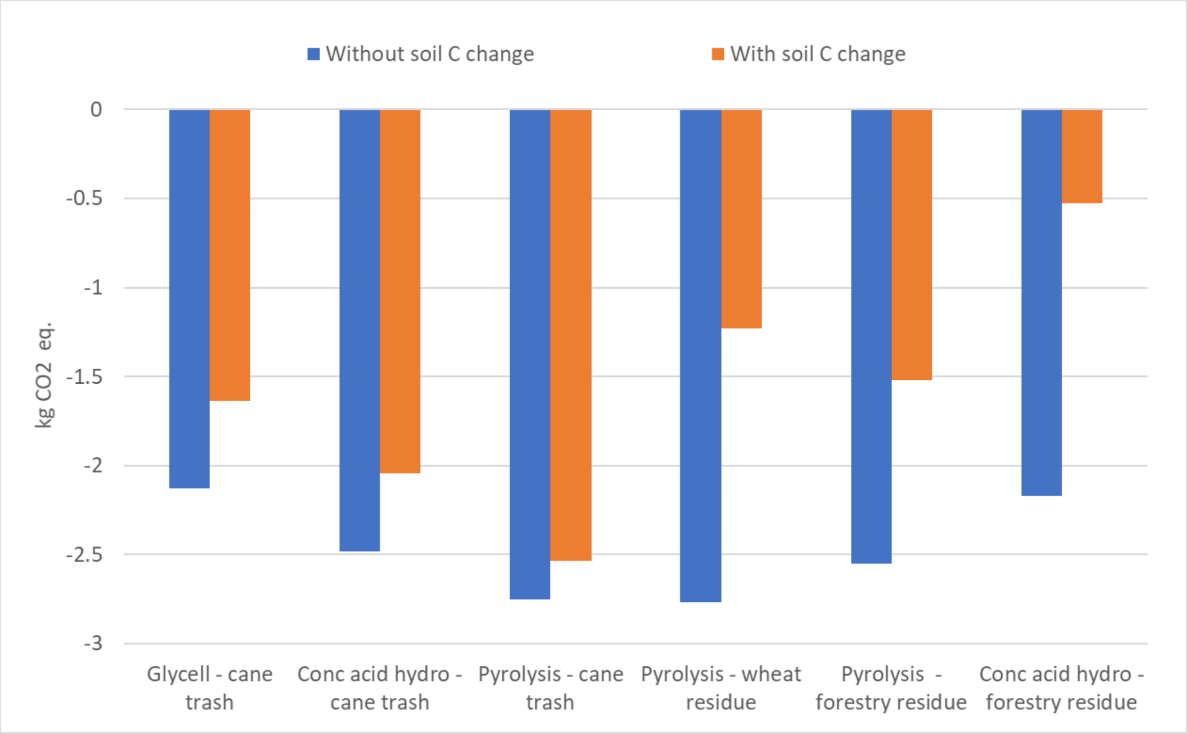


Figure 21 Sensitivity of including possible soil carbon change from removing biomass from cane, wheat and forest systems on fuels made from these residues.

7.2.6 The inclusion of iLUC

To test the potential influence of indirect land use change iLUC, iLUC factors provided by CARB (California Air Resources Board 2015) were used. In this study only five scenarios are based on crops and therefore have potential impact on iLUC.

In this approach, waste/co-products including residues, bagasse, tyres, gin trash and other wastes have no iLUC value. Carinata value was 14.5 g CO_2 per MJ of fuel, which was also used for tobacco, while for sugarcane the value was 11.8 g CO_2 per MJ of fuel (California Air Resources Board 2015). No factors have been found for agave, so the agave scenarios used the same value as sugarcane.

Figure 22 shows the potential change to climate change impact when iLUC values are included for biodiesel from Carinata and tobacco, and ethanol from sugarcane and agave. The impacts are not insignificant; however, they do not negate the overall climate change benefits of these fuels.

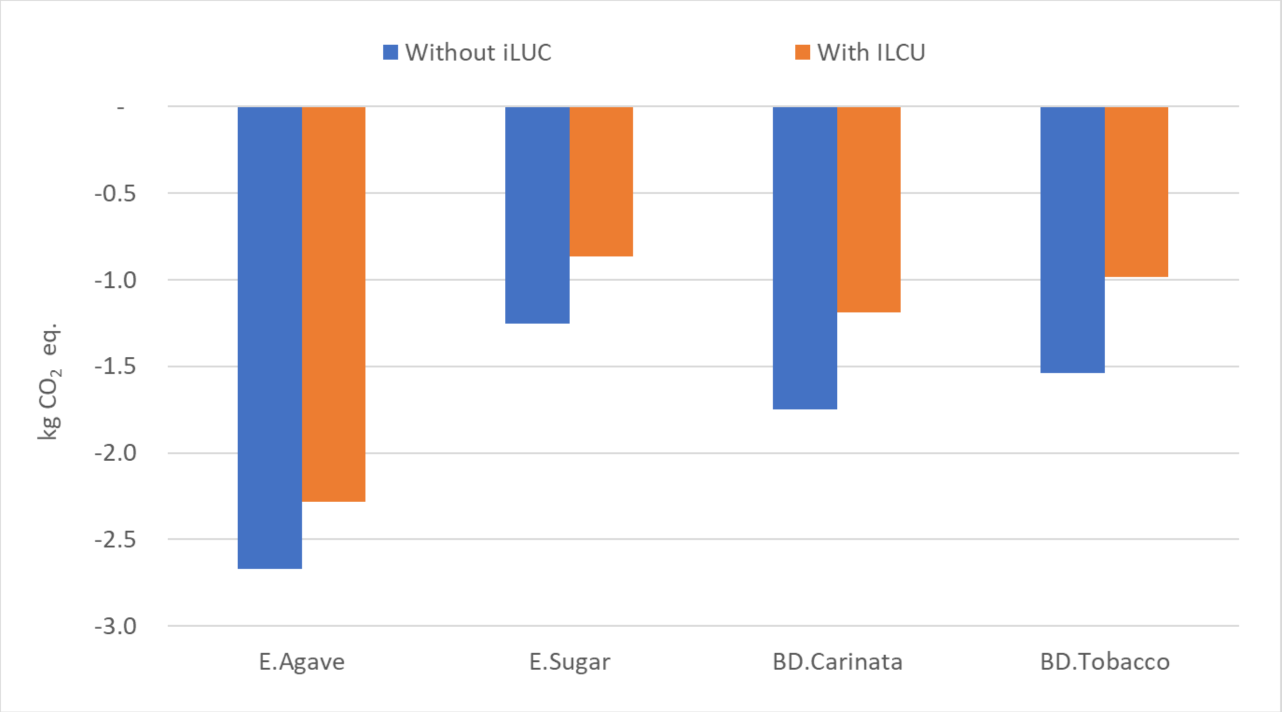


Figure 22 Sensitivity of climate change impacts of iLUC on biofuels from dedicated cropping systems.

7.2.7 Alternative markets for carbon from pyrolysis and destructive distillation

For the scenarios that have a dry carbon product export, there is some uncertainty around the destination markets for that product.

Four scenarios were tested:

- petroleum coke – a product used in the steel industry (this is a default scenario used in the study)
- charcoal – a product with a range of uses including filtration and combustion
- carbon black – this can be used as a filler in plastics and tyres
- no market – this scenario provides no credit for exported carbon, which forms a baseline for the minimum performance of the option.

Data for all three products have been taken from ecoinvent LCA database.

Figure 23 shows that the assumptions around the carbon market have a significant effect on the overall performance of the pyrolysis biofuel scenarios and that the petroleum coke scenario is the most conservative in the sense that it gives the least benefit to the biofuel scenarios of the three products tested. Even in the extreme case where there is no market for the carbon exported, the scenarios are still favourable from a climate change perspective for all scenarios with the exception of tyres processed through destructive distillation.

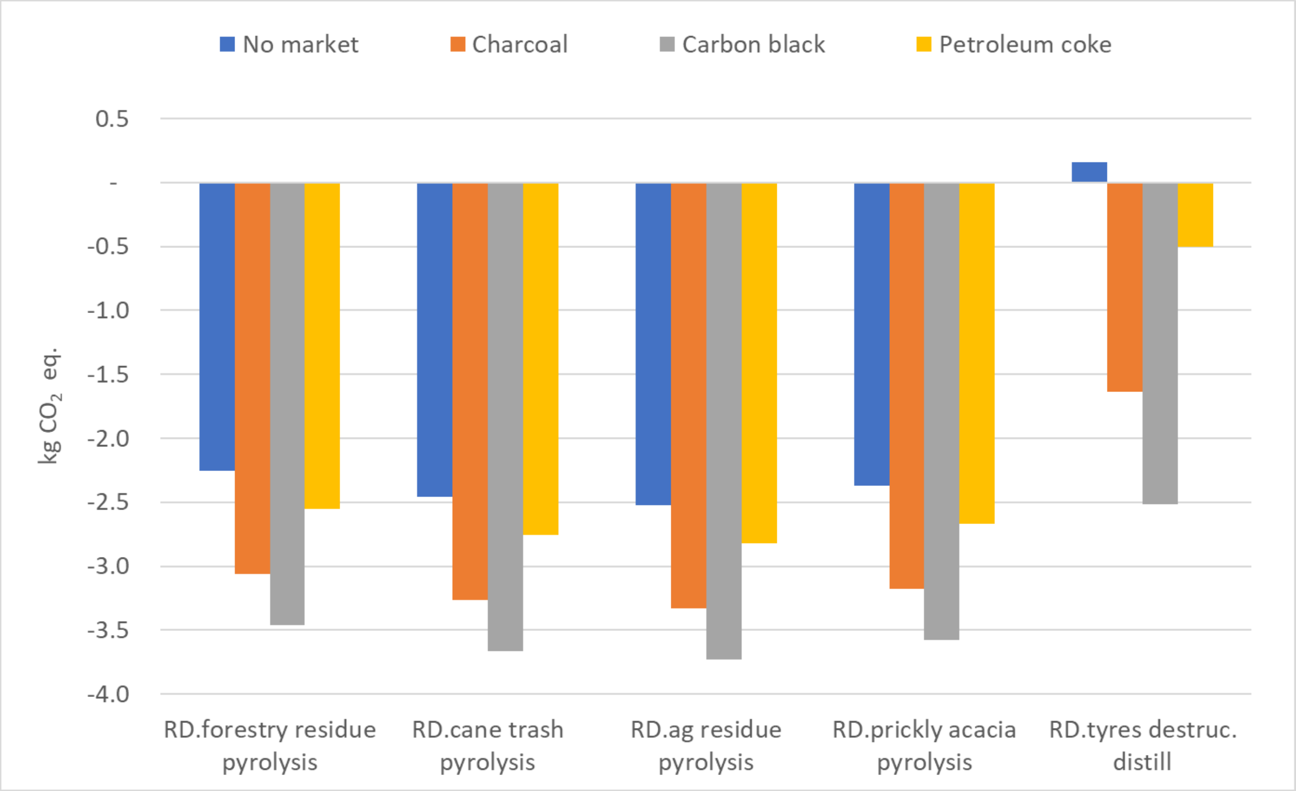


Figure 23 Sensitivity of alternative and markets for carbon exported from pyrolysis processes.

7.3 Data quality assessment and uncertainty analysis

A systematic uncertainty analysis is not possible in this scope of this study; however, to test the robustness of results, a set of conservative assumptions tests have been applied to each scenario based on the data quality commentary. The selection of criteria is based on authors' judgements of the areas of greatest importance and uncertainty in each scenario.

Table 18 lists the data quality consideration for both the feedstock and the biofuel production process for each scenario. The 4th column provides the parameters that were varied in the scenario to test the robustness of the results to potential variation. The last two columns provide the results of the study as well as the results using the robustness check.

For the 17 scenarios that have greater than 20% climate change savings, all of these pass the robustness test, and none of them fall below 29%. There is a significant reduction in benefits from removing energy and carbon product exports.

Table 18 Data quality statement and robustness assessment.

SCENARIO NAME	DATA QUALITY FEEDSTOCK	DATA QUALITY FUEL SYSTEM	ROBUSTNESS CHECK ASSUMPTIONS	STUDY RESULT	ROBUSTNESS CHECK
				CLIMATE CHANGE SAVINGS FROM BIOFUEL REPLACEMENT OF FOSSIL	
E.agave ferm.	Agave is not grown at a commercial scale but growth trial data is local to Australia.	Commercial applications of ethanol as biofuel from agave are not common, even in Mexico; however, commercial application is common for tequila production. Energy co-production is taken from sugarcane system, so level of energy export has some uncertainty.	No energy credit 20% lower agave yield 10% lower ethanol yield	76%	45%
E.sugarcane integ. bioref. ferm.	Established cropping system with low uncertainty	Established fermentation and distillation technology. While Australia has traditionally used molasses as feedstock, Brazil has used sugar juice for many years.	No bio-dunder credit	42%	39%

SCENARIO NAME	DATA QUALITY FEEDSTOCK	DATA QUALITY FUEL SYSTEM	ROBUSTNESS CHECK ASSUMPTIONS	STUDY RESULT	ROBUSTNESS CHECK
				CLIMATE CHANGE SAVINGS FROM BIOFUEL REPLACEMENT OF FOSSIL	
E.agave & moll. ferm.	Molasses component of scenario is well-tested and based on real data – for agave component see prior scenario.	Molasses component of scenario is well tested and based on real data – for agave component see prior scenario.	No energy credit 20% lower agave yield 0% lower ethanol yield	90%	64%
E.cane trash Glycell	Availability of cane trash and tops is not under contention. Harvesting and aggregation approach may have some uncertainty.	Commercial applications of the technology are not readily available. In the study a number of potential co-products have already been excluded from this scenario.	Acid recycle efficiency change from 99% to 90% Ethanol yield dropped by 10% Double glycerine used 300 km for transport of cane trash instead of 100 km No benefit from nitrous oxide reduction from cane trash application	42%	39%
E.cane trash conc. acid	Availability of cane trash and tops is not under contention. Harvesting and aggregation approach may have some uncertainty. It is also suggested that unutilised bagasse may also be sourced for this technology.	While concentrated acid hydrolysis is not a new technology, the version proposed in this study has not proceeded past pilot plant stage.	Acid use doubled Ethanol yield dropped by 10% 300 km for transport of cane trash instead of 150 km No benefit from nitrous oxide reduction from cane trash application	80%	65%
E.wood waste conc. acid	Supply of sufficiently clean wood waste may be limited.		Acid use doubled Ethanol yield dropped by 10% 200 km for transport of wood waste instead of 100 km	72%	67%
E.cotton GT dilute acid	Cotton gin trash is a waste product that is available and centralised.	Established technology, although not applied in Australia. All data are from European database.	20% lower ethanol yield No electricity export	102%	66%
BD.Carinata transest.	Similar to canola, which is commonly grown in Australia, so very low uncertainty.	Transesterification is a proven technology. Markets for glycerine are sometimes difficult.	10% lower yield No co-product credits for glycerine or potassium carbonate	52%	48%

SCENARIO NAME	DATA QUALITY FEEDSTOCK	DATA QUALITY FUEL SYSTEM	ROBUSTNESS CHECK ASSUMPTIONS	STUDY RESULT	ROBUSTNESS CHECK
				CLIMATE CHANGE SAVINGS FROM BIOFUEL REPLACEMENT OF FOSSIL	
BD.tobacco transest.	This variety has not been grown on scale in Australia so some uncertainty around yield. Italian study is thought to under-report yield.	Transesterification is a proven technology. Markets for glycerine are sometimes difficult.	10% lower yield No co-product credits for glycerine or potassium carbonate	46%	41%
RD.forestry resid. pyrolysis	Actual source of residue has not been specified yet, there are also unknown implications for soil carbon.	Well established pilot plant is in place although final mix of technology options is still being explored. The exact markets for carbon co-product has some uncertainty.	500 km transport for forestry residue instead of 150 km 10% lower yield in bio-oil from pyrolysis No carbon export	76%	69%
RD.cane trash pyrolysis	Good quality data on availability and supply. Unknown implications for soil carbon.		Soil carbon loss from removal 10% lower yield in bio-oil from pyrolysis No carbon export	82%	79%
RD.wheat straw pyrolysis	Good quality data on availability and supply. Unknown implications for soil carbon.		Soil carbon loss from removal. 10% lower yield in bio-oil from pyrolysis No carbon export	84%	30%
RD.prickly acacia pyrolysis	Harvesting data based on sugarcane harvesting.		500 km transport instead of 150 km 10% lower yield in bio-oil from pyrolysis No carbon export	80%	73%
RD.tyres destruc. distill.	Exact source and type of tyres used is uncertain, as is the fate of tyres if they are not used in biofuel.	No commercial plant available so data is from small-scale plants and process models.	500 km transport instead of 100 km 10% lower yield in destructive distillation No carbon export	18%	28%

SCENARIO NAME	DATA QUALITY FEEDSTOCK	DATA QUALITY FUEL SYSTEM	ROBUSTNESS CHECK ASSUMPTIONS	STUDY RESULT	ROBUSTNESS CHECK
				CLIMATE CHANGE SAVINGS FROM BIOFUEL REPLACEMENT OF FOSSIL	
RD.CCA W. waste cata. depoly.	Source type of wood waste is uncertain, as is the fate of timber waste if not used in a biofuel system.	Well studied at small scale but pilot and commercial-scale plants are not available.	200 km transport instead of 100 km 20% lower yield of diesel	-18%	-18%
RD.green waste cata. depoly.	Green waste supply is well understood, although the catchment required to source material is uncertain.		200 km transport instead of 100 km 20% lower yield of diesel	35%	33%
RD.forestry res. cata. depoly	Actual source of residue has not been specified yet, there are also unknown implications for soil carbon.		500 km transport instead of 150 km 20% lower yield of diesel	39%	36%
RD.food waste cata. depoly	Food waste collections still being established so the catchment required to source material is uncertain.		200 km transport instead of 100 km 20% lower yield of diesel	35%	33%
RD.tyres. cata. depoly.	Exact source and type of tyres used is uncertain, as is the fate of tyres if they are not used in biofuel.		500 km transport instead of 100 km 20% lower yield of diesel	-29%	-21%
RD.MSW gasification FTP	Supply of MSW is well understood, although composition of material used in biofuel production is uncertain.	Well established technology, which has been used outside of Australian for many years.	10% lower yield No electricity export	593%	118%

8 Discussion and conclusions

The aim of this report is to determine the climate change benefits of potential biofuels for Queensland. Of the 20 scenarios assessed, 17 of them had greater than 20% benefit compared to conventional fossil fuel. The three fuels that do not meet this threshold would meet it if storage of carbon in landfill was excluded, as it is in Australia's national greenhouse accounts.

Because most of the scenarios were based on non-commercial technologies, a robustness check was undertaken to test how the results would shift if the scenario parameters were pushed to a highly conservative (in favour of fossil fuel) position. All 17 scenarios that initially passed the 20% threshold still had more than 20% savings after applying the robustness check.

There are some generalisations that can be drawn from the 20 scenarios in relation to climate change impacts.

- Biofuels which address waste management challenges with highly degradable carbon, such as MSW, food & green waste can have dramatic benefits, especially if the biofuel helps to keep these materials from going to landfill.
- Biofuels based on highly stable carbon wastes such as tyres and wood waste need to compete with alternative treatment methods which can include landfill but also other fuel using processes such as cement kilns. In these scenarios the local supply situation will be critical to determine the alternative fate of these materials and therefore the overall environmental performance.
- Biofuels based on accessing woody wastes are otherwise breaking down in the environment, such as forestry and agriculture residues and prickly acacia, have performed very well with the only possible concern being the effects of these removals on soil carbon.
- Biofuels based on high biomass yields that combine to produce liquid fuels and electricity perform well and however they do increase indirect land use pressure and for some overall water demand.
- Biofuels based on vegetable oils have the benefits of low processing impacts and valuable protein co-products. There is also benefits of using these crops between other cereal crops for beneficial break crop effects.

Other environmental indicators provide insights to the trade-offs required to address climate change impacts. Unsurprisingly, growing crops leads to impacts of land use indicators, and irrigated crops have impacts on water scarcity. The sugarcane growing system has significant potential impacts on eutrophication, which is already well understood in the sugar industry and is reduced through best practice programs such as Smartcane BMP Program. Particulate matter impacts are mostly higher from fossil fuel production; however, where biomass combustion is included in the biofuel system there is potential for significant impacts, which will ultimately be a function of the quality of the emissions control technology.

Care needs to be taken in interpreting the results, with consideration of the following parameters:

- the level of energy and carbon product exports from biomass systems
- ability to extract biomass without detrimental impacts to underlying soil carbon
- in the case of waste inputs, accessing the most likely alternative fate of the waste products that should be used as the baseline for comparison.

The transport of feedstocks has a low impact on the overall biofuel production footprint; it is likely that economic cost of transport will be the limiting factor to aggregating material before the environmental impacts become a dominant factor.

Appendix A. Feedstock and fuel details

A.1 Biomass feedstocks

A.1.1 Overview of the waste feedstocks

This appendix provides additional detail on waste products used as feedstocks including collation and alternative fates for that material if it is not used for biofuels.

The waste feedstocks assessed were:

- cane trash and tops (shortened to cane trash)
- agricultural residues – taken here to be cereal straw residues
- forestry residues
- prickly acacia
- green waste
- timber waste
- CCA treated timber waste
- food waste
- municipal solid waste (organic material fraction)
- waste tyres.

A.1.2 Cane trash and tops

Cane trash and tops are the residues after cane harvesting, which represent 25% of the biomass of a sugarcane crop (Botha 2009). The energy content of cane trash and tops is approximately 15 MJ/kg on a dry mass basis; however, after harvesting it has a water content of approximately 78% (Botha 2009). Botha also states that the relative energy content of trash and tops is 19.2% of total cane crop energy.

The economic value was assumed to be low in the field because the material is currently not collected for sale. The transport distance for cane trash and tops was assumed to be 150 km by road given the proximity of sugarcane throughout Queensland within proximity of potential biofuel facilities.

The impact of removing cane trash and tops from the field is twofold. Firstly, residual material left on cropland leads to nitrous oxide emissions. The relationship between the amount of residue remaining and nitrous oxide emissions was assumed to be linear and is described in the National Inventory Report (Commonwealth of Australia 2017).

The second effect is the potential change in soil carbon levels due to lower inputs of residue. While there is evidence that soil carbon changes with inputs of residues and fertilisers, there is no simple relationship. Robertson and Thorburn (2007) suggest a potential for an 8 to 15% increase in soil carbon when changing from a burnt cane to a green cane system with trash blankets over many years. However, a reduction from 100% to 50% of residue is a different situation. The default assumption was that trash management can be managed to maintain soil carbon at the same levels as at 100%. Assuming a soil carbon content of approximately 30 t/ha, a 10% increase over 20 years would equate to 0.5% per annum or 150 kg carbon per annum. This is used as a sensitivity assessment in section 7.2.5.

A.1.3 Forestry residues

Forestry residues are a waste biomass of trims from harvested trees in forestry operations. In Australia, 41% of the country's forested areas are in Queensland, which has 52.5 million hectares of native forests and 233,000 hectares of plantations (Figure 24). In this study only plantation forestry residues. On average, of every 100 tonnes of trees that are harvested, 65 tonnes is left behind in the forest to degrade (Andrew Macintosh 2018).

Forestry residues play a role in soil carbon accumulation (Achat, Fortin et al. 2015); however, detailed modelling of this is beyond the scope of this LCA. In the sensitivity section of this report, a scenario has been run whereby a difference of 5000 kg of carbon per ha is assumed due to biomass removal over a 35 year period, which is the assumed length of a softwood rotation. Figure 24 shows the distribution of plantations along the coastal region with a more significant plantations located int eh south east.

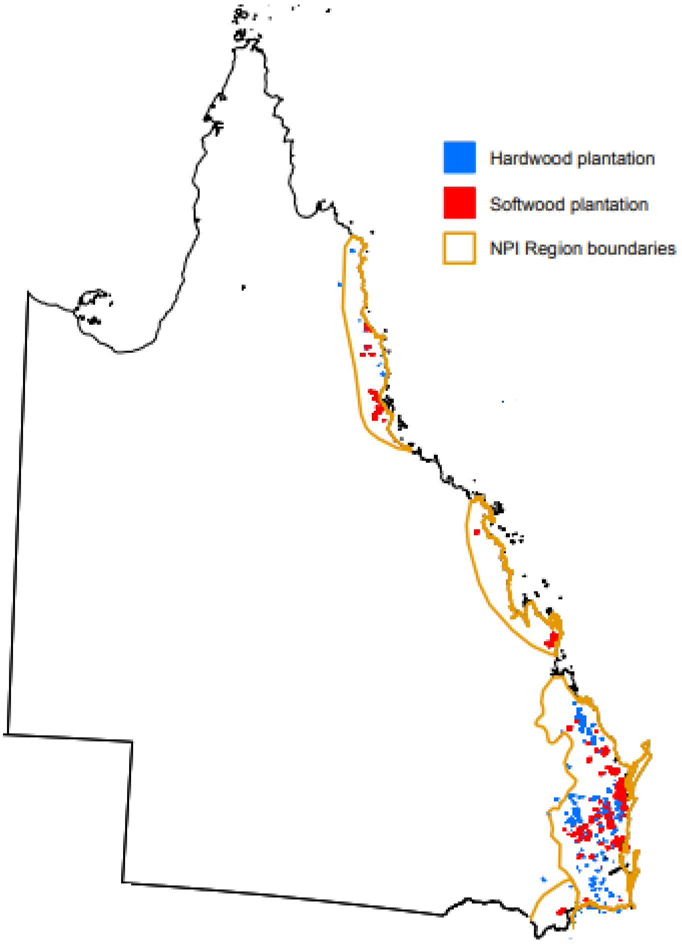


Figure 24 Map of plantations in Queensland.

Source: (Montreal Process Implementation Group for Australia 2013)

The process data for collection and delivery of forestry residues to a biofuel facility are shown in Table 19.

Table 19 Data for collection and delivery of 1 tonne of forestry residues to biofuel facility.

Item	Unit	Flow	Transportation distances (km)
Transport, truck, 28 t	tkm	150	150 km transport (author's assumption)
Wood chipping, mobile, diesel	hr	0.1	Author's estimate on time. Process consumes 70 L diesel per hour

A.1.4 Agricultural residues

Cereal residues were assumed to be from wheat, barley and similar grains. Wheat has been used in this study as a typical source of residues. Wheat production in Queensland is shown in Figure 25. The highest amounts of residue are from the southern parts of the state, but there is significant production up into central Queensland. It was assumed that a biofuel facility would be located within a few hundred kilometres of the grain growing areas, so the transport distance has been estimated to be an average of 150 km.

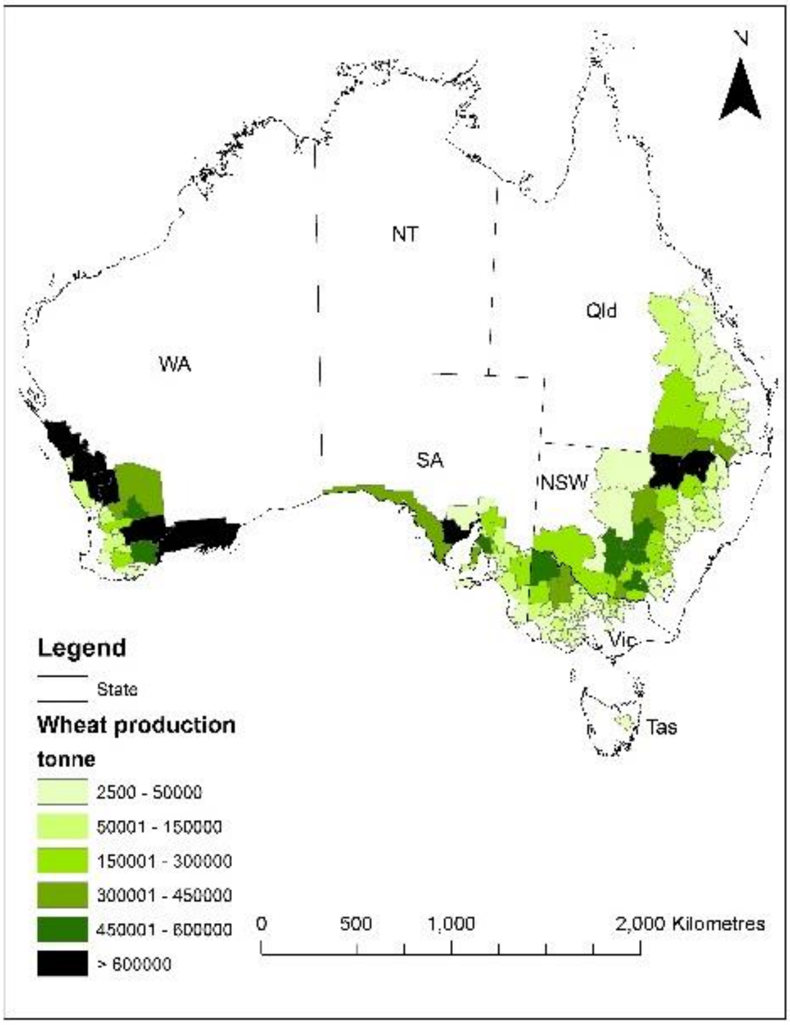


Figure 25 Production (t/year) for wheat, averaged over four years. Source: (Australian Bureau of Statistics 2015).

Wheat residue was treated in similar way to cane trash, with zero economic value and an impact on nitrous oxide emissions as described in the National Inventory Report (Commonwealth of Australia 2017). The energy content of straw and wheat grain was assumed to be 18 MJ/kg (Feedipedia 2016), making the energy allocation the same as a mass allocation between residue and grain.

For potential changes in soil carbon, the change has been estimated using currently unpublished data from CSIRO which used APSIM (an agricultural simulation tool). Data for the Queensland cereal growing region was used to look at soil carbon accumulation. The current soil carbon accumulation in this region is 218 kg/ha/year. For a sensitivity analysis, the assumption was that cereal residue harvesting will be gained through shifting from average to 15% removal of residue to 50% removal. This results in 35% less retained biomass, which was then assumed to reduce soil carbon accumulation by 35%, equating to 76.3 kg/ha/year.

Table 20 shows the process for the supply of wheat straw to a biofuel facility. The transport distance for residues was assumed to be 150 km by road, and a shift from cropping with 15% stubble removal to 75% stubble removal. This allows for 25% to be retained for soil stability.

Table 20 Process data for collection and delivery of 1 tonne of agricultural residues to biofuel facility.

Item	Unit	Flow	Transportation distances (km)
Transport, truck, 28 t	tkm	150	150 km transport (author's assumption)
Wheat, dryland, 75% stubble removed	t	1113	Practice in higher biomass harvest scenario
Wheat, dryland, 15% stubble removed	t	-1113	Current typical practice (Umbers, Watson et al. 2016)

A.1.5 Prickly acacia

Prickly acacia is thorny shrub or small tree that is native to India, but in Australia it is a widespread invasive plant that can encourage erosion, threaten biodiversity and reduce pasture productivity. Prickly acacia is a restricted invasive plant under the *Biosecurity Act (2014)*.

A map of distribution of prickly acacia is shown in Figure 26. For a biorefinery located in Gladstone there is a significant supply of the crop within 150 km. The majority of the prickly acacia, however, sits 500 km west of Gladstone. The baseline assumption for the use of prickly acacia was based on a transport distance of 150 km by articulated truck, with a sensitivity analysis undertaken using 500 km of road transport and rail transport.

Energy use in harvesting prickly acacia was based on 2sugarcane harvesting as suggested by Schmidt, Giles et al. (2012). No alternative fate was attributed to prickly acacia, and benefits of its removal are not included in this study. The data for delivering prickly acacia to a biofuel facility is shown in Figure 26.

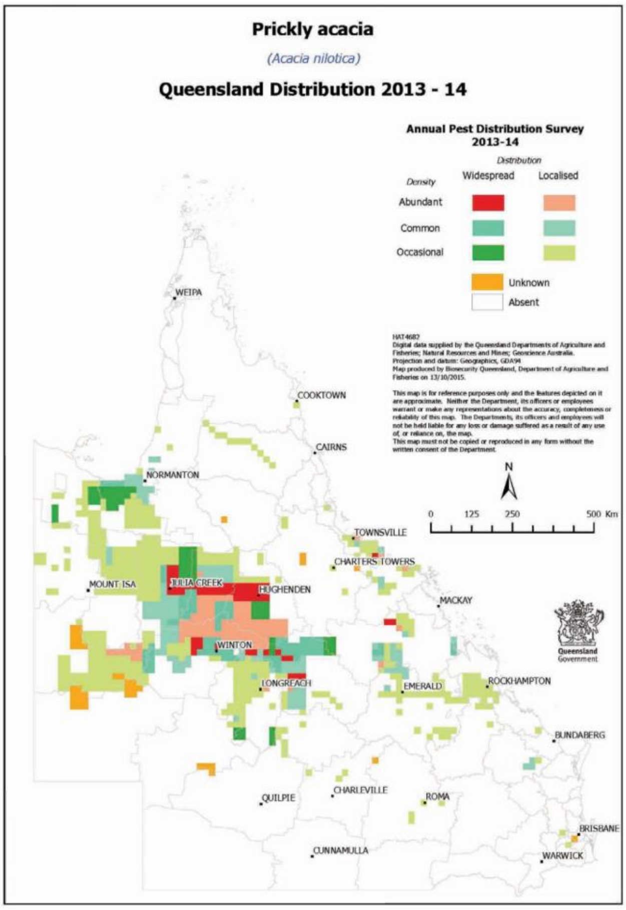


Figure 26 Distribution of prickly acacia in Queensland. (Department of Agriculture and Fisheries 2016)

Table 21 Process data for delivering 1 tonne of prickly acacia to biofuel facility.

Process	Unit	Flow	Comment
Tractor operation, diesel use	L	1.7	Based on sugarcane harvesting energy use (Renouf, Wegner et al. 2011)
Transport, truck 40 t	tkm	150	

A.1.1 Green waste and food waste

Green waste and food waste may be supplied through either households, which have source separated organics collections, or from commercial collections from businesses. For the purpose of this study it was assumed that these collections are in place for waste management reasons, with commercial composting assumed to be the alternative fate of this material.

Green waste in 2015 was 619,017 t, making up 11.7% of the total waste recovered. Combined food waste from domestic, commercial and industrial facilities was 59,383 t, adding another 1.1% of total waste recovered (Waste Data and Reporting 2016).

Process data for supply of food or garden wastes are shown in Table 22. The data for commercial composting are shown in Table 23 and the benefits of using this compost is shown in Table 24.

A sensitivity analysis was undertaken in section 7.2.3 where the alternative fate of the material was landfill. The rationale is that a strong market for this material due to biofuel demand could increase separation from waste streams. The main differences between food and green waste are the moisture content and the degradation behaviour when it is sent to landfill. Landfill degradation and emissions data were based on the information in the National Inventory Report (Commonwealth of Australia 2017).

Table 22 Process data for delivering 1 tonne of food and garden waste to biofuel facility.

Item	Unit	Amount	Transportation distances (km)
Transport, truck, 40 t	tkm	100	100 km transport (author’s assumption)
Wood chipping, mobile, diesel	hr	0.1	Author’s estimate on time. Process consumes 70 L diesel per hour
Composting garden and food waste	t	-1	Alternative fate of material

Table 23 Process data for composting garden and food waste.

Process	Unit	Amount	Comment
Compost output	t	0.5	50% compost yield from input material
Inputs			
Diesel machinery use	L	3.307	
Electricity	kWh	8.80	
Water	m^3	11.00	

Source: Pers. comm., Jefferies Compost Soil and Mulch

Table 24 Process data for application of compost.

Outputs	Unit	Amount	Replaces
Nitrogen (N)	%	1.2%	Urea
Phosphorus (P)	%	0.2%	Triple super phosphate
Potassium (K)	%	1.0%	Potassium chloride

Source: Pers. comm., Jefferies Compost Soil and Mulch

A.1.2 Wood waste and treated wood waste

Besides general wood waste such sawdust and timber offcuts, another category of wood waste includes timber treated with chemicals such as copper chrome arsenate (CCA), high temperature creosote (HTC), pigmented emulsified creosote (PEC) and light organic solvent preservative (LOSP). This category of timber comes from engineered timber products from the construction and demolition waste stream, packaging and transport, and utilities sources.

The amount of timber waste recovered in 2015 was 180,504 tonnes, which accounted for 3.4% of total waste generated (Waste Data and Reporting 2016).

The only scenario in this report using wood waste was based on the use of CCA wood, so landfill is the assumed alternative fate because CCA timber cannot be composted. Landfill degradation and emissions data were based on the information in the National Inventory Report (Commonwealth of Australia 2017). The transport distance was assumed to be 100 km for supply of wood waste to the biofuels facility; pre-processing of the material was incorporated into the catalytic depolymerisation process data.

A.1.3 Waste tyres

Used tyres represent a significant waste management problem. This is partly due to the volume of tyres produced and some unique challenges in the storage and disposal of waste tyres. This includes problems compacting landfills that contain tyres, fire risks, mosquitos breeding in stored tyres and leaching of hazardous compounds from tyre dumps.

Determining the alternative fate of tyres was difficult because many tyres are not able to be accounted for; some are exported and some abandoned (especially in the case of mining tyres).

The share of end of life arisings for tyres in Queensland has been adopted from (Mountjoy, Hasthanayake et al. 2015) with the quantities in terms of equivalent passenger units (EPU) shown in Table 25. Table 26 shows the composition of different types of tyres. The important components are the steel, which can be recycled, and the natural and synthetic carbon components, which end up in the biofuel.

Table 25 Tyre end-of-life share in Queensland.

Item	No. of EPU	Share (%)	Distance to biofuel producer (km)
Passenger vehicles	3261783	29	100
Trucks	3581578	31	100
Other vehicles	4559469	40	500

Source: (Emma Mountjoy, Dharshi Hasthanayake et al. 2015)

Table 26 Natural rubber and steel content in various types of tyres.

Item	Natural rubber %	Synthetic rubber (%)	Other carbon-based constituents (%)	Steel (%)	Other non-carbon constituents (%)
Passenger vehicles	6.58	40.42	27	16.5	9.5
Trucks	12.15	32.85	22	25	8
Other vehicles (mining etc.)	47	0	29	12	12

Sources:– (Anne and Evans 2006)

A.2 Agave for ethanol production

A.2.1 Description of process and allocation approaches

This pathway uses agave, which is traditionally used to make tequila, to produce fermentable sugars that can be used to produce ethanol. The advantages of agave are in its efficient use of water and high yields of fermentable sugars.

For this analysis, the fibre was assumed to be combusted to produce electricity and process heat to run the ethanol distillation process.

The agave was assumed to have been grown without irrigation and harvested after seven years. Agave modelling was based on agave grown in Mexico (Nunez, Rodriguez et al. 2011), which has similar soil conditions to Australia. Energy from bagasse was assumed to be used throughout the biofuel plant for electricity and heat impacts. While it is expected that the system may also export electricity to the grid, this was not included in the base case (Figure 27).

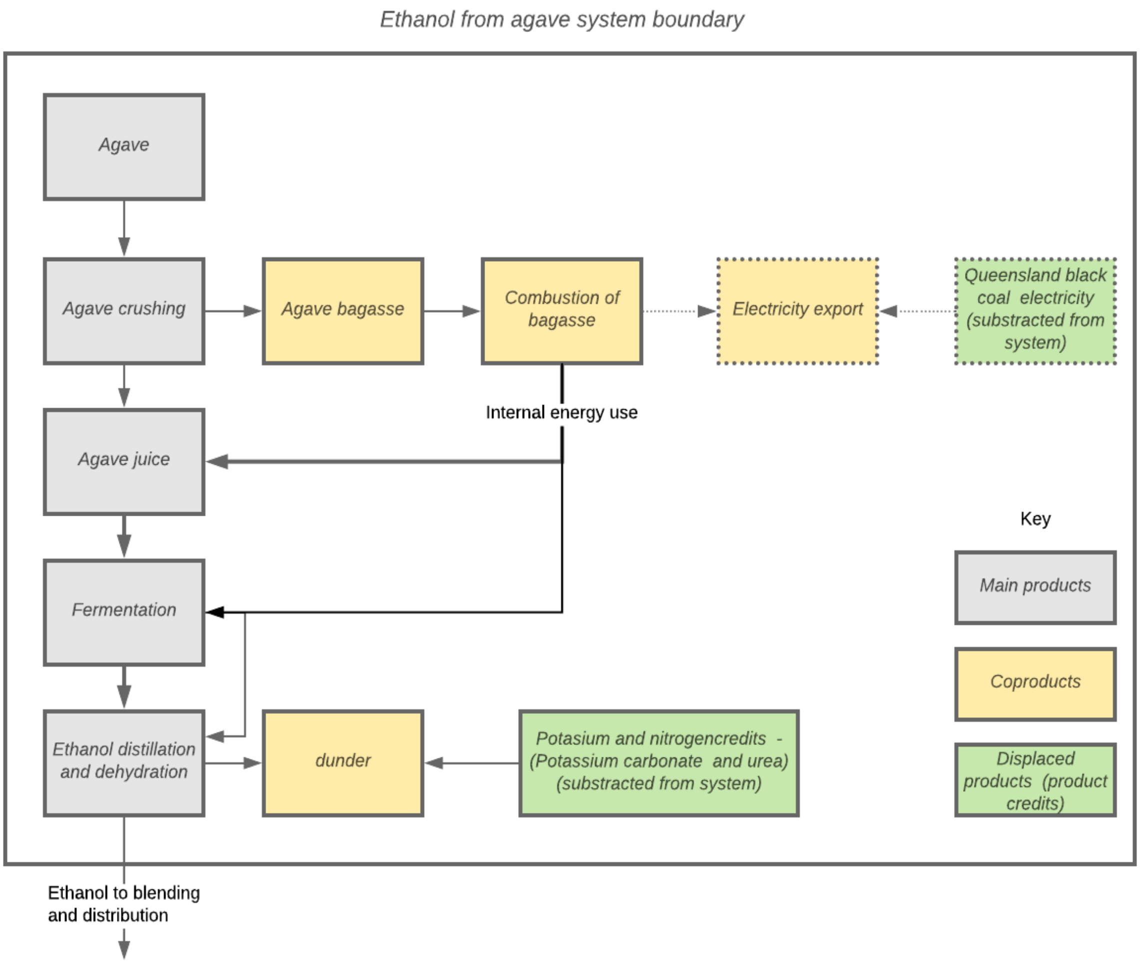


Figure 27 System model for ethanol from agave.

It is not clear what the properties of dunder from agave are but they have been assumed to be similar to the properties of dunder produced from molasses fermentation. Dunder from molasses is high in potassium and nitrogen and is blended with other materials and used either as a fertiliser or as a feed supplement in cattle feed. The credits for use of agave dunder were calculated directly from the nutrient value of molasses-based dunder and the most common alternative forms of providing those nutrients. These are shown in Table 27.

Table 27 Substitution assumptions for agave dunder production.

Item	Amount (kg dry matter)	N	P	K	N	P	K
		% content			Dunder dry matter (kg/kg)		
Dunder	1.68	0.5	0.1	3	0.0084	0.00168	0.0504
Offsets							
Potassium chloride	0.097			52			0.0504
Urea	0.018			46	0.0084		
Triple super phosphate	0.0084			20		0.00168	

Table 28 shows the energy and economic data used for the alternative allocation approach for agave juice and agave bagasse. As commercial quantities of these products are not traded, the price data have been estimated using equivalents for the sugar industry. Energy data are based specifically on agave juice and agave bagasse.

Table 28 Energy and economic data used for agave juice and agave bagasse allocation.

Material	Wholesale price ($/t)	Gross energy (MJ/kg)	Price reference
Agave juice	500	12	Prices based on cane sugar; energy based on agave syrup (Self Nutrition Data 2017)
Agave bagasse	20	16.35	Energy content from (Linan-Montes, De La Parra-Arciniega et al. 2014); price based on sugar bagasse (Kent 2007)

A.2.2 Data sources

The inventory data for agave is shown in Table 29 and is based on (Nunez, Rodriguez et al. 2011) but modelled using emission factors for agriculture in Queensland based on the National Inventory Report (Commonwealth of Australia 2017). The nitrogen and phosphorus emissions from AusLCI methodology for agriculture (Grant, Eady et al. 2015).

The milling process for agave was assumed to be similar to sugarcane in terms of energy use (Table 30 and Table 31).

Table 29 Unit process data for agave production.

Outputs	Flow	Unit	Comment
Agave	200,000	kg	Yield in kg/ha stem leaf matter 200 t
Inputs			
Cultivating	2	ha	Assumed 2 times the normal cultivation as intensive land preparation is required
Grader operation	2	ha	Assumed 2 grader operations for intensive cultivation
Spraying	21	ha	Assumed 3 sprays per year for 7 years
Planting	1	ha	Planting of agave
Fertilising	21	ha	Assumed 3 fertilising operations per year for 7 years
Glyphosate	153	kg	Derived from economic analysis in (Nunez, Rodriguez et al. 2011)
Urea	5,074	kg	Derived from economic analysis in (Nunez, Rodriguez et al. 2011)
Monoammonium phosphate	2,956	kg	Derived from economic analysis in (Nunez, Rodriguez et al. 2011)
Harvesting, broadacre crop	7	ha	Assumed 7 times the normal harvesting, being intensive
Insecticides	39	kg	Derived from economic analysis in (Nunez, Rodriguez et al. 2011)
Transport, truck, 28 t	2.02E+06	kgkm	Calculated assuming a distance of 250 km
Emissions to air			
Nitrous oxide	8.262	kg	Direct emissions from fertilisers
Nitrous oxide	4.13	kg	Indirect emissions from fertilisers
Nitrous oxide	0.399	kg	Fertilisers leaching (nitrous oxide emissions)
Ammonia	319.238	kg	Direct emissions from fertilisers (ammonia)
Carbon dioxide, biogenic	3,720.93	kg	Emissions from urea application
Nitrous oxide	5.43	kg	Emissions from residues above ground (assumes residue to crop ratio is 20%)
Emissions to water			
Nitrate	149.115	kg	Fertilisers leaching
Phosphorus	0.0965217	kg	Phosphorus leaching to groundwater
Phosphorus	0.633617	kg	P run-off to surface waters
Phosphorus	1.15845	kg	P emissions through erosion

Table 30 Unit process data for agave crushing

Outputs	Unit	Flow	Comment
Agave juice	t	0.893	Mass bagasse (wet basis, 50% moisture). (Yang, Lu et al. 2015)
Bagasse	t	0.107	Mass bagasse (wet basis, 50% moisture). (Yang, Lu et al. 2015)
Inputs			
Sugarcane, harvested	t	1	
Lime, hydraulic	kg	0.545	From sugar milling data
Lubricating oil	kg	0.007	From sugar milling data
Steel, low-alloyed	kg	0.50	Estimate based on 1,000 t steel consumed for annual maintenance for a ‘typical’ mill.
Emissions to air			
Methane	kg	0.228	From sugar milling data emissions to air from anaerobic digestion of COD in mill wastewater.
Emissions to water			
Chemical oxygen demand	kg	0.013	From sugar milling data based on BOD
Suspended substances	kg	0.047	From sugar milling data based on 30 mg/L TSS limit, treated water flow per day and 460 t/hr crush rate.

Table 31 Unit process data for ethanol production from agave.

Flow	Unit	Value	Comment
Products			
Distillery, from agave	L	0.7899	
Dunder	kg	5.6	From sugar milling data 30% solids and 3% K, 0.5% N and 0.1% P on dry matter basis (Gao 2016).
Inputs			
Tap water,	kg	2.3	Beer, Grant et al. 2001
Agave juice	kg	4	Beer, Grant et al. 2001
Bagasse from agave, combustion, at biorefinery	MJ	10.5	Beer, Grant et al. 2001
Lime	kg	0.002	Beer, Grant et al. 2001
Emissions to air			
Water	kg	2.3	From water balance
Carbon dioxide, biogenic	kg	0.955	From calculation
Emissions to air			
Waste water treatment	L	2.3	50% of water input (assumption)
Disposal, silage from molasses fermentation	kg	2.05	

A.2.3 Climate change results

Figure 28 shows the contribution analysis of replacing one litre of gasoline with ethanol. The savings were mainly through carbon dioxide absorbed through the crop cycle and avoided fossil fuel impacts. On the emissions side, the main emissions were from crop production though on farm emissions such as nitrous oxide from fertiliser application, with further emissions from fertiliser production. This was due to the high input of fertilisers (5 t of urea and 3 t of monoammonium phosphate over 7 years). With bioenergy used for distillation energy, the impacts of biofuel production process were minimal.

Figure 29 shows the results for gasoline replacement with ethanol from a biorefinery with 50% agave and 50% molasses feedstock. The molasses was a lower impact as feedstock because it is a by-product of sugarcane. The data do not currently account for the potential of electricity exports from agave bagasse combustion.

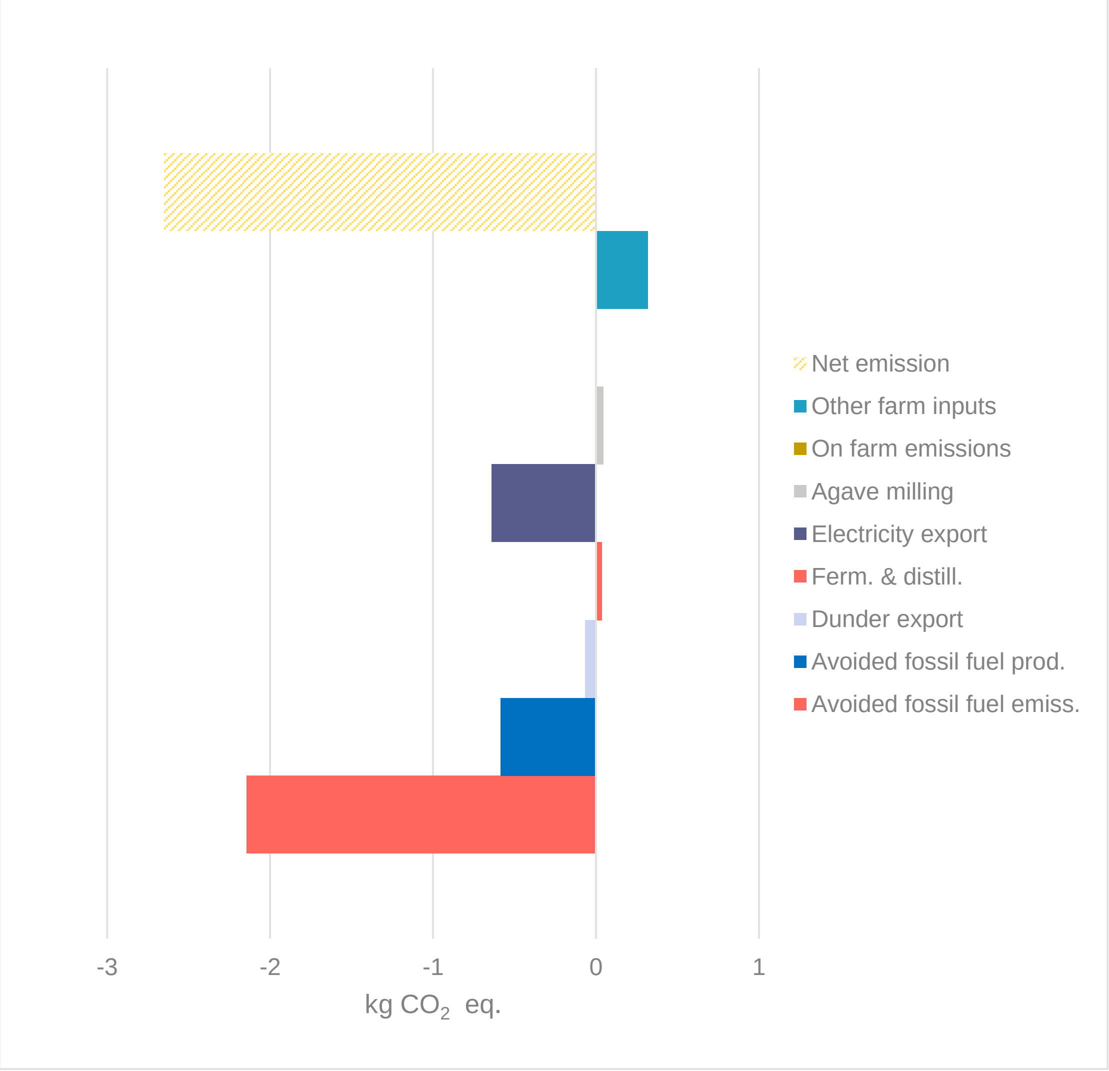


Figure 28 Climate change impacts from replacing gasoline with equivalent ethanol biofuel from agave.

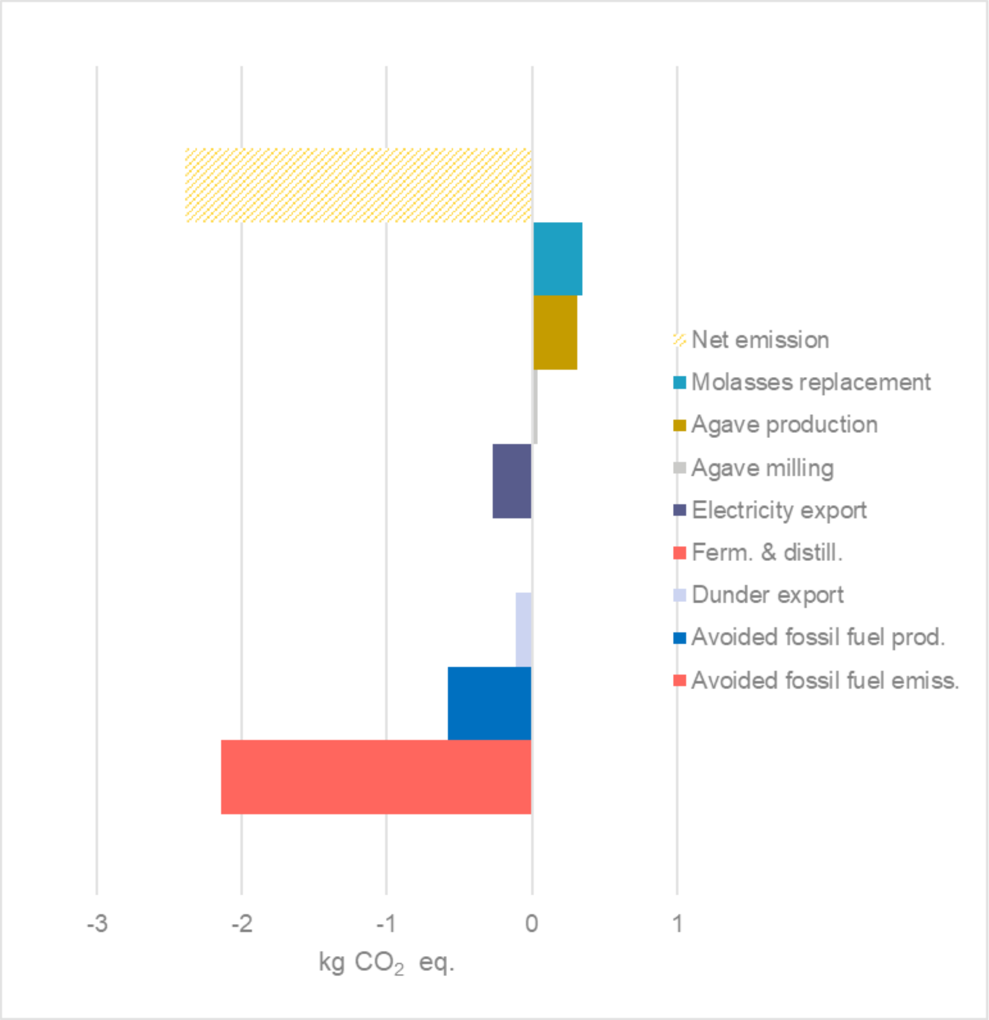


Figure 29 Climate change impacts from replacing gasoline with equivalent ethanol biofuel from agave and molasses.

A.3 Ethanol from sugarcane biorefinery

A.3.1 Description of the process

This process involves using sugarcane production in a dedicated biorefinery with 100% of the sugar juice used for fermentation to ethanol, and the bagasse used for production of energy for internal use on the sugarcane farm. Sugarcane production data was based on data from Renouf (Renouf, Wegner et al. 2011) for the Burdekin region in North Queensland.

Energy for ethanol production and distillation was based on current practice but assumed 100% of fuel would be based on biomass energy. No electricity export is assumed, as the proposal for this technology by Renewable Developments Limited is for only for internal use of energy.

A.3.2 Process data

The following table (Table 32) lists the AusLCI dataset (ALCAS 2017) for sugarcane in the Burdekin region, which is based on (Renouf, Wegner et al. 2010). Table 33 shows the data for extraction of sugar juice from Table 34 shows the conversion of sugar juice into ethanol through distillation.

Table 32 Production, water and chemical input for sugarcane production in the Burdekin.

Flows	Unit	Amount	Comment
Product outputs			
Sugarcane	kg	89,744	Production for 1 ha per year
Material & process inputs			
Water	ML	9.97	
Urea	kg	421	
Diammonium phosphate	kg	136	
Potassium chloride	kg	71	
Ammonium sulfate	kg	48	
Gypsum	kg	326	
2,4-D	g	380	Pesticides
Asulum	g	36	Pesticides
Atrazine, at regional storehouse	g	416	Pesticides
Chlorpyrifos	g	199	Pesticides
Diuron, at regional storehouse	g	416	Pesticides
Fluroxypyr	g	36	Pesticides
Glyphosate	g	54	Pesticides
MSMA	g	18	Pesticides
Paraquat	g	217	Pesticides
Pendimethalin	g	18	Pesticides
Trifluralin	g	18	Pesticides
Transport, transoceanic freight ship	tkm	5,849	Estimate of shipping effort from overseas
Transport, truck, 28 t	tkm	255	Estimate of domestic road freight.
Transport, freight, rail	tkm	215	Estimate of domestic rail freight.
Transport, truck, 3,5 to 16 t,	tkm	15	Estimate of local freight from retailer
Harvest and haulout, green cane	t	5	Percentage of cane harvested green
Harvest and haulout, burnt cane	t	86	Percentage of cane harvested burnt cane

Transport, cane, rail	tkm	1,998	89% of cane harvested utilises the cane railway for transport to mill.
Tractor engine operation,	L	227	
Tractor, production	kg	5	Estimate based on 3 tractors in service).
Agricultural machinery, general, production	kg	2	Estimate based on 5 implements
Pipe irrigation system, production, per ha	ha	1	100% of farms have irrigation infrastructure

Table 33 Unit process data for milling sugar juice.

Flow	**Unit**	**Value**	**Comment**
Products			
Sugar juice	t	0.171	41% yield from sugars
Avoided products			
Energy from bagasse electricity production and export	MWh	0.219	From 0.28 tonnes of bagasse combustion – 84% exported, 16% used internally
Materials and energy			
Sugarcane, Burdekin	t	1	
Bagasse combustion	GJ	2.688	28% bagasse at 9.6 MJ/kg and 35% efficiency

Table 34 Unit process data for distillation of sugar juice.

Flow	Unit	Value	Comment
Products			
Ethanol distillery, from molasses, at plant	kg	0.7899	41% yield from sugars
Avoided products			
Dunder offset	kg	5.6	
Materials and energy			
Water	kg	2.3	Beer, Grant et al. 2001
Sugar (dry matter)	kg	1.91	Sugars are in water from 11.69 kg of cane
Steam, from bagasse combustion	MJ	10.5	
Lime, hydraulic, at plant	kg	0.002	Beer, Grant et al. 2001
Ethanol fermentation plant	p	4.19E-10	From ecoinvent
Waste to treatment			
Treatment, sewage, to wastewater treatment, class 3	L	2.3	50% of water input, assumption
Disposal, silage from sugar fermentation	kg	2.054	

A.3.3 Climate change results

Figure 30 shows the results for fossil fuel replaced by ethanol from sugarcane. The economic driver for this facility is cogeneration of electricity; this comes through in the climate change results showing the generation of electricity co-products as the main benefit of the scenario.

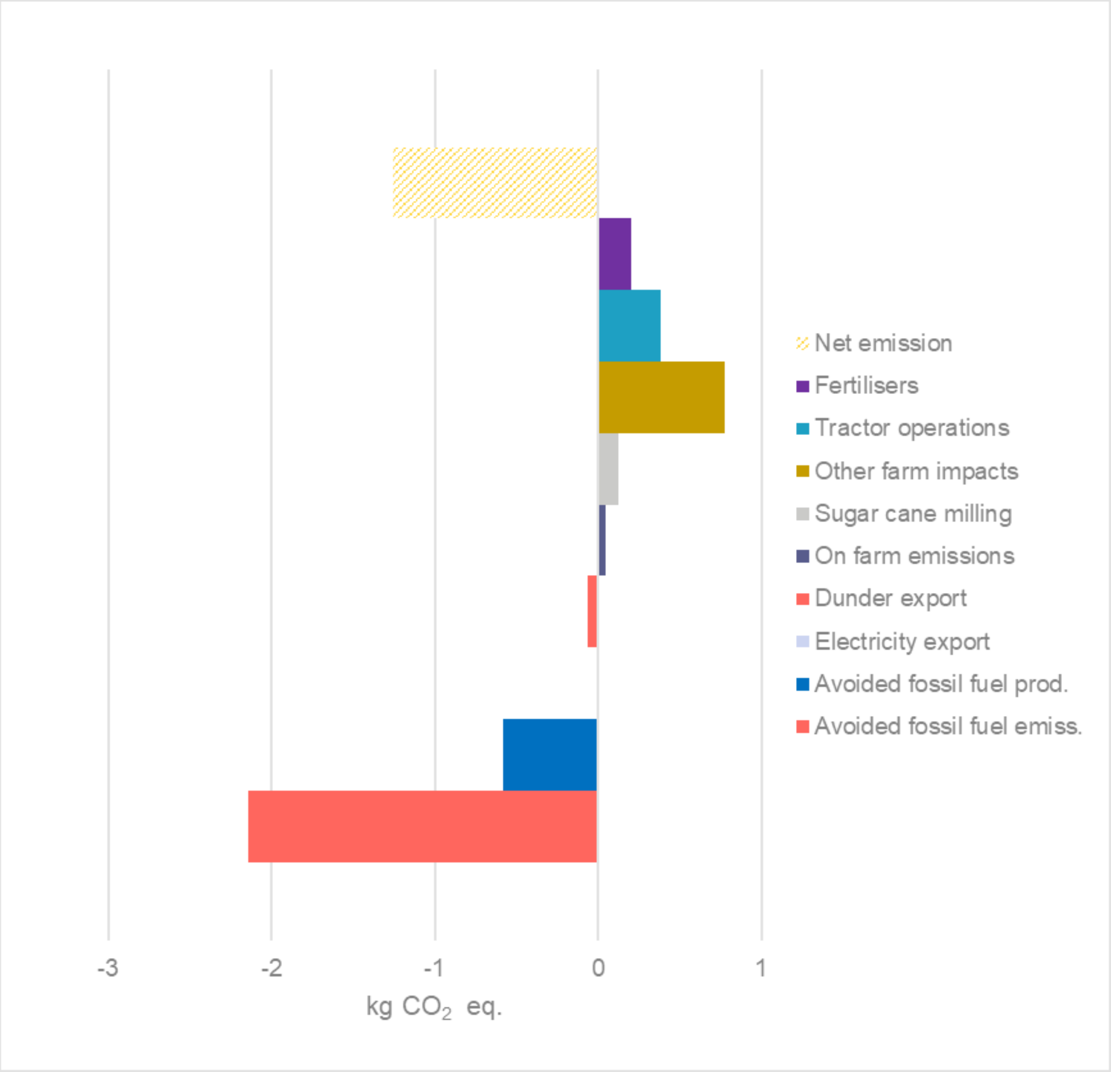


Figure 30 Climate change impacts from replacing gasoline with equivalent ethanol biofuel from sugarcane.

A.4 Cane trash to ethanol via Glycell™ process, acid hydrolysis and fermentation

A.4.1 Description of the process and allocations

Leaf resources uses a patented Glycell™ technology to pre-treat biomass with crude glycerol to separate the three main components of biomass cellulose, hemicellulose and lignin. In the process of this a refined version of glycerol is also produced. The cellulose and hemicellulose are treated using acid hydrolysis to make fermentable sugars and from these a range of products can be produced including biobased chemicals, bioplastics and biofuels.

For this study, sugarcane trash and tops were the biomass assumed to be the feedstock (Figure 31). Glycerol was assumed to be sourced from local biodiesel production and was recycled through the process with a small loss. While Leaf Resources claim that the glycerol can be upgraded from crude to a refined glycerol through this process, this has not been included in this study.

The potential for energy exports from acid hydrolysis was estimated from a study by (Tao, Schell et al. 2014), which suggests net energy exports can be 0.69 kWh per litre of ethanol.

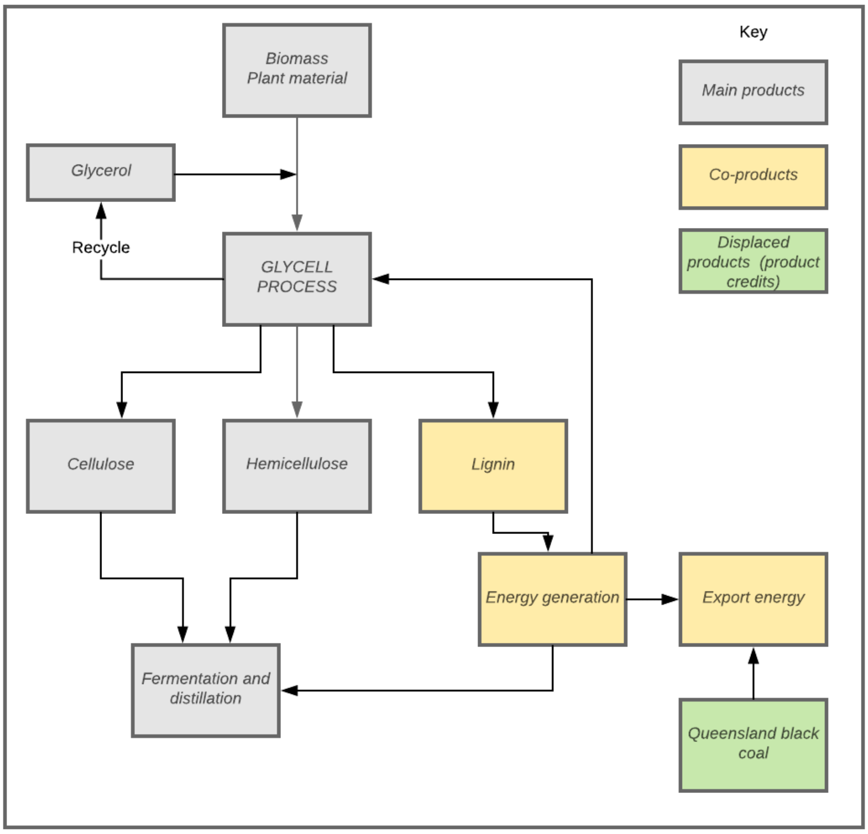


Figure 31 System boundary for ethanol from biomass via Glycell™ process.

A.4.2 Process data

The production step from hemicellulose and cellulose to ethanol was based on the ecoinvent process for ethanol from wood, with adjustments for the composition of feedstock (Table 35 and Table 36).

Table 35 Unit process data for GlycellTM process.

Item	Flow	Unit	Comment
Products			
Hemicellulosic & cellulosic	5.43	t	
Lignin from Glycell^{TM} process	2.08	t	
Materials/fuels			
Glycerine, from canola oil	2.03	t	
Cane trash and tops, at mill	25	t	
Enzymes	0.07	t	
Sulfuric acid	0.1	t	
Energy, from wood waste and black liquors	359,600	GJ	

Table 36 Unit process data for distillery.

Item	Flow	Unit	Comment
Product			
Ethanol from hemicellulose, Glycell^{TM} process	0.7899	kg	
Electricity	0.699	kWh	(McIntosh, Vancov et al. 2014)
Materials/fuels			
Hemicellulosic & cellulosic	1.7	kg	Based on 90% efficiency in ethanol production.
Energy, from wood waste and black liquors	10.5	MJ	From ecoinvent
Magnesium sulfate	0.00043	kg	ecoinvent data for acid hydrolysis
Calcium chloride, $CaCl_2$	0.00095	kg	ecoinvent data for acid hydrolysis
Ammonia, liquid	0.0522	kg	ecoinvent data for acid hydrolysis
Ammonium sulfate	0.004	kg	ecoinvent data for acid hydrolysis
Lime, hydraulic	0.025417	kg	ecoinvent data for acid hydrolysis
Starch	0.02091	kg	ecoinvent data for acid hydrolysis
Tap water, at user, Australia	1	L	Glycell^{TM} data
Waste			
Treatment, sewage, to wastewater treatment, class 3	1	L	Water output is assumed to balance with input
Disposal, silage from fermentation	1.085	kg	

A.4.3 Climate change results

Figure 32 shows the results for climate change impacts for the replacement of 1 litre of gasoline replaced by 1 litre of gasoline from cane trash and tops. The processing emissions from production are small due the supply of energy from lignin and other biomass combusted for energy. This means that the avoided fuel production and avoided fossil fuel emissions dominate the net benefit of the replacement.

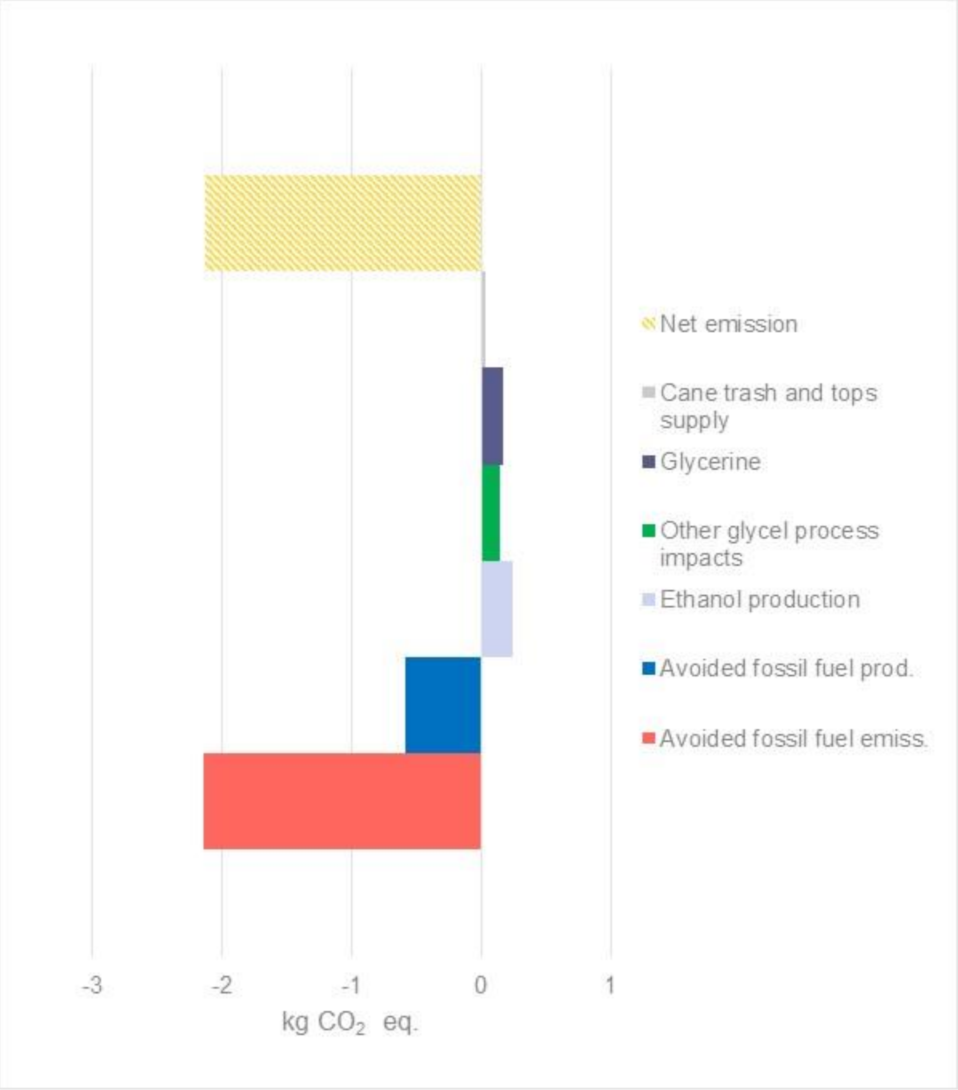


Figure 32 Contribution analysis for replacing 1 litre of gasoline with ethanol from cane trash and tops using the Glycell^{TM} process.

A.5 Ethanol from biomass using concentrated acid hydrolysis

A.5.1 Description of process

This pathway uses lignocellulosic biomass materials, such as sugarcane tops and trash, as well as forestry residues to produce ethanol. The scenario was based on a new technology process being developed by Ethanol Technologies Limited (Ethtec) and implemented by North Queensland BioEnergy Corporation Limited (NQBE). Figure 33 shows the supply of the different potential feedstocks for the concentrated hydrolysis process.

Sugarcane bagasse may also be used from un-utilised bagasse at sugar mills, with the underlying assumption that the material used had no current use or significant economic or environmental value.

Forestry residues similarly were assumed to be sourced from forestry operations using material that is currently not utilised.

The Ethtec process uses several steps to produce ethanol from lignocellulosic biomass. Once collected, the lignocellulosic feedstock is impregnated with concentrated sulfuric acid using a tailored twin screw extruder. The extruded product is then adjusted to optimum acid concentration so that it undergoes a rapid hydrolysis reaction, which converts the cellulose and hemicellulose components of the feedstock to fermentable sugars. This material is then filtered with the lignin component of the feedstock being recovered for energy production and the acid being separated from the sugars for reuse. The sugars are then fermented to ethanol, which is recovered using an induced phase separation process. The ethanol recovery process simultaneously produces a solid waste stream, which is combusted along with the lignin for energy recovery.

As there are some gaps in available data, these have been filled with publicly available data, and where necessary proxy data from similar processes.

An additional sensitivity analysis has been undertaken where sugarcane bagasse was the feedstock assumed to compete with bagasse for use in electricity generation.

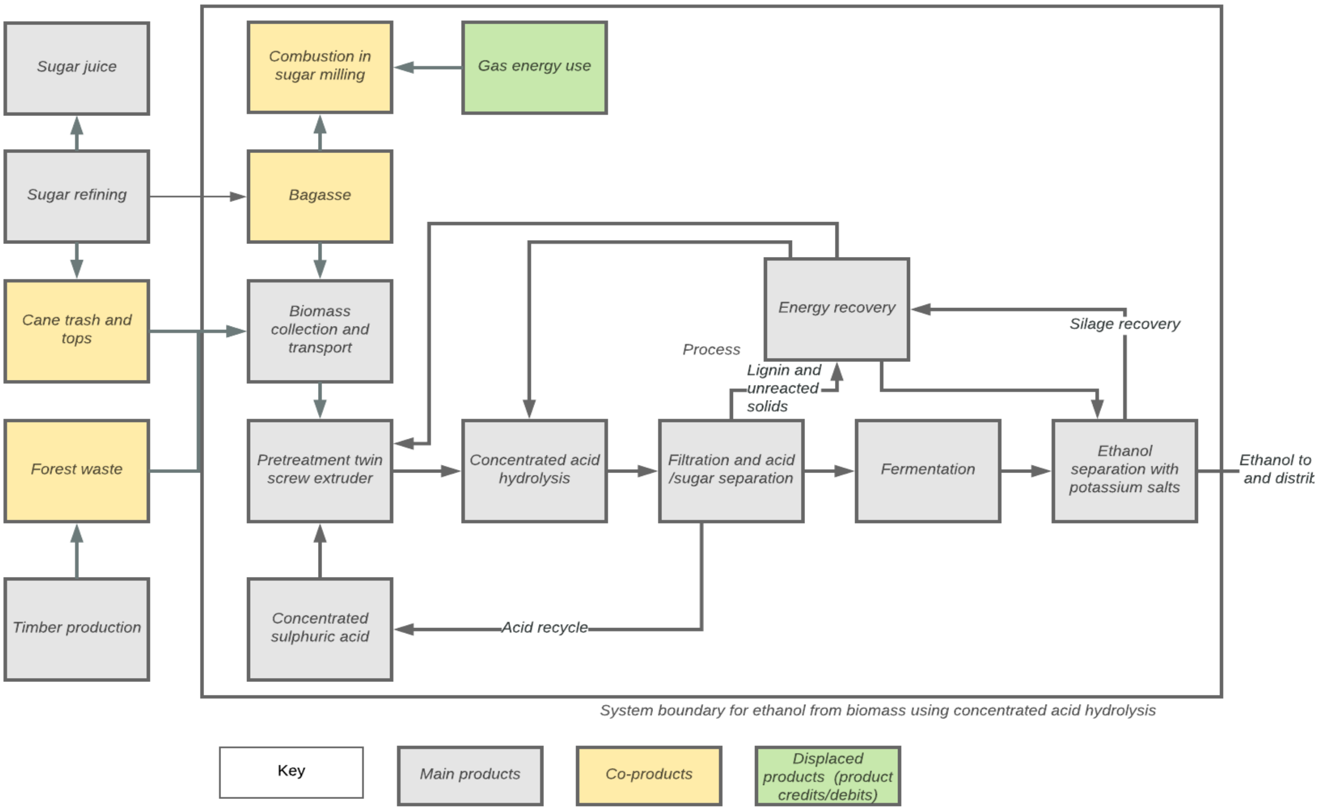


Figure 33 Sugarcane bagasse, tops and trash, and forestry residues to ethanol via concentrated acid hydrolysis.

A.5.2 Process data

Table 37 shows the pre-treatment data. Energy use for pre-treatment was provided by Ethtec. The Ethtec process is expected to be energy self-sufficient in steam and electricity by combustion of the lignin and solid waste components from the process. Acid consumption was based on 1.2% of total acid loading.

Table 37 Data for pre-treatment per dry tonne of sugarcane bagasse/trash.

Process	Value	Unit	Source comment
Inputs			
Twin screw extruder	50	kWh	Pre-treatment, 0.4–0.06 kWh per kg dry matter. Internal data from Ethtec.
Sulfuric acid	12	kg	Assumed to be make up acid – 1.2% assuming acid load of 1:1 with dry solids content.
Outputs			
Treated biomass **Dry matter basis**	1	t	1 tonne of biomass and 1 tonne sulfuric acid

Energy data for hydrolysis has been ignored based on the assumption that the Ethtec process would be self-sufficient in electricity and steam. The hydrolysis process used concentrated (40% C) sulfuric acid (Hamelinck, Hooijdonk et al. 2005) (Waldron 2010), and the acid was assumed to be recovered after the hydrolysis process with a net consumption of 1.2%. The process flows assumed for the hydrolysis process are shown in Table 38. The process flows for ethanol production are shown in Table 39 and the assumptions from ecoinvent data for combustion of lignin material for energy production are shown in Table 40. All energy was assumed to be supplied from locally generated steam and electricity from lignin and solid waste combustion; however, no energy export was assumed. While there are unique processes being developed for simultaneous ethanol recovery and waste treatment that are not based on distillation, no data are available on this process, so as a replacement, distillation was assumed, based on energy from lignin and solid waste material combustion.

Table 38 Main assumptions for hydrolysis process.

Flow	Unit	Value	Comment
Outputs			
Sugars from hydrolysis process	kg	0.78	
Lignin and other residual biomass to energy	kg	0.22	Based on assumption of 22% lignin (Franco, Pimenta et al. 2013)
Materials and energy			
Sugars from hydrolysis reactor	kg	1	From ecoinvent, based on enzymatic process
Energy from lignin and solid waste combustion			

Table 39 Main assumptions for fermentation and ethanol separation.

Flow	Unit	Value	Comment
Outputs			
Ethanol, azeotropic	kg	1	
Residual material sent to bioenergy combustion with lignin.	kg		Amount not specified but assumes that all biomass is used for energy generation and will match requirements of the process.
Inputs			
Sugars from hydrolysis reactor	kg	2.17	Assumes 90% fermentation efficiency, i.e. ~0.46 kg ethanol/kg sugars, Pers. comm., Dr. Russel Reeves, Ethtec
Potassium carbonate	kg	0.25	Gross amount assumed. Recycling of K_2CO_3 needs to be accounted for.
Quicklime	kg	0.032	Assumed to be needed for neutralisation – from ecoinvent process
Water	kg	2	Pers. comm., Dr. Russel Reeves, Ethtec
Energy from lignin and waste biomass combustion	MJ		Amount not specified but assume that all biomass is used for energy generation and will match requirements of the process.

Table 40 Lignin waste energy process.

Flow	Unit	Value	Comment
Products			
Lignin (biomass) combusted for energy[2]	MJ	1	Per unit of fuel input
Materials and energy			
Urea, as N	kg	3.49E-05	Adapted from the dataset 'wood chips, in cogen 6400 kWh, wood, emission control', according to actual water, carbon and energy content of the fuel (unconverted solids, mainly lignin)
Sodium chloride, powder	kg	5.35E-06	
Lubricating oil	kg	4.28E-06	
Water, decarbonised, at user	kg	1.03E-03	
Emissions to air			
Phenol, pentachloro-	kg	1.15E-11	
Toluene	kg	4.24E-07	
Formaldehyde	kg	1.83E-07	
PAH, polycyclic aromatic hydrocarbons	kg	1.56E-08	
Hydrocarbons, aliphatic, alkanes, unspecified	kg	1.28E-06	
Nitrogen oxides	kg	5.74E-05	
NMVOC,	kg	8.61E-07	
Particulates, <2.5 µm	kg	7.08E-06	
Nitrous oxide	kg	2.87E-05	
Acetaldehyde	kg	7.99E-08	
Methane, biogenic	kg	6.13E-07	
Benzo(a)pyrene	kg	7.08E-10	
Ammonia	kg	2.22E-05	
Benzene, ethyl-	kg	4.24E-08	
Sulfur dioxide	kg	3.25E-06	
Benzene, hexachloro-	kg	1.01E-14	
Carbon monoxide, biogenic	kg	9.86E-06	
Hydrocarbons, aliphatic, unsaturated	kg	4.38E-06	

A.5.3 Climate change results

Figure 34 shows the climate change results for 1 litre of fossil fuel being replaced with the equivalent ethanol. The major benefit from the climate change impacts perspective is the absorption of carbon from the atmosphere. There are small benefits from avoiding nitrous oxide by removing excess trash from the sugarcane field. Assuming an additional soil carbon loss of 0.5 t per ha from removing 50% of cane trash has almost no effect on the climate change impacts. The effect of feedstock from sugarcane trash and tops is almost zero as there are small emissions savings from removing trash from the field, and small emission impacts from transporting material to the biofuel facility. For forestry residues there is a larger impact due to transport and chipping of forestry residue.

The third column shows the results of using bagasse as the feedstock in the situation where it is taken away from use in cogeneration plants. This results in a positive emission result, suggesting that the climate change benefits of direct use of bagasse to offset natural gas would be preferable to its use in biofuels.

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[2] Analysis by SGS Australia P/L of the lignin cake from the Ethtec Process shows gross calorific values of 14.8 MJ/kg at 34.0% moisture and 20.1 MJ/kg at 10.3% moisture. Pers. comm., Dr. Russel Reeves, Ethtec.

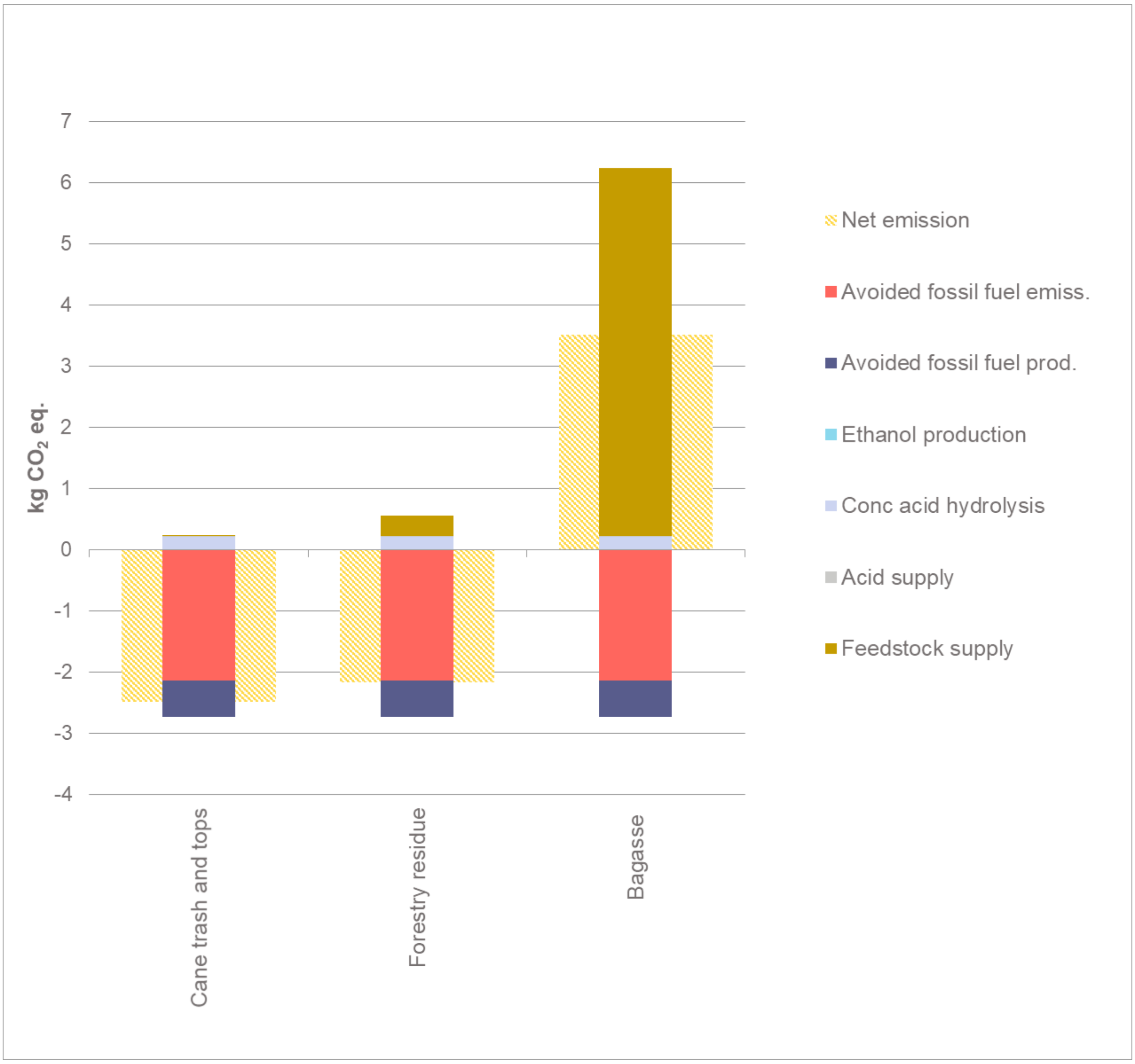

Figure 34 Breakdown of impacts for replacement of one litre gasoline with equivalent ethanol from sugarcane trash via concentrated acid hydrolysis.

A.6 Ethanol from cotton trash using dilute acid hydrolysis

A.6.1 Overview of the process

Ethanol is produced through the fermentation of cotton gin trash after treatment with a dilute acid hydrolysis and enzyme treatment. This process is based on the enzymatic hydrolysis of cellulose and co-fermentation of glucose and xylose to ethanol. First, the cellulosic material undergoes a pre-treatment, which starts the degradation of the waste. This step releases the sugars in hemicellulose, which is then transferred to the main treatment process. Here, the pre-treated solids are fermented with the cellulose enzyme to release glucose from the cellulose. Finally, an organism is added that ferments the sugars from hemicellulose and the glucose released from the cellulose into ethanol.

The output of this process contains 5% (by volume) of ethanol and goes through a distillation process where it is concentrated to 95% (by volume). The solid output is then burnt to generate heat and electricity used during the process. A schematic of the process is shown in Figure 35.

In the context of cotton gin trash, the material is of such a low value that no alternative fate was modelled for this material. As such, it was considered that there are no prior burdens associated with its production.

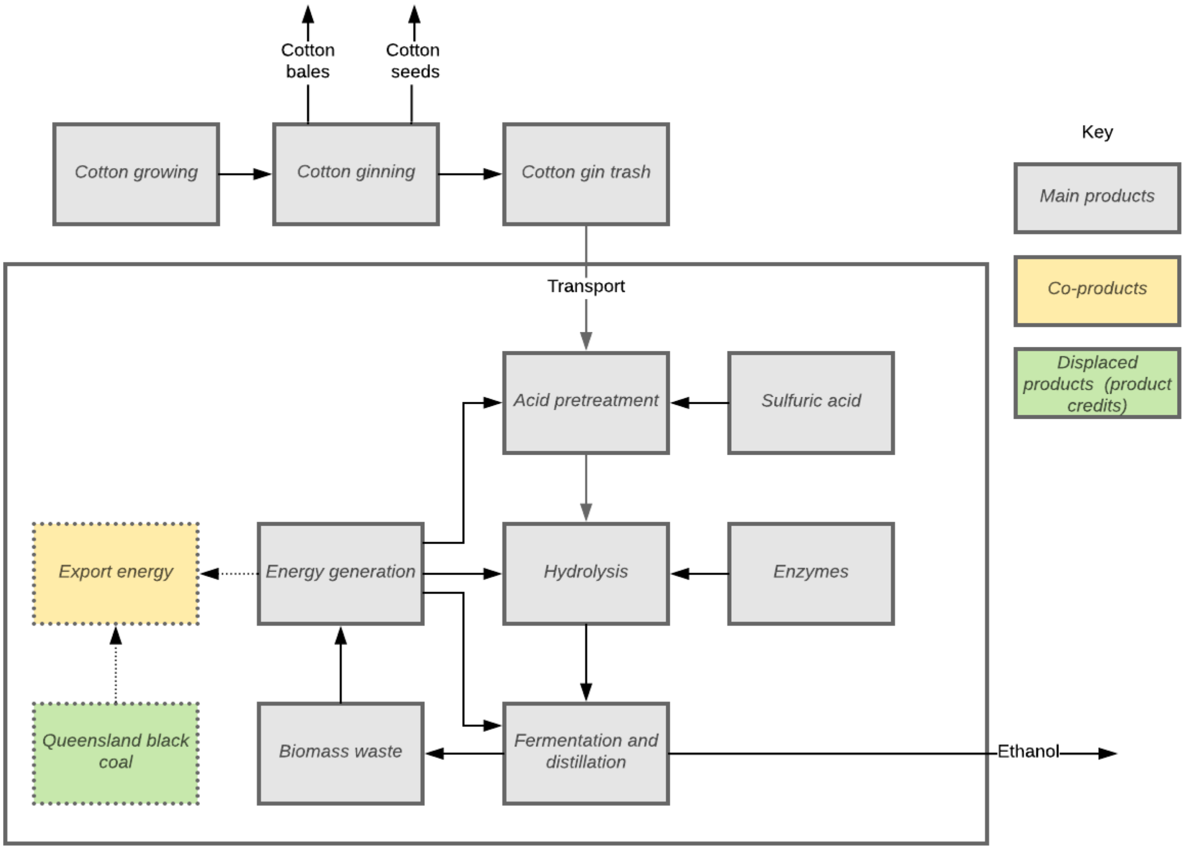

Figure 35 Overview of process for production of ethanol from cotton gin trash.

The combustion of residual material was assumed to provide all internal energy requirements for the process, with excess energy exported for electricity to the grid. For the system expansion, it was assumed that the electricity would replace electricity from black coal in Queensland.

The primary energy content of fuel into electricity and the energy value of ethanol were used for energy allocation as shown in Table 41.

Table 41 Data used for economic and energy allocation of ethanol and electricity.

Product	Wholesale price (AUD per L or kWh)	Energy (MJ per L or kWh)	Price reference
Ethanol	$0.66	23.4MJ	(EnergyQuest Pty Ltd 2010); Energy content based on anhydrous ethanol
Electricity	$0.10	10.9 MJ	(Australian Energy Regulator 2017) Energy value assumes primary energy-based fuel efficiency of 33%

A.6.2 Process data

In the absence of primary data sources, the production of ethanol from cotton gin trash was based on ethanol yield data from (McIntosh, Vancov et al. 2014) with dilute acid hydrolysis data from NREL (Tao, Schell et al. 2014) and ecoinvent (Jungbluth, Chudacoff et al. 2007) (Table 42). Background processes from AusLCI were used to replace the original inputs from the ecoinvent model where applicable (ALCAS 2016).

Table 42 Data used for ethanol production from cotton gin trash and electricity.

Products	Flow	Unit	Comment
Neat ethanol	0.79	kg	1 L of ethanol
Grid electricity	0.699	kWh	Next export to the grid based on NREL (Tao, Schell et al. 2014)
Resource consumption			
Cotton gin trash	9.04	kg	Based on 140 litres of ethanol per t gin trash. (McIntosh, Vancov et al. 2014)
Sulfuric acid	0.0910	kg	NREL (Tao, Schell et al. 2014)
Sodium hydroxide (caustic soda)	0.0305	kg	NREL (Tao, Schell et al. 2014)
Ammonia	0.0151	kg	NREL (Tao, Schell et al. 2014)
Corn steep liquor	0.0415	kg	NREL (Tao, Schell et al. 2014)
Diammonium phosphate	0.0043	kg	
Urea	0.0016	kg	ecoinvent (Jungbluth, Chudacoff et al. 2007)
Glucose	0.0956	kg	Sugar used as input NREL (Tao, Schell et al. 2014)
Host nutrients	0.0027	kg	Starch used as nutrient source NREL (Tao, Schell et al. 2014)
Sulfur dioxide	0.0006	kg	NREL (Tao, Schell et al. 2014)
Quicklime	0.0197	kg	NREL (Tao, Schell et al. 2014)
Magnesium sulfate	0.0005	kg	ecoinvent (Jungbluth, Chudacoff et al. 2007)
Makeup water	6.62	kg	NREL (Tao, Schell et al. 2014)
Air emissions			
Water (H_2O)	9.53	kg	NREL (Tao, Schell et al. 2014)
Nitrogen (N_2)	19.15	kg	NREL (Tao, Schell et al. 2014)
Oxygen (O_2)	3.12	kg	NREL (Tao, Schell et al. 2014)
Carbon dioxide (CO_2)	4.23	kg	NREL (Tao, Schell et al. 2014)

Methane (CH_4)	0.00012	kg	NREL (Tao, Schell et al. 2014)
Nitrogen dioxide (NO_2)	0.0029	kg	NREL (Tao, Schell et al. 2014)
Carbon monoxide (CO)	0.0028	kg	NREL (Tao, Schell et al. 2014)
Ethanol	0.0002	kg	NREL (Tao, Schell et al. 2014)
Sulfur dioxide (SO_2)	0.0012	kg	NREL (Tao, Schell et al. 2014)
Waste streams			
Ash disposal	0.204	kg	NREL (Tao, Schell et al. 2014)
Wastewater (brine)	0.401	kg	NREL (Tao, Schell et al. 2014)

A.6.3 Climate change results

Figure 36 shows the results for replacing 1 litre of gasoline with equivalent ethanol fuel from dilute acid hydrolysis of cotton gin trash. Avoided fossil emission and fossil fuel production plus the credit for offsets results in significant benefits from replacing conventional gasoline with ethanol from cotton trash. The impacts of trash are limited to transport, which is relatively small, and ethanol production, which was based on the use of bioenergy.

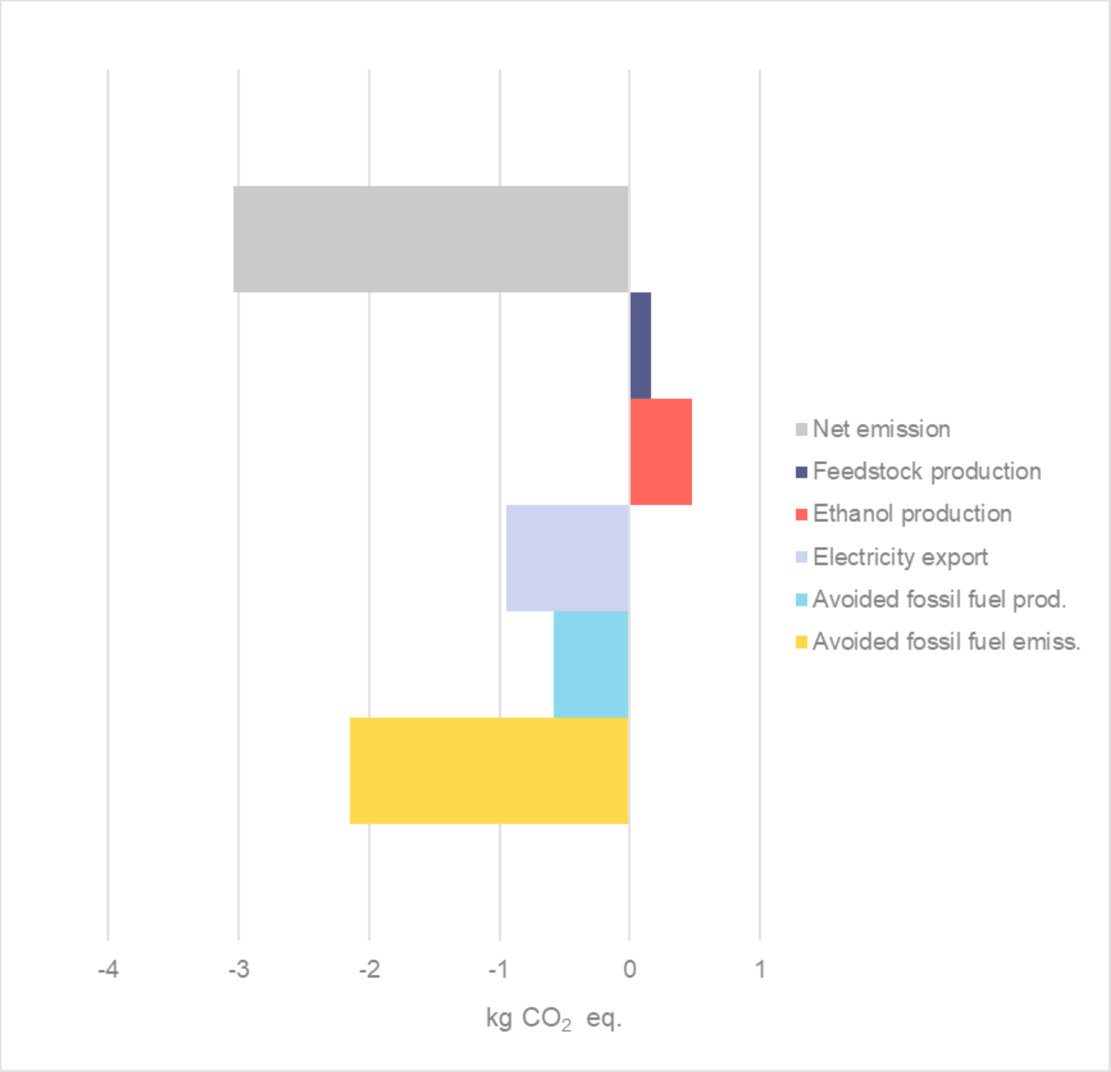

Figure 36 Climate change impacts from replacing gasoline with equivalent ethanol from cotton gin trash via dilute acid hydrolysis.

A.7 Carinata for biodiesel production

A.7.1 Overview of the process

Carinata is a crop similar to canola except that it is extremely tolerant to heat, cold, drought and disease and is not suitable for human consumption. Its high oil content and favourable fatty acid profile makes it suitable for biofuel production. The crop's residue can be ground into a meal for use in cattle markets, increasing its crop value. The scenario was modelled using internal data received from Agrisoma, which developed and sell the crop *Brassica carinata*.

While the oil has currently been processed using hydrogenation to produce jet fuel, naphtha and renewable diesel, the oil is suitable for biodiesel production using conventional transesterification. In this study it is being assessed for use as a biodiesel via transesterification.

Figure 37 shows how Carinata oil is transformed to biodiesel through extraction of oil from the seed, using a crushing and hexane extraction, which produces Carinata meal as a co-product, which is offsets high protein cattle feed. The yield of oil from seed is 38%, with meal production the other 62%.

There are two main co-products from Carinata biodiesel production: Carinata meal from seed crushing and glycerine from transesterification. Figure 37 shows the credit from meal production was sorghum feed and Lucerne was added to balance the co-product. It also shows the credit provided for glycerine production was forage sorghum.

The justification for the Carinata substitute is explained in Table 43 with the substitution of Carinata meal with Lucerne needing to be balanced with supplementation of the meal with sorghum. This is because additional energy was added to the feed to offset the very high protein content of Carinata meal (35% protein) with Lucerne (47% protein). This energy was offset with a lower protein feed such as sorghum grain (11% protein). While this may seem convoluted, the process of making up animal feed balances many different inputs with different energy, protein and other nutrient qualities based on availability and cost of each input.

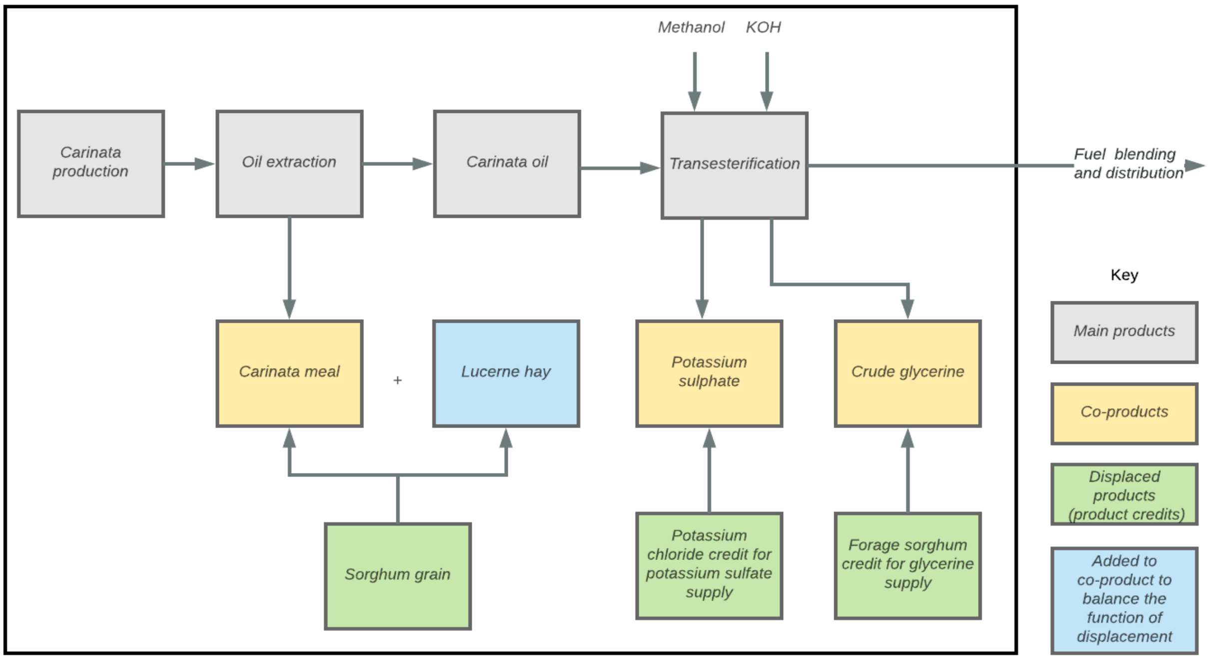

Figure 37 System boundary for vegetable oil production from Carinata.

Table 43 Assumptions for credit provided for Carinata meal derived from Carinata oil production.

Item	Amount used (kg)	Energy (MJ)	Protein (kg)
Carinata meal	1	11.44	0.35
Sorghum (added to canola meal to match Lucerne nutrient value)	1.2	16.47	0.11
Nutrient value of mix (meal + sorghum)		27.91	0.46
Lucerne	3	27.06	0.47

A.7.3 Data sources

Cropping data for Carinata was adopted from the data provided by Agrisoma for Carinata cropping. The data gaps were filled by gross margin for canola as shown in Table 44. The oil extraction data shown in Table 45 was taken from ecoinvent data on rape seed oil and is shown in the production process (Jungbluth, Dinkel et al. 2007), with electricity supply taken from the Queensland grid process.

Table 44 Unit process data for Carinata production.

Products	Flow	Unit	Comment
Products			
Carinata	2,100	kg	Yield in kg/ha
Materials/fuels			
Planting	1	ha	No. of planting operation
Spraying	5	ha	Canola gross margin
Fertilising	1	ha	Canola gross margin
Liming	0.1	ha	Canola gross margin
Scarifying	0.1	ha	Canola gross margin
Grain collection	1	ha	Canola gross margin
Harvesting	1	ha	Canola gross margin
Urea	103	kg	From data supplied
Potassium chloride	107	kg	From data supplied
Monoammonium phosphate	122	kg	From data supplied
Limestone	29.7	kg	From data supplied
Glyphosate	2.16	kg	From data supplied
Herbicides	2.91	kg	From data supplied
Insecticides	0.006	kg	From data supplied
Transport by truck	137,908	kgkm	Calculated using 250 km distance
Emissions to air			
Nitrous oxide	0.795602	kg	Direct emissions from fertilisers, based on NIR 2017
Nitrous oxide	0.0936002	kg	Indirect emissions from fertilisers based on NIR 2017
Nitrous oxide	0.011562	kg	Fertilisers leaching, based on NIR 2017
Ammonia	7.23301	kg	Direct emissions from fertilisers, based on NIR 2017
Carbon dioxide, biogenic	75.5333	kg	Emissions from urea application,
Nitrous oxide	0.775828	kg	Emissions from residues
Nitrous oxide	0.0135491	kg	Emissions from burning residues based on NIR 2017
Nitrogen oxides	0.78287	kg	Emissions from burning residues based on NIR 2017

Products	Flow	Unit	Comment
Methane, biogenic	0.235244	kg	Emissions from burning residues based on NIR 2017
Carbon dioxide, biogenic	5,978.84	kg	Emissions from burning residues
Non-methane volatile organic compounds, unspecified origin	0.535	kg	Emissions from burning residues
Carbon monoxide, biogenic	9.1755	kg	Emissions from burning residues
Carbon dioxide, fossil	13.068	kg	Emissions from lime application
Emissions to air			
Nitrate	4.3135	kg	Fertilisers leaching, based on NIR 2017
Phosphorus	0.0176048	kg	Phosphorus leaching to groundwater
Phosphorus	0.0469652	kg	P run-off to surface waters
Phosphorus	0.0526446	kg	P emissions through erosion by water

Table 45 Carinata oil extraction process.

Products	Flow	Unit	Comment
Products			
Carinata oil	2.6	kg	
Avoided products			
Sorghum	5.0	kg	
Materials/fuels			
Heat	0.31408	ha	Data from literature survey (1998–2006) & biodiesel producers
Transport	0.00092659	ha	Based on ecoinvent Guidelines, standard distances
Transport, truck, 28 t	0.00015443	ha	Based on ecoinvent Guidelines, standard distances
Transport, truck, 16 t	0.040692	ha	Based on ecoinvent Guidelines, standard distances
Oil mill	8.73E-10	ha	Calculation, according to feed capacity and lifetime of the plant
Bentonite	0.0010398	ha	Data from literature survey (1998–2006) & biodiesel producers
Hexane	0.00048707	ha	Data from literature survey (1998–2006) & biodiesel producers
Phosphoric acid	0.00093405	kg	Data from literature survey (1998–2006) & biodiesel producers
Electricity	0.15352	kWh	Data from literature survey (1998–2006) & biodiesel producers
Carinata	2.6	kg	Data from literature survey (1998–2006) & biodiesel producers (sum of all type of canola seeds)
Emissions			
Hexane	0.00048	kg	

Table 46 Biodiesel esterification process from Carinata.

Products	Flow	Unit	Comment
Products			
Biodiesel esterification	0.9727	kg	
Avoided products			
Glycerine	0.0837	kg	
Potassium sulfate	0.041	kg	

Materials/fuels			
Carinata oil	1	kg	
Electricity	0.041141	kWh	Literature data & biodiesel producer
Heat	0.89856	MJ	Literature data & biodiesel producer
Methanol	0.1105	kg	Literature data & biodiesel producer
Vegetable oil esterification plant	9.09E-10	p	Calculation, according to feed capacity and lifetime of the plant
Water	0.01	kg	ecotect
Phosphoric acid	0.0044768	kg	Literature data & biodiesel producer
Potassium hydroxide	0.011046	kg	Literature data & biodiesel producer

A.7.4 Climate change results

Figure 38 expresses the results for climate change from biodiesel production from a Carinata crop. Carinata production was the biggest contributor followed by the biodiesel production process. Avoided fossil fuel emissions is the highest benefit followed by benefits from avoiding fossil fuels production and co-products credits from the Carinata crushing process.

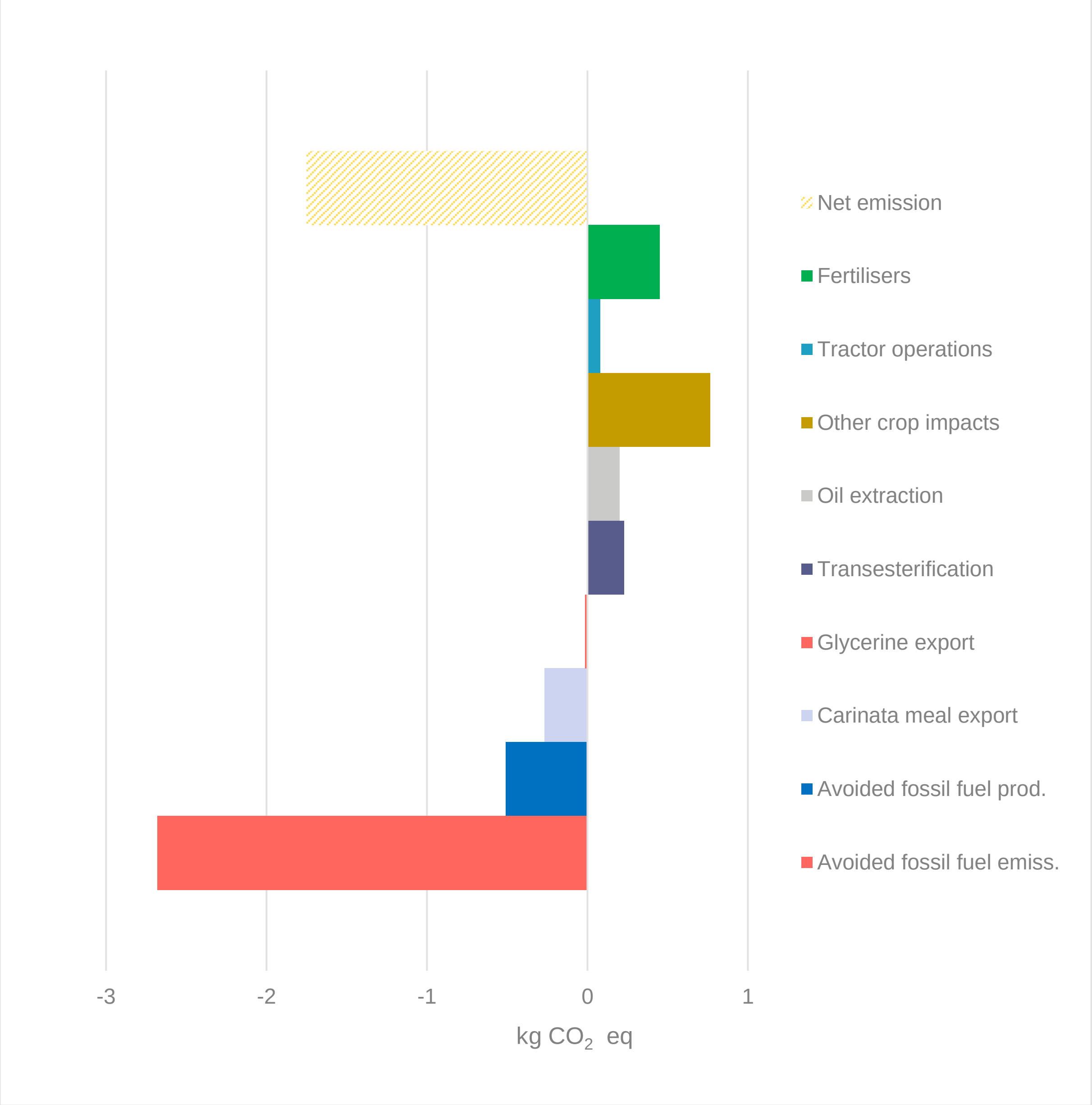

Figure 38 Contribution analysis for replacing diesel replaced with biodiesel produced from Carinata.

A.8 Tobacco for biodiesel production

A.8.1 Overview of the process and allocation issues

This scenario is based on a nicotine-free tobacco variant (Solaris), which has a large head and small leaf area compared with conventional tobacco. The plant is hardy and tolerates drier areas and high temperatures. Depending on the location, the seed head may be harvested twice or even three times a year. The seeds are pressed to produce vegetable oil while the cake can be used in high protein meal. While the oil has currently been processed using hydrogenation to produce jet fuel, naphtha and renewable diesel, the oil is suitable for biodiesel production using conventional transesterification.

This scenario is based on experimental production of tobacco in two fields (Grisan, Polizzotto et al. 2016) averaged across and processed using local oil extraction and transesterification plants, with the protein meal used to feed piglets. Figure 39 shows how tobacco is transformed to biodiesel through extraction of oil from the seed, using crushing and hexane extraction, which produces animal meal as a co-product, and then the crude oil is refined and transesterified to biodiesel. The yield of oil from seed is 33% with meal production the other 67%. Tobacco seed cake has a high protein the energy content (Rossi, Fusi et al. 2013)

There are two main co-products from tobacco biodiesel production: tobacco meal from seed crushing and glycerine from transesterification. Table 47 shows the credit from meal production was sorghum feed; Lucerne was added to balance the co-product. Figure 39 shows the credit provided for glycerine production was forage sorghum. The justification for tobacco substitute is explained in Table 47, with the substitution of tobacco meal with Lucerne needing to be balanced with supplementation of the meal with sorghum. This is because additional energy was added to the feed to offset the very high protein content of tobacco meal (35% protein) with Lucerne (47% protein). This energy was offset with a lower protein feed such as sorghum grain (11% protein). While this may seem convoluted, the process of making up animal feed balances many different inputs with different energy, protein and other nutrient qualities based on availability and cost of each input.

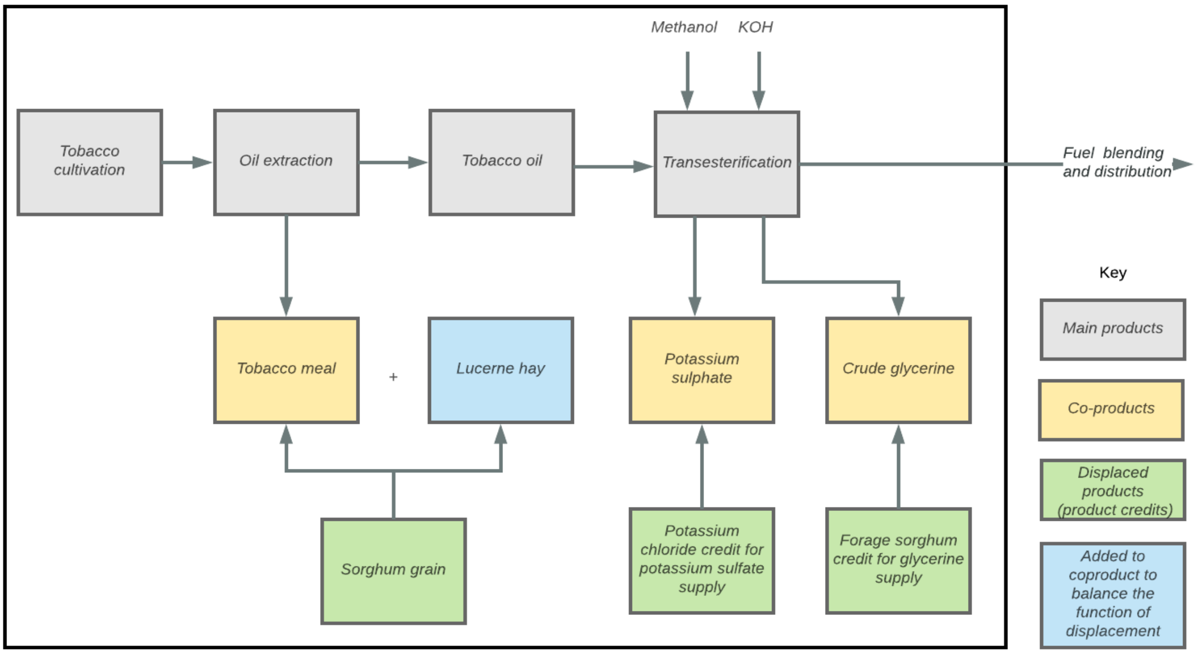

Figure 39 Biodiesel production from tobacco (Solaris).

Table 47 Assumptions for credit provided for tobacco meal derived from tobacco oil production.

	Amount used	Energy	Protein
Tobacco meal	1	11.44	0.35
Sorghum	1.2	16.47	0.11
Nutrient value of mix		27.91	0.46
Lucerne	*3*	27.06	0.47

A.8.2 Data sources

Tobacco cultivation data was sourced from (Grisan, Polizzotto et al. 2016) as the average plantation from the two trial fields. Table 48 shows the unit process data for tobacco cultivation. Table 48 shows the data for oil extraction from tobacco and Table 50 shows the transesterification processes for biodiesel from tobacco oil.

Table 48 Unit process data for tobacco production.

Products	Unit	Flow	Comment
Products			
Tobacco	kg	3,500	Yield in kg/ha
Resources			
Water	m^3	1,083	Water used for irrigation
Materials/fuels			
Pumping, irrigation	m^3	1,083	Average data from the two experimental fields from (Grisan, Polizzotto et al. 2016)
Irrigation, drip irrigation system	ha	1	Field 2 irrigation system from (Grisan, Polizzotto et al. 2016)
Poultry manure	kg	450	Averaged for the two fields from (Grisan, Polizzotto et al. 2016)
Monoammonium phosphate	kg	320	Average data from the two experimental fields from (Grisan, Polizzotto et al. 2016)
Ammonium nitrate	kg	233	Average data from the two experimental fields from (Grisan, Polizzotto et al. 2016)
Potassium fertiliser	kg	33	Averaged for the two fields from (Grisan, Polizzotto et al. 2016)
Spraying	ha	2	Assumed number of sprays
Planting	ha	1	Planting operation
Harvesting	ha	1	Harvesting operation
Fertilising	ha	2	Assumed number of fertilising operations
Insecticides	kg	0.35	Assumed insecticide
Transport	kgkm	80,087.5	Calculated assuming a distance of 250 km
Emissions to air			
Nitrous oxide	kg	0.100544	Direct emissions from fertilisers based on NIR 2017
Nitrous oxide	kg	0.050272	Indirect emissions from fertilisers
Nitrous oxide	kg	0.00486382	Fertilisers leaching based on NIR 2017
Ammonia	kg	3.8848	Direct emissions from fertilisers based on NIR 2017
Nitrous oxide	kg	0.448942	Emissions from residues based on NIR 2017
Nitrous oxide	kg	0.0109212	Emissions from burning residues based on NIR 2017
Nitrogen oxides	kg	0.631031	Emissions from burning residues based on NIR 2017
Methane, biogenic	kg	0.189618	Emissions from burning residues based on NIR 2017

Products	Unit	Flow	Comment
Carbon dioxide, biogenic	kg	4,967.88	Emissions from burning residues
Non-methane volatile organic compounds	kg	0.431612	Emissions from burning residues
Carbon monoxide, biogenic	kg	7.39589	Emissions from burning residues
Emissions to water			
Nitrate	kg	1.81458	Fertilisers leaching based on NIR 2017
Phosphorus	kg	0.0137888	Phosphorus leaching to groundwater ecoinvent report on agriculture
Phosphorus	kg	0.0405391	P run-off to surface waters ecoinvent report on agriculture
Phosphorus	kg	0.165492	P emissions through erosion by water to surface waters

Table 49 Tobacco oil extraction process.

Products	Unit	Flow	Comment
Products			
Tobacco oil	kg	2.6	
Avoided products			
Sorghum	kg	5.0	
Materials/fuels			
Heat	ha	0.31408	Data from literature survey (1998–2006) & biodiesel producers
Transport	ha	0.00092659	Based on ecoinvent Guidelines, standard distances
Transport, truck, 28 t	ha	0.00015443	Based on ecoinvent Guidelines, standard distances
Transport, truck, 16 t	ha	0.040692	Based on ecoinvent Guidelines, standard distances
Oil mill	ha	8.73E-10	Calculation, according to feed capacity and lifetime of the plant
Bentonite	ha	0.0010398	Data from literature survey (1998–2006) & biodiesel producers
Hexane	ha	0.00048707	Data from literature survey (1998–2006) & biodiesel producers
Phosphoric acid	kg	0.00093405	Data from literature survey (1998–2006) & biodiesel producers
Electricity	kWh	0.15352	Data from literature survey (1998–2006) & biodiesel producers
Tobacco	kg	2.6	Data from literature survey (1998–2006) & biodiesel producers – sum of all type of canola seeds
Emissions			
Heat	MJ	0.19	
Hexane	kg	0.00048	

Table 50 Biodiesel esterification process from tobacco.

Products	Flow	Unit	Comment
Products			
Biodiesel esterification	0.9727	kg	
Avoided products			
Glycerine	0.0837	kg	
Potassium sulfate	0.041	kg	

Materials/fuels			
Tobacco oil	1	kg	
Electricity	0.041141	kWh	Literature data & biodiesel producer
Heat	0.89856	MJ	Literature data & biodiesel producer
Methanol	0.1105	kg	Literature data & biodiesel producer
Vegetable oil esterification plant	9.09E-10	p	Calculation, according to feed capacity and lifetime of the plant
Water	0.01	kg	ecotect
Phosphoric acid	0.0044768	kg	Literature data & biodiesel producer
Potassium hydroxide	0.011046	kg	Literature data & biodiesel producer

A.8.3 Climate change results

Figure 40 shows the results for climate change from biodiesel production from a tobacco crop. Tobacco production was the biggest contributor followed by the biodiesel production process. Carbon absorption by the crop brought the highest benefit followed by benefits from avoiding fossil fuels and co-products from the Carinata process.

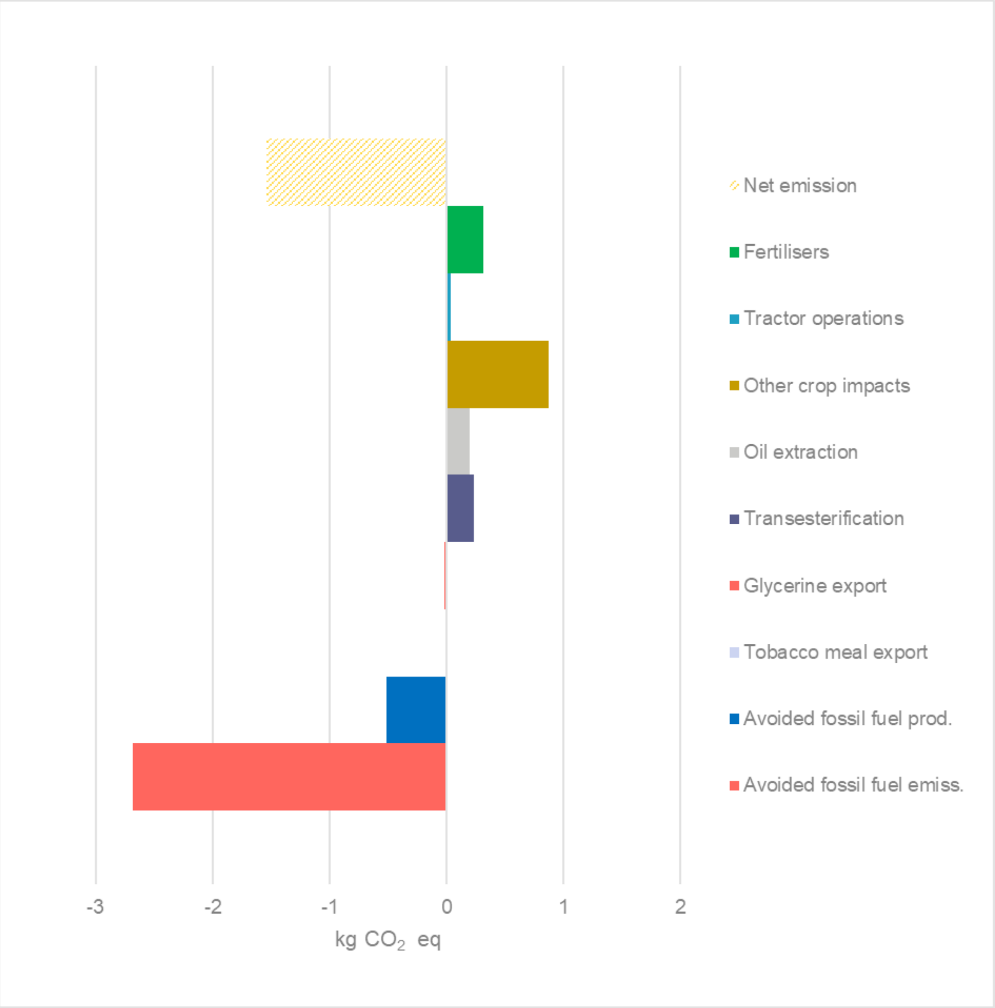

Figure 40 Contribution analysis of 1 litre of conventional diesel being replaced by biodiesel produced from tobacco.

A.9 Renewable diesel from pyrolysis of biomass sources

A.9.1 Description of the process

Northern Oil Refinery at Yarwun, near Gladstone, Queensland is currently in pilot stage to produce renewable fuels from biomass. The biomass may include sugarcane bagasse and prickly acacia as feedstock to produce bio-crude oil, which will be refined into saleable kerosene and diesel products.

While there are a wide range of options for operation and feedstock of this LCA will focus on the following pathways:

- forestry waste
- sugarcane trash and tops
- agriculture residues
- prickly acacia
- waste tyres through Green Distillation Technologies (GDT) to renewable diesel.

Figure 41 shows the system boundary and allocations involved in the production of renewable diesel from pyrolysis. The two main co-products are char and oils (light and heavy) as well as lubricants.

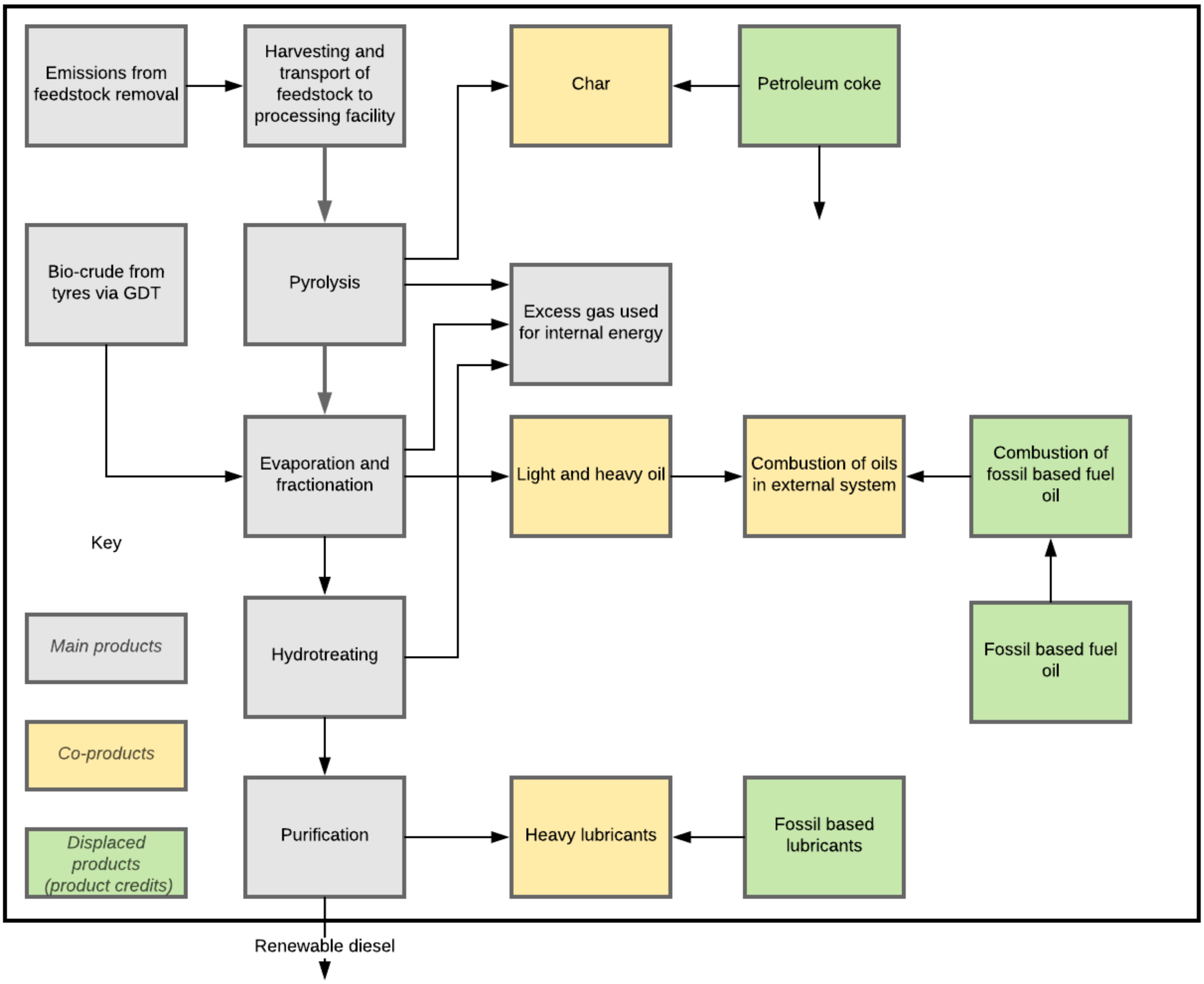

Figure 41 System boundary for renewable diesel from pyrolysis.

A.9.2 Process data

The process for renewable diesel production is broken up into 4 steps:

- pyrolysis unit operation
- evaporation and fractionation
- hydrotreating
- purification.

The inputs and outputs of these four steps are shown in Table 51 to Table 53. Table 52 has data for both processing bio-oil from the pyrolysis plant, and from feedstock from a destructive distillation process which produces a bio-oil from tyres.

Table 51 Unit process data for pyrolysis.

Item	Amount	Unit	Comment
Inputs			
Wood waste	100		
Electricity use	7	kWh	
External fuel inputs	3	MJ	
Outputs			
Bio-oil	30	kg	
Char (10 kg/hr)			
Excess gas	50	kg	
Waste water	10	kg	

Table 52 Unit process data for hydrotreating.

Item	Unit	Wood/cane trash/prickly acacia	Oil from destructive distillation	Comment
Inputs				
Middle Distillate	kg	100	100	
Hydrogen	kg	7.5	7.5	
Water	kg	2	2	
Electricity	kWh	2	2	
External fuel inputs – Gas	MJ	133.2	133.2	Listed as 37kWh
Outputs				
Hydrotreated Middle Distillate	kg	65	95	
Gas	kg	7.5	2.5	
Water	kg	37	2.5	

Table 53 Unit process data for purification and fractionation.

Item	Unit	Amount	Comment
Inputs			
Hydrotreated middle distillate	kg	100	
External fuel inputs (gas)	MJ	43.2	12 kWh
Outputs			
Diesel	kg	97	
Gas	kg	0.5	
Heavies (lube)	kg	2.5	

A.9.3 Climate change results

Figure 42 shows that for all feedstocks there is a climate change benefit (negative GHG emissions) from replacing conventional diesel with renewable diesel using a pyrolysis process. The benefit accrues through the avoidance of fossil fuel emissions, fossil fuel production and from avoided carbon black production for char produced through the process.

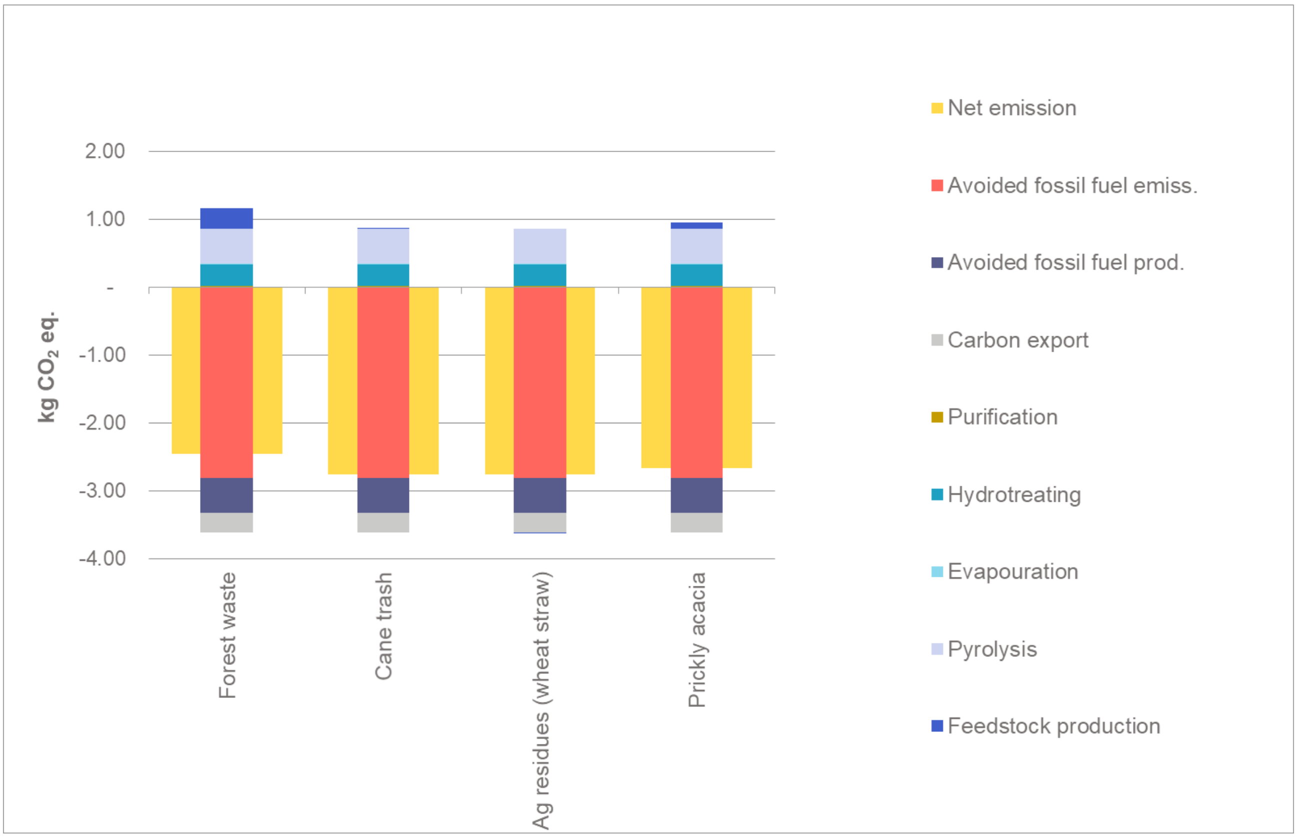

Figure 42 Climate change impacts from replacing 1 litre of diesel with equivalent renewable diesel via pyrolysis of different feedstocks.

A.10 Used tyres to renewable diesel via destructive distillation

A.10.1 Description of the process

Used tyres from passenger vehicles, trucks, buses and mining are converted to three main outputs via a process of destructive distillation (Figure 43). The outputs are a bio/waste derived crude oil, carbon and steel, and the process is self-sustaining in energy terms using the process derived energy products. The bio-crude is transported to Northern Oil Biorefinery where it is processed through evaporation, hydrotreating and purification steps.

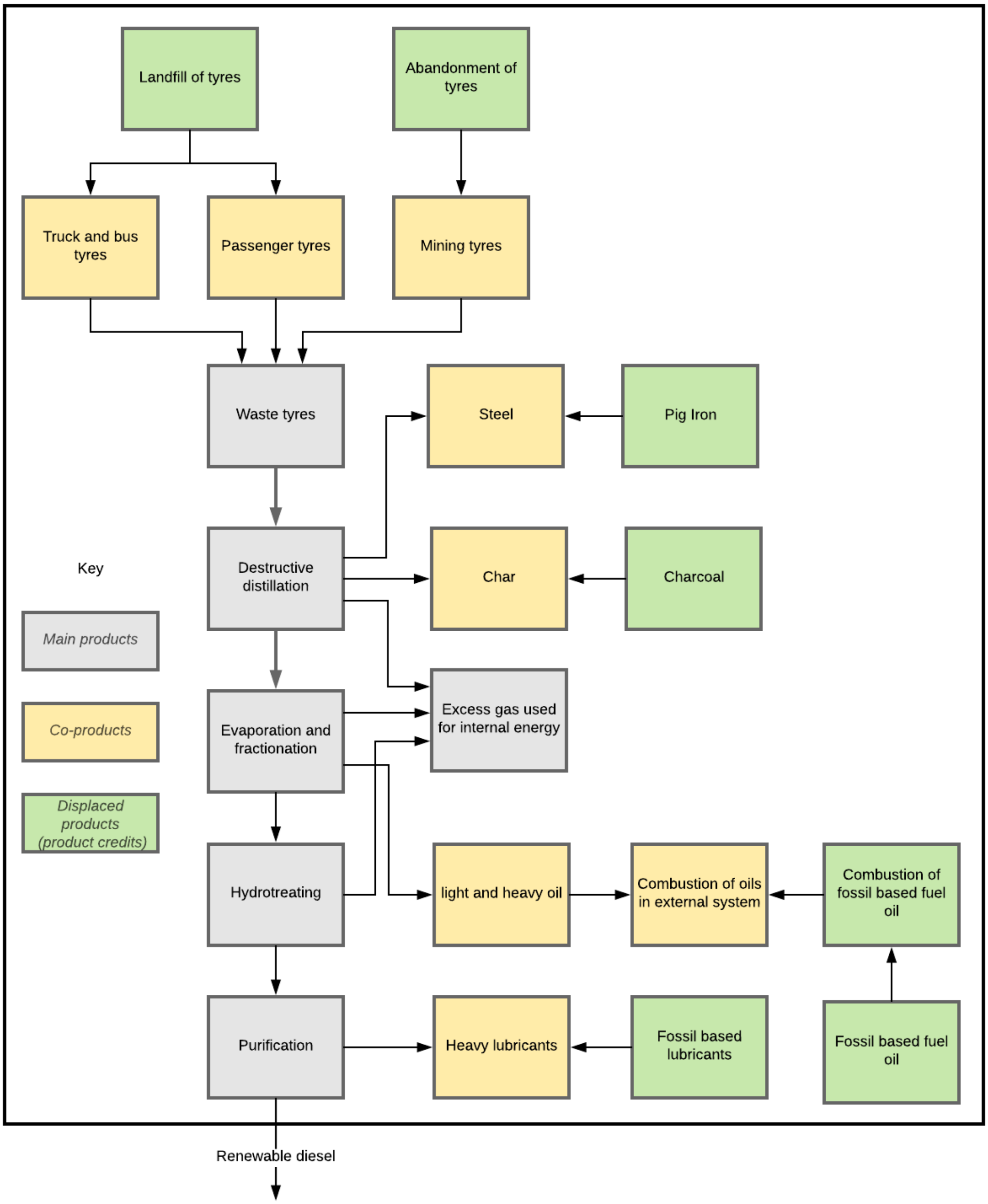

Figure 43 System boundary for renewable diesel from destructive distillation of tyres.

A.10.2 Inventory data

Table 54 shows the inputs and outputs of the destructive distillation process for tyres.

Table 54 Process data inputs for catalytic depolymerisation of tyres.

Item	Units	Amount	Comments/Source/ confidentiality
Inputs			
Tyres	kg	1,000	
Electricity	kWh	150	
Outputs			
Bio-crude	kg	390 kg	The specific density of the oil is 0.92 kg/L
Carbon	kg	400 kg	Replacement for carbon black
Steel	kg	200 kg	Steel to recycling

Source: Pers. comm., Trevor Bayley, Global Distillation Technologies

Details of tyre supply were based on a 2015 audit (Mountjoy, Hasthanayake et al. 2015).

Processing of the bio-crude was assumed to be done at Northern Oil Refinery, this data for that process were used for the evaporation and fractionation units (Table 55).

Table 55 Unit process data for evaporation.

Item	Amount	Units	Comments
Inputs			
Electricity use	1	kWh	
External fuel inputs	39.6	MJ	11 kWh
Outputs			
Middle distillate	80	kg	Higher yield that pyrolysis feedstock from lignocellulosic materials.
Light oils	10	kg	
Heavy oils	5	kg	
Gas	5	kg	

Details on hydrotreating and purification are shown in the appendix for pyrolysis.

A.10.3 Climate change results

Two main things of interest from the results are the impacts of the alternative fate of tyres, which had a substantial impact, and the impacts of charcoal offsets. The offsets of charcoal need to be validated as this may not be the most representative product that carbon from the process offsets. Apart from these, the inputs to destructive distillation were relatively small with large savings from avoided fossil fuel emissions and avoiding the need to produce diesel fuel (Figure 44).

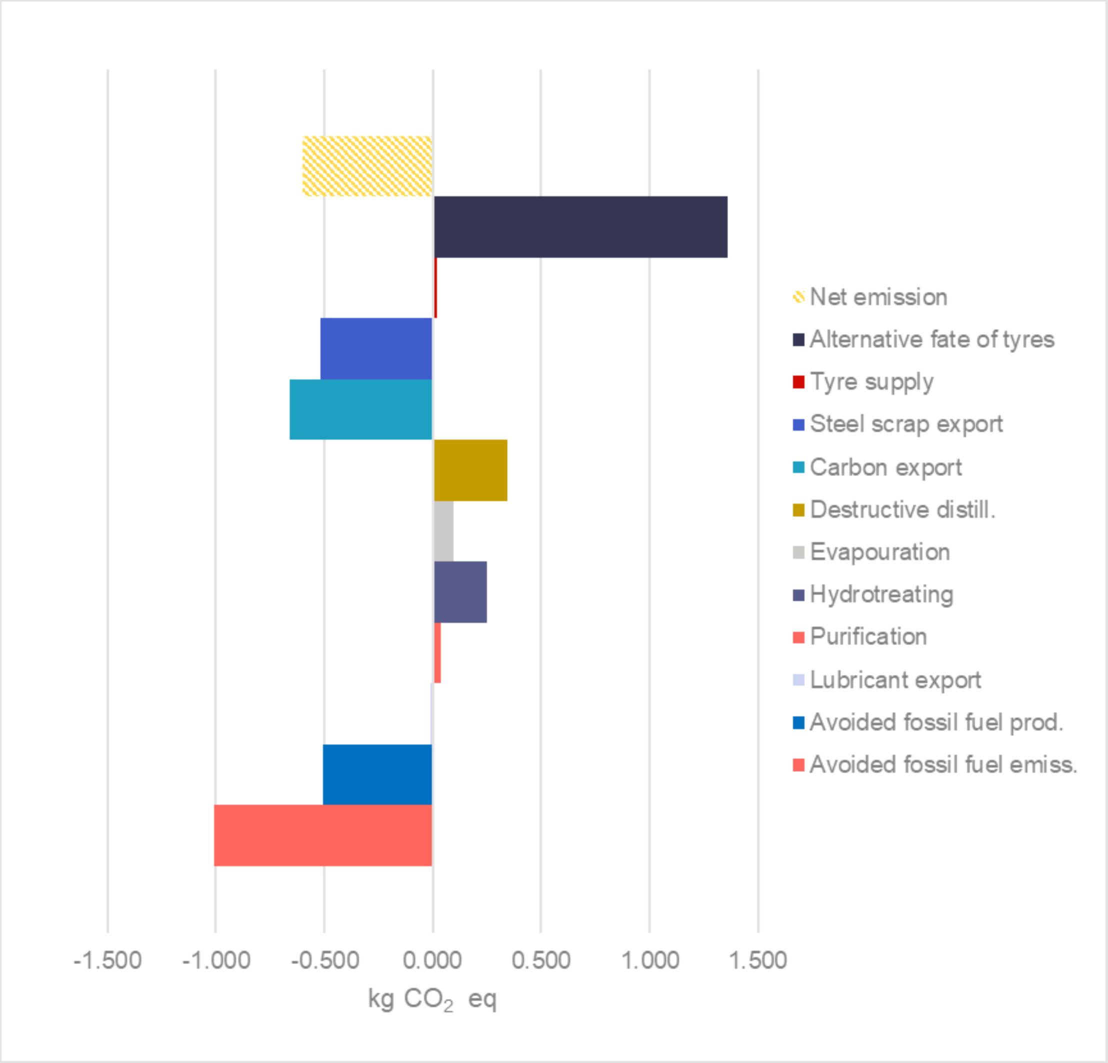

Figure 44 Climate change impacts from replacing 1 litre of diesel with equivalent renewable diesel via destructive distillation of tyres.

A.11 Biomass to renewable diesel via catalytic depolymerisation

A.11.1 Description of the process and co-product assumptions

Catalytic depolymerisation is a process where organic materials are essentially dissolved in a carrier fluid and then processed to produce renewable diesel-based fuels. The process has the ability to help separate organic material, including polymers, from mixed waste streams.

For this study four biomass sources were assessed including food waste, wood waste, forest residues and waste tyres (Figure 45).

Data for this process was sourced directly from CPD Waste2Energy, who are currently developing this approach for use in Australia.

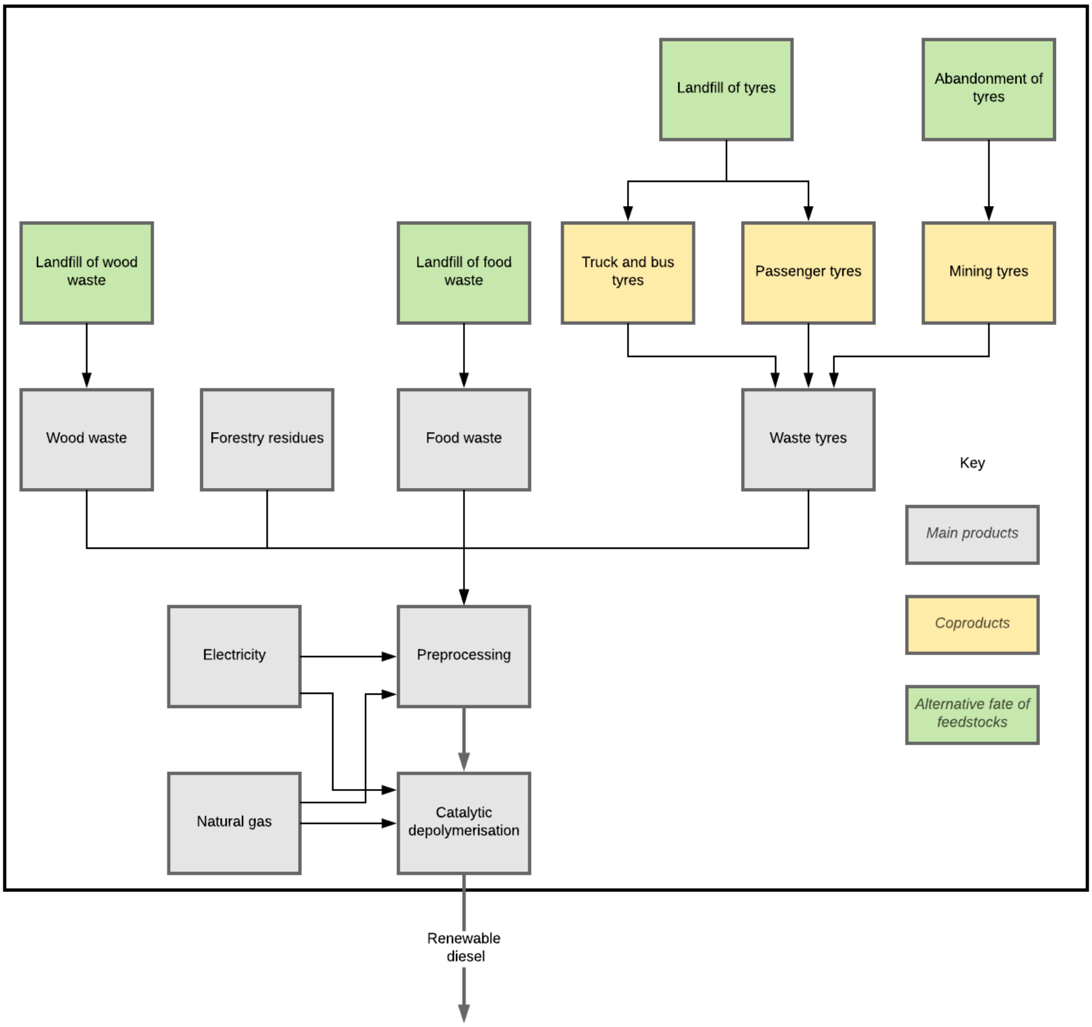

Figure 45 Overview of process for production of renewable diesel using catalytic depolymerisation.

A.11.2 Process data

Table 56 shows the main inputs for pre-processing of feedstocks for catalytic depolymerisation. Table 57 shows the process inputs for catalytic depolymerisation that produces renewable diesel. Table 58 shows the process inputs for hydrotreating diesel.

Table 56 Unit process data for pre-processing.

Flow	Unit	Value	Comment
Outputs			
Prepared feedstock	kg	8,911	
Inputs			
Supply of feedstock	kg	11,700	Dry wood content of mixed feedstock (dry matter basis)
Carrier fluid	kg	120	Net makeup rate
Catalyst	kg	125	
Lime	kg	125	
Gas energy use	MJ	16,920	
Electricity	kWh	504	Required for wood waste and forestry waste. *1.6 for tyres and *0.7 for food waste.
Emissions to air			
Water	kg	3,630	
Waste to treatment			
Waste water	L	3,430	

Table 57 Unit process data for catalytic depolymerisation.

Flow	Unit	Value	Comment
Outputs			
Renewable diesel	kg	2,526	
Inputs			
prepared feedstock	kg	8,060	
Natural gas energy	kWh	2,000	
Electricity	kWh	2,520	
Waste to treatment			
Residues to landfill	kg	111	
Waste water	L	1,360	

Table 58 Unit process data for hydrotreating diesel.

Flow	Unit	Value	Comment
Outputs			
Renewable diesel, hydrotreated	L	3,000	
Inputs			
Renewable diesel	kg	2,512	
Natural gas energy	MJ	3,510	
Electricity	kWh	2,711	

A.11.3 Climate change results

Figure 46 shows the results for diesel replaced by renewable diesel from catalytic depolymerisation. The production process including pre-processing were very similar for each feedstock source. The main difference between the feedstocks were the alternative fate of the source material. Food waste utilisation had benefits by avoiding emission to landfill. For wood waste and tyres, the alternative fate had a significant carbon store in landfill, which registered as a positive climate change outcome.

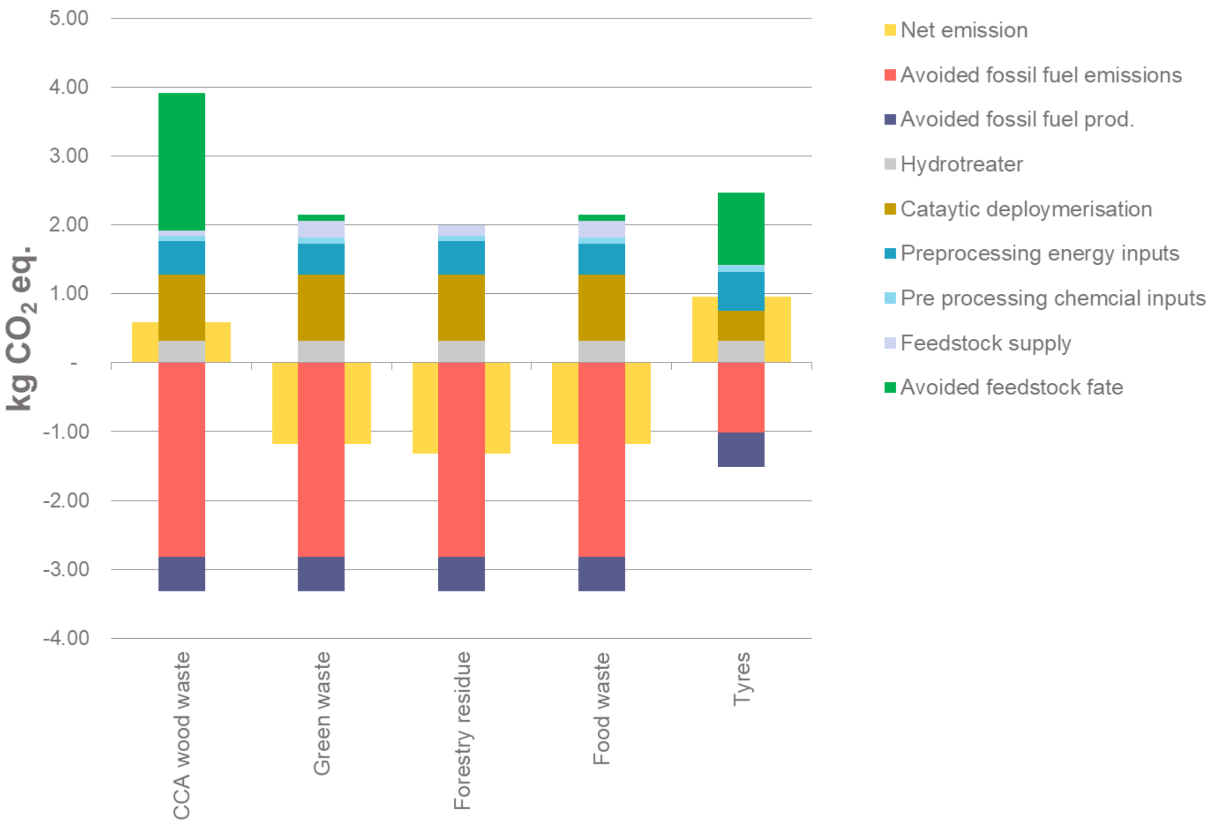

Figure 46 Climate change impacts from replacing diesel with equivalent renewable diesel via catalytic depolymerisation.

A.12 Renewable diesel from municipal solid waste using gasification and Fischer–Tropsch

A.12.1 Description of the process

This scenario begins with processing of municipal solid waste to remove recyclable fractions and inorganic materials from the waste stream (Figure 47). For the scenario, the remaining material contained a mix of organic materials including plastics and lignocellulosic waste. This material is processed with a gasification reactor to produce a syngas.[3] The syngas is then refined and converted to a liquid fuel using a Fischer–Tropsch process. This scenario was loosely based on the technology implemented by Fulcrum bioenergy.

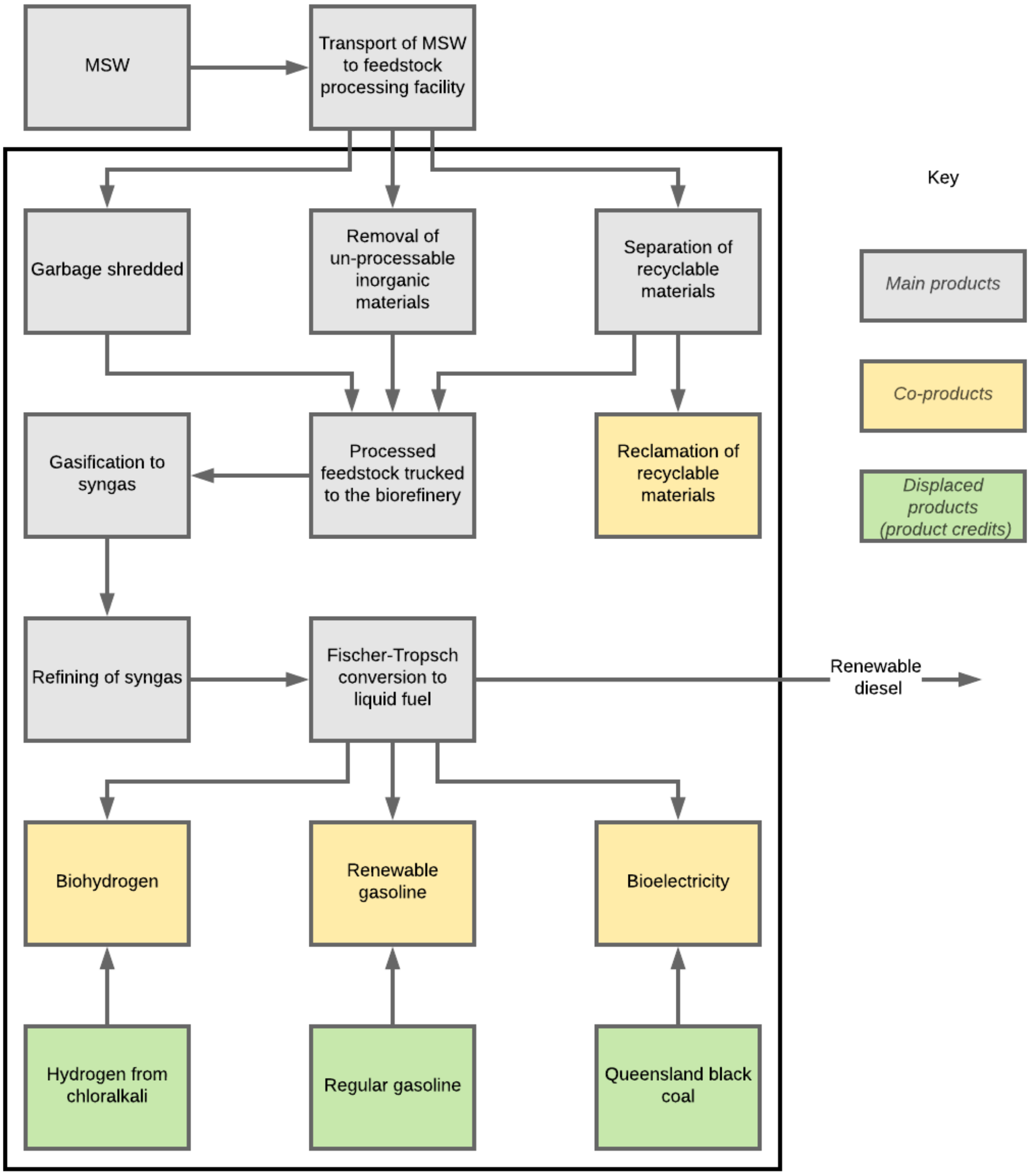

Figure 47 System boundary for renewable diesel from gasification and Fischer–Tropsch from municipal solid waste.

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[3] Syngas is an abbreviation for synthesis gas, a mix of carbon monoxide, carbon dioxide and hydrogen that can be used to create chemicals such as ammonia, methanol and other fuels.

A.12.2 Process data

Waste composition data were taken from the National Inventory Report (Commonwealth of Australia 2017), with the separation of the plastics fraction taken from (Hyder Consulting 2006).

Given the policy drivers for treating MSW, the alternative fate for MSW was assumed to be aerobic stabilisation whereby 80% of DOC was reduced prior to landfilling (Said-Pullicino, Erriquens et al. 2007). A sensitivity was undertaken where the alternative fate was landfill.

Table 59 shows the Fischer–Tropsch process which is based on (Iribarren, Susmozas et al. 2013) and Table 60 shows the data for synthesis gas production from MSW organic fractions.

Table 59 Unit process data for Fischer–Tropsch process.

Flow	Unit	Value	Comment
Outputs			
Renewable diesel from FTP, syngas from MSW gasification	kg	98.9	
Renewable gasoline	kg	41.83	
Electricity, from Fischer–Tropsch	MWh	1.21	
Renewable hydrogen	kg	0.34	
Inputs			
Catalyst (for methanol plant)	kg	0.29	1.15 kg/Nm3
Synthetic gas	m^3	10,000	

Table 60 Syngas production from gasification of MSW organic components.

Flow	Unit	Value	Comment
Outputs			
Synthetic gas, at fluidised bed gasifier	m^3	1	
Inputs			
Sulfuric acid	kg	0.0032898	From ecoinvent
Sodium hydroxide	kg	0.00082799	From ecoinvent
Zeolite, powder	kg	0.0020803	From ecoinvent
Dolomite	kg	0.01015699	From ecoinvent
Silica sand	kg	0.01259799	From ecoinvent
Water	kg	0.14325989	From ecoinvent
MSW organic residue	kg	0.50403226	
Electricity	kWh	0.02662298	From ecoinvent
Emissions to air			
Acetic acid	kg	5.84E-08	From ecoinvent
Propane	kg	7.79E-08	From ecoinvent
Particulates, <2.5 µm	kg	7.79E-08	From ecoinvent
Toluene	kg	7.79E-08	From ecoinvent
Nitrous oxide	kg	3.89E-08	From ecoinvent
Sulfur dioxide	kg	2.14E-07	From ecoinvent
Methane, biogenic	kg	7.79E-07	From ecoinvent
Carbon monoxide, biogenic	kg	8.18E-07	From ecoinvent
Mercury	kg	1.17E-11	From ecoinvent
Formaldehyde	kg	3.89E-08	From ecoinvent
Carbon dioxide, biogenic	kg	0.322	From ecoinvent
Nitrogen oxides	kg	6.97E-06	From ecoinvent
Benzo(a)pyrene	kg	3.89E-12	From ecoinvent
Benzene	kg	1.56E-07	From ecoinvent
Propionic acid	kg	7.79E-09	From ecoinvent
Acetaldehyde	kg	3.89E-10	From ecoinvent
Water/m^3	m^3	2.15E-05	From ecoinvent
Butane	kg	2.73E-07	From ecoinvent
PAH, polycyclic aromatic hydrocarbons	kg	3.89E-09	From ecoinvent
Pentane	kg	4.67E-07	From ecoinvent

A.12.3 Climate change results

Figure 48 shows the results for climate change impacts for the replacement of 1 litre of diesel with renewable diesel made via gasification and Fischer–Tropsch. Gasification is a high energy process with substantial emissions however the avoidance of landfill of organic fractions dominate the climate change results of this scenario. This is due to avoided methane emissions from avoiding landfill of organic fractions.

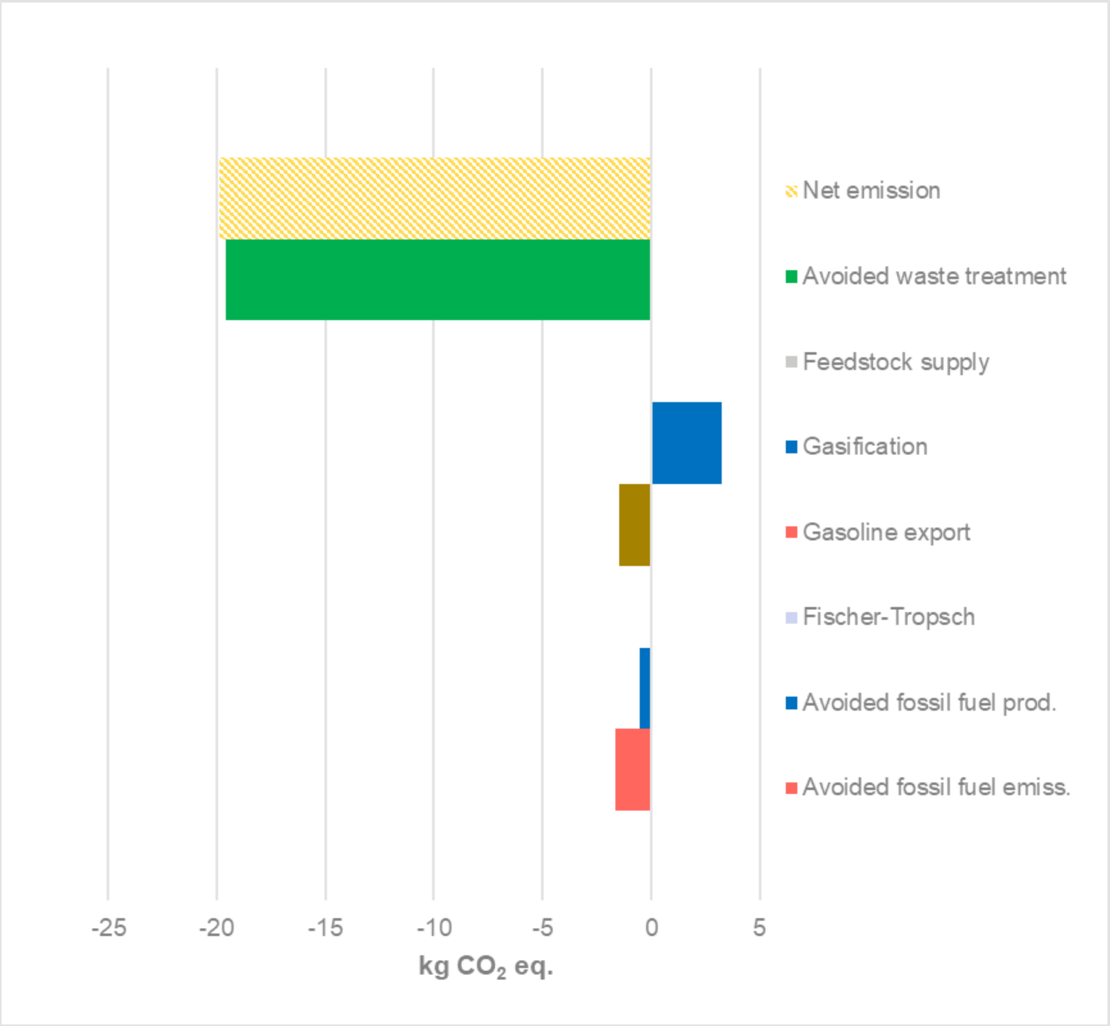

Figure 48 Contribution analysis for replacing diesel with renewable diesel produced from MSW using gasification and Fischer–Tropsch.

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