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Australia's Bioenergy Roadmap

Appendix – Production Pathways

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Australian Government
Australian Renewable Energy Agency

ARENA

1. Key findings

- **Bioenergy markets can be served by multiple bioenergy pathways.** Pathways are a combination of feedstocks, processing technologies and end-products. More than one hundred bioenergy pathways were identified through the development of this Roadmap.
- **All end-use markets except aviation can be addressed by mature bioenergy production pathways.** In addition, new pathways are being investigated globally to make better use of organic wastes and residues. In particular, in transport markets, these pathways could address sustainability challenges and limited availability of agricultural resources. Although technologically mature and commercial overseas, some bioenergy pathways do not have commercial applications in Australia yet.
- **Compared to low emissions alternatives, bioenergy production pathways could be more easily integrated into existing energy systems.** This is especially the case for:
    - ◊ transport markets, where biofuels could be blended into petroleum-derived fuels or even act as a direct substitute without upgrading existing refuelling infrastructure or engines
    - ◊ the gas market, where biomethane's very close chemical composition to natural gas allows for direct injection into the gas grid with limited upgrades
    - ◊ the electricity market, where bioelectricity's dispatchable nature could allow for lower integration costs than other intermittent renewables.
- **Potential cost advantages of bioenergy production pathways include:**
    - ◊ Bioenergy represents a cost-competitive source of renewable industrial heat.
    - ◊ It is also cost-competitive with dispatchable renewable electricity generation, especially in niche applications, such as in off-grid areas where diesel generators are used and feedstock is available.
    - ◊ Road transportation biofuels can be cost-competitive, with conventional fuels depending on relative feedstock and conventional fuels costs.
    - ◊ Biojet fuels are not cost-competitive with conventional jet fuels.
    - ◊ Biomethane from landfill gas offers an early cost-competitive opportunity to reduce emissions in Australia's gas networks.
- **Long-term cost reductions are limited in all end-use markets due to mature technologies or the dispersed nature of bioenergy resources.** Feedstock collection and transport costs may be reduced through supply chain improvements, but not significantly enough to make all bioenergy pathways cost-competitive.

- **Bioenergy is capable of delivering significant lifecycle greenhouse gas emissions savings compared to fossil fuel alternatives, depending on feedstock sustainability.**

  Bioenergy can significantly reduce greenhouse gas emissions across all end-use markets when compared to conventional fuels. It also has the greatest emissions-reduction potential in end-use markets where there are no or few alternatives, such as aviation and road transportation, particularly heavy-duty vehicles.

  Emissions benefits of bioenergy are, however, heavily dependent on the sustainability of resources used. Wastes and residues resources achieve the greatest emissions reductions while emissions-reduction benefits of primary agricultural and forestry resources depend on land use considerations.

  This highlights the importance of sustainability frameworks and proper resource governance.

- **There are a range of other benefits related to bioenergy production, including:**
  - job creation
  - new source of income for farmers
  - waste management and circular economies
  - utilisation of co-products.

2. Appendix overview

This appendix assesses the technical, economic and environmental performance of bioenergy production pathways.

Specifically, it

- defines and categorises bioenergy pathways
- gives an overview of bioenergy's technical, economic and environmental performance
- assesses bioenergy pathways' maturity, costs and technical characteristics compared to competing technologies and emissions-reduction potential.

3. Bioenergy pathway definition

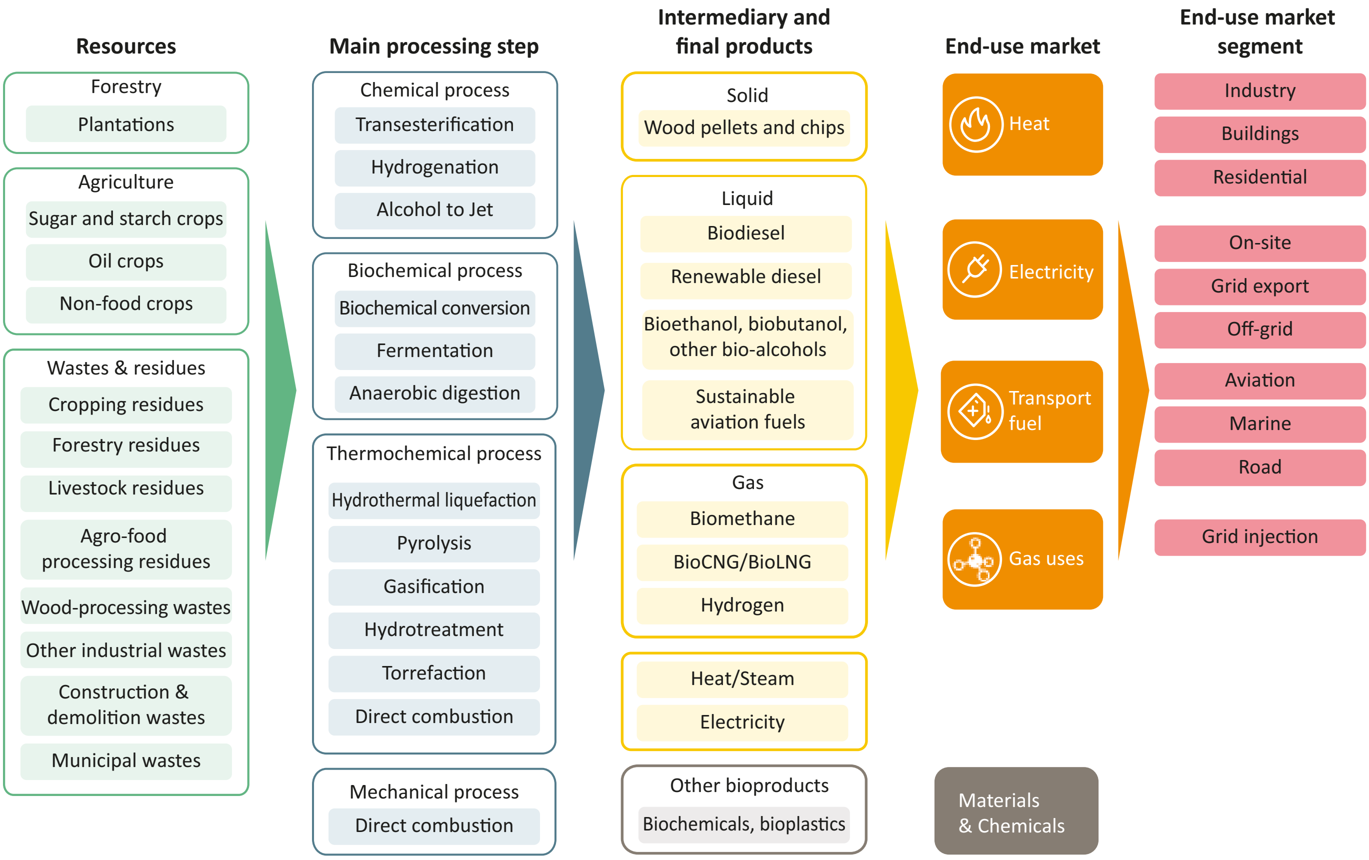
Bioenergy can serve multiple end-use markets and market segments. The availability and accessibility of resources will drive the types of end-products that can be produced.

End-products can be heat or electricity, transport fuels such as bioethanol or renewable diesel, and gases such as biomethane. Bioenergy resources are converted to end-use products using different types of conversion technologies based on chemical, biochemical, thermochemical and mechanical processes.

1. A ***chemical process*** changes one or more chemical compounds
2. A ***biochemical process*** is a chemical process that occurs in living things
3. A ***thermochemical process*** uses heat to assist and often quicken a chemical transformation
4. A ***mechanical process*** transforms resources through physical force.

A bioenergy pathway is the combination of resources, also known as feedstocks, processing technologies, and energy end uses.

Figure 1 – Illustration of bioenergy pathways



Source: Enea Consulting

Each end-use market can be addressed by multiple bioenergy pathways based on different combinations of resource, processing technology and end-products. Bioenergy is a multi-faceted industry given that:

1. processing technologies can use a variety of resources
2. processing technologies can produce different types of end-products and co-products
3. end-products can be used in multiple end-use markets and market segments.

Given the diversity and/or complexity of resources for bioenergy in terms of chemical composition, they generally require complex processing steps to produce the required end-product. This is particularly relevant for biofuels, which must meet tight specifications to be acceptable for engine consumption.

One combination of resource and processing technology may produce several end-products that can be used in different markets or market segments.

For example, the anaerobic digestion of organic wastes and residues produces biogas (an intermediate product), which can be used for electricity or heat generation. Alternatively, biogas can be upgraded to biomethane and used as an alternative to natural gas. Biomethane can also be liquefied or compressed to produce liquid natural gas (bioLNG) or compressed natural gas (bioCNG) for uses in gas vehicles or industry. Also, biorefineries may produce different types of biofuels for different end-use market segments, such as road, aviation and marine transports in addition to other co-products.

Bioenergy pathways may also produce co-products that may be used as an input to other bioenergy pathways or for value-adding opportunities.

For example, the production of bioethanol from sugarcane co-produces bagasse that can be used to generate heat or electricity. Other co-products may not have energy applications. For example, animal feed as a co-product of bioethanol production or nutrient-rich fertiliser (digestate) as a by-product of biogas production.

Bioenergy pathway categories and market opportunities

Research and analysis as part of the development of this Roadmap identified more than one hundred bioenergy pathways based on different combinations of resources, processing technologies and end-products.

These pathways have been grouped into categories based on the key market opportunities identified, including:

1. Industrial heat generation
2. Dispatchable renewable electricity generation
3. Biofuels for passenger vehicles
4. Biofuels for long-haul transport
5. Sustainable aviation fuels (SAF)
6. Renewable gas for grid injection.

To further define these market opportunities, the performance of select bioenergy pathway categories (see Table 1) was analysed and compared to fossil fuel and low carbon alternatives, as detailed in the following sections.

Table 1 – Categorisation of bioenergy pathways by end-use market

Bioenergy pathways	Fossil fuel alternatives	Low carbon alternatives
Heat		
• **Heat from biogas** • **Heat from solid biomass**	• Heat from natural gas • Heat from coal • Heat from oil	• Heat from thermal solar • Heat from geothermal
Electricity		
• **Electricity from biogas** • **Electricity from wastes** • **Electricity from solid biomass** • **Electricity from solid biomass + carbon capture and storage (CCS)**	• Electricity from coal • Electricity from natural gas • Electricity from diesel	• Solar electricity • Wind electricity • Solar electricity + storage • Wind electricity + storage
Transport		
• **1G bioethanol** • **2G bioethanol** • **1G biodiesel** • **Renewable diesel** • **BioCNG/BioLNG** • **Sustainable aviation fuels**	• Petrol • Diesel • Conventional jet fuels • Hydrogen from fossil fuels • Hydrogen from electrolysis + grid electricity	• Electricity from grid • Hydrogen from electrolysis + renewables • Hydrogen from fossil fuels + CCS
Gas grid injection		
• **Biomethane from anaerobic digestion** • **Biomethane from landfill gas** • **Hydrogen from biomass gasification**	• Natural gas • Hydrogen from fossil fuels	• Hydrogen from electrolysis + renewables • Hydrogen from electrolysis + grid electricity • Synthetic natural gas from methanation

4. Bioenergy pathways performance

Bioenergy pathways link bioenergy resources to end-use markets and market segments via processing technologies.

The relevance of bioenergy pathways to end-use markets will depend on their current and future technical, economic and environmental performance.

Pathways have been grouped into categories based on the market opportunities and resource types. Representative pathways for further analysis have been selected based on maturity and potential to address end-uses where there are limited or no other options for reducing greenhouse gas emissions.

A summary of the assessed pathways can be seen in Table 2 below. The pathways are then further detailed in the sections that follow.

Image: Southern Meats Generator

Table 2 – Technical, economic and environmental performance of bioenergy production pathways

Bioenergy pathway	Maturity	Cost competitiveness	Technological advantages	Low emissions potential
Heat				
Heat from biogas	Mature technology with commercial examples in Australia	Competitive with most conventional fuels and low emissions alternatives	Can address most industrial heat applications, unlike low emissions alternatives	Low emissions potential with no or limited alternatives
Heat from solid biomass				
Electricity				
Electricity from biogas	Mature technology with commercial examples in Australia	Competitive with wind and solar combined with batteries but not conventional fuels	Can provide dispatchable electricity, use on-site wastes	Low emissions potential but not as much as other renewables
Electricity from solid biomass		Not competitive	Can provide dispatchable electricity, use on-site wastes, co-firing with existing coal plants	
Electricity from wastes	Mature technology with first commercial projects operating in Australia	Competitive with wind and solar combined with batteries but not conventional fuels		Low emissions potential due to avoidance of waste emissions
Electricity from solid biomass + CO2 capture & storage (CCS)	Demonstration with no projects in Australia	Not competitive, even with significant cost reductions		Can achieve negative net lifecycle emissions
Transport				
1G bioethanol	Mature technology with commercial examples in Australia	Can be competitive on a total cost of ownership basis	Can be used in existing engines and some refuelling infrastructure with blending limits, although there are low emissions alternatives	Low emissions potential but there are alternatives, such as electric vehicles with varying levels of emissions savings
1G biodiesel		Could be competitive depending on relative feedstock and conventional fuel costs		
2G bioethanol	Demonstration with no examples in Australia	Competitive with low emissions alternatives but not conventional fuels		
Renewable diesel	Mature technologies with demonstration projects in Australia	Can be competitive on a total cost of ownership basis	Can be used in existing engines and infrastructure with limited low emissions alternatives	Low emissions potential but there are alternatives, such as hydrogen with varying levels of emissions savings
BioCNG/LNG	Mature technology with trials in Australia	Competitive with hydrogen but not conventional fuels	Can be used in limited existing engines and refuelling infrastructure	
Biojet fuels as SAF	Research and development with demonstration projects in Australia, standards have been developed for 7 pathways	Not competitive with conventional jet fuels	Can be used in existing engines and infrastructure with blending limits, with no likely low emissions alternatives	Low emissions potential with limited alternatives in the short to medium term
Renewable gas grid injection				
Biomethane from anaerobic digestion	Mature technology but no commercial examples in Australia	Competitive with hydrogen but not natural gas	Can be used in existing grid even at high/any penetration(s), unlike hydrogen	Low emissions potential with no or limited alternatives in the short term
Biomethane from landfill gas		Close to being competitive		
Hydrogen from biomass gasification	Demonstration but no projects in Australia	Competitive with other hydrogen pathways but not natural gas	Limited use before upgrading infrastructure and appliances	Low emissions potential but not cost competitive with biomethane

This analysis has used information from international and Australia-specific literature.

Australia-specific inputs have been used where available. However, given some bioenergy pathways do not have commercial applications in Australia, international inputs have also been used.

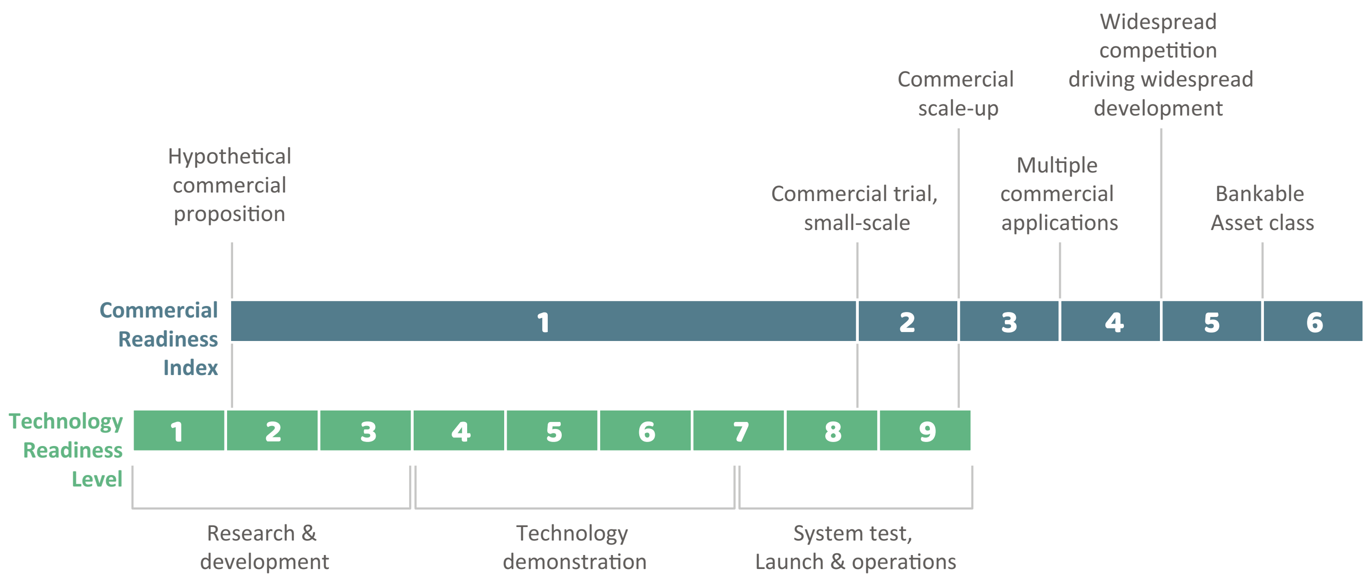
5. Technology maturity and commercial readiness

All end-use markets except aviation can be addressed by mature bioenergy technologies, while new pathways are being investigated globally to make better use of organic wastes and residues.

Using the scale depicted in Figure 2, most bioenergy pathways have a high 'Technology Readiness Level' or are in the technology demonstration phase (see Figure 2).

Bioenergy pathways are considered commercially established when they are readily available to consumers and cost-competitive with other energy sources. Note that 'Commercial Readiness Index' is country dependent, and has been assessed in this Roadmap for Australia.

Figure 2 – Technology Readiness Level and Commercial Readiness Index Scales



Source: IEA [1]

Despite being technologically mature and highly developed overseas, waste-to-energy (WtE, or heat-from-waste and electricity-from-waste) is only just starting to gain traction in Australia.

In 2018, the Kwinana WtE Project was announced as Australia's first thermal utility-scale WtE facility. The project will process approximately 400,000 tonnes of waste (diverting approximately 25 per cent of Perth's post-recycling rubbish from landfill sites) to generate 36 MW of dispatchable electricity.

A second WtE plant was announced in 2020 in Rockingham Industrial Zone outside of Perth. This plant will generate electricity (29 MW capacity) from 300,000 tonnes of municipal, industrial and commercial rubbish annually.

Table 3 – Technology and commercial readiness of bioenergy pathways in Australia

Bioenergy pathway	Technology Readiness Level	Commercial Readiness Index in Australia
Heat		
Heat from solid biomass	8-9	6
Heat from biogas	8-9	6
Electricity		
Electricity from biogas	8-9	6
Electricity from wastes	8-9	3
Electricity from solid biomass	8-9	6
Electricity from solid biomass + CCS	3-7	1
Transport		
1G bioethanol	8-9	6
1G biodiesel	8-9	6
BioCNG/LNG	7-8	1
2G bioethanol	6-7	1
Renewable diesel	4-8	1
Sustainable aviation fuels	2-7	1
Gas grid injection		
Biomethane from anaerobic digestion	8-9	1
Biomethane from landfill gas	7-8	1
Hydrogen from biomass gasification	4-5	1

Advanced biofuels ,such as renewable diesel and 2G bioethanol, are less technologically mature than conventional biofuels (1G biodiesel and 1G bioethanol).

They will still need to be considered to help address sustainability issues and limited resource availability faced by conventional biofuels.

The maturity of biojet fuels production pathways is increasing.

As of May 2020, seven pathways for biojet fuels have been certified by the international technical standards organisation ASTM International under the standard ASTM D7556 [2]. Across the seven pathways, oil, sugar, starch or lignocellulosic (wood and wood residue) feedstocks are converted to biojet fuels via chemical, biochemical or thermochemical processes.

Depending on the pathway used, biojet fuels can be blended with conventional jet fuel from 10 to 50 per cent [3]. Synthetic Paraffinic Kerosene from Hydroprocessed Esters and Fatty Acids (HEFA-SPK) is the most commercially advanced pathway. Examples of operational plants include AltAir's facility in Paramount, California.

There are also emerging bioenergy pathways, which require investment in research and development and technology demonstration. Research is being undertaken to develop new pathways that could overcome feedstock supply constraints, either by leveraging new bioenergy resources (such as algae), low-quality resources (such as wastes and residues) or a diversified supply. This is especially important where biofuels are concerned, since 1G pathways are leveraging agricultural commodities and could face limited resource supply in the future.

Australian small-scale, commercial trials for both renewable diesel and biojet fuels

Virgin Australia's biofuels trial at Brisbane Airport

Globally, this is one of the first examples of delivering biojet fuels though the general fuel supply system.

Biojet fuel was blended with traditional jet fuel and supplied into the general fuel supply system at Brisbane Airport. Since August 2018, Virgin Australia has led the pilot in partnership with the Queensland Government, Brisbane Airport Corporation, US-based biofuel producer Gevo Inc., and supply chain partners Caltex and DB Schenker.

Following the success of the pilot, Gevo Inc. has been awarded funding from the Queensland Government to support the assessment of sugarcane waste, and wood waste for biojet fuel production.

Southern Oil's advanced biofuels pilot plant

With funding from the Queensland Government, Southern Oil is trialling the production of renewable diesel from waste plastic, tyres, agriculture and forestry waste, and biosolids.

This renewable diesel is intended for use in heavy machinery trucks and machine engines. As part of the trial, the performance of the fuel against petroleum-based diesel, including wear and tear on the engine, will be assessed.

6. Cost-competitiveness

Production costs associated with bioenergy pathways vary due to different combinations of conversion technologies and resources.

The levelised cost of energy (LCOE) assesses the costs of energy production over the lifetime of the plant, presented as cost per unit of energy. It can be used to compare the competitiveness of bioenergy to other sources of energy.

Resource costs can vary from negative (where disposal costs are avoided for some wastes) to significant (as is the case with dedicated energy crops). WtE plants are primarily waste treatment plants, meaning that most of their revenue[2] comes from waste disposal fees.

The cost of collecting and transporting resources to bioenergy processing facilities also determines the economic viability of projects [4]. Among other benefits, bioenergy hubs could allow for building up supply chains, thereby reducing collection and transport costs.

While these LCOEs are based on the cost of energy, some bioenergy pathways produce co-products that can provide additional revenue streams to a bioenergy project. This would reduce the price required for the sale of bioenergy products in certain end-use markets.

Revenue from co-products is key to the economic viability of bioenergy projects

The economic viability of bioenergy is often integrated with the production and sale of other bio-based products. Most bioenergy pathways produce co-products, which can provide additional revenue to a bioenergy project.

For example, the production of 1G bioethanol (from corn) also produces animal feed, known as 'distillers' grains', and the anaerobic digestion of organic wastes and residues also produces nutrient-rich fertiliser called digestate. In 2017, co-products made up 21 per cent of bioethanol refinery revenues in the US [5].

The importance of these co-products will depend on the bioenergy pathway. Regardless, this highlights the importance of considering bioenergy within a broader bioeconomy perspective.

[2] Up to 70 per cent

Current bioenergy pathway costs

Levelised cost of heat

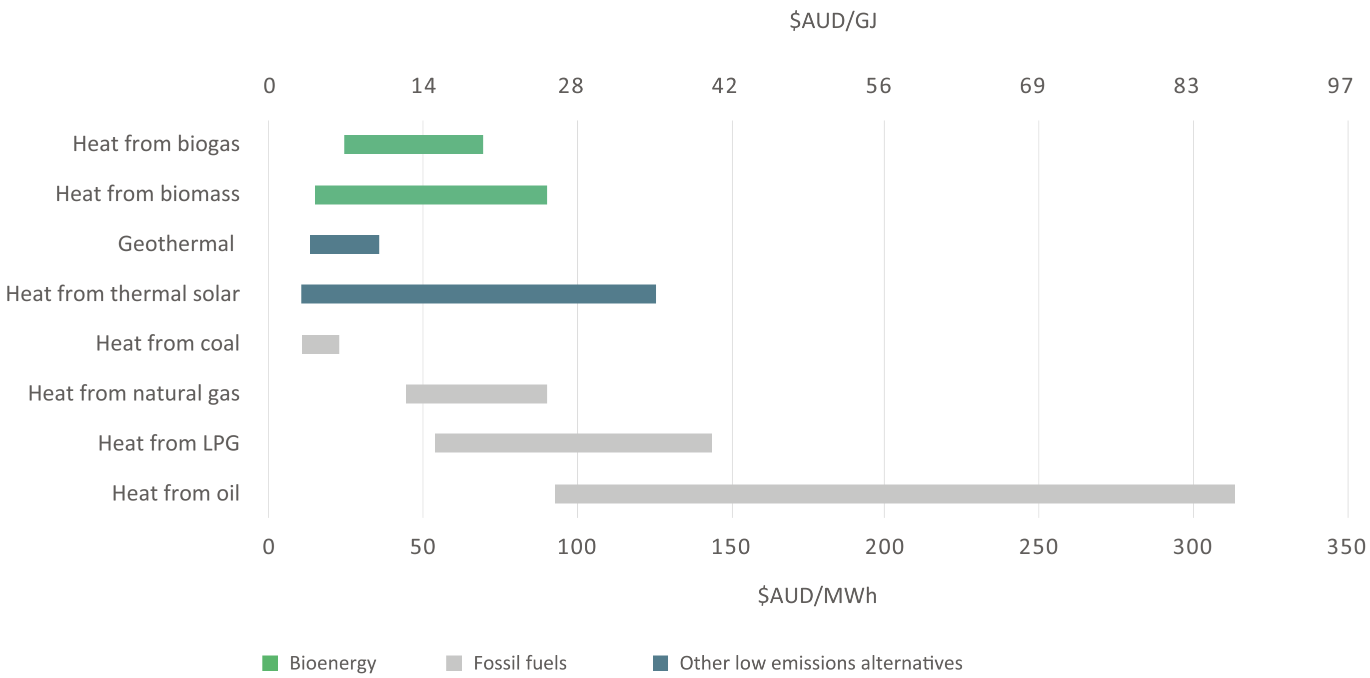
Bioenergy is a cost-competitive source of renewable energy for industrial heat generation.

Industrial heat generation from bioenergy is less expensive than some conventional heating methods (natural gas and oil) and other sources of renewable energy such as solar thermal (see Figure 3). Also, other sources of renewable energy may not be suitable for certain industrial applications that require high temperatures or could be limited due to resource availability. This includes geothermal solutions, generally limited to temperatures below 95 degrees Celsius and limited by the availability of underground heat sources.

Bioenergy is cost-competitive with natural gas, Australia's largest source of energy for industrial heat. In some cases, bioenergy is half the costs of natural gas.

However, expectations amongst industry for short payback periods combined with a low-risk appetite can prevent further uptake. Improved heat generation is often treated as an energy efficiency initiative, which needs to have shorter payback periods to be considered [6].

Figure 3 – Levelised cost of heat



Note: *These LCOEs are based on Enea's analysis of different sources incl. ITP Thermal for ARENA 2019, 'Renewable Energy Options for Industrial Process Heat' [6] ; IRENA 2019, 'Solid Biomass Supply for Heat and Power' [7]; Enea 2019, 'Biogas opportunities for Australia' [8]; IEA 2020, 'Outlook for biogas and biomethane - Prospects for organic growth' [9]*

Levelised cost of electricity

Electricity generation from bioenergy is generally more expensive than other sources of renewable energy and fossil fuels.

However, bioenergy can be competitive with intermittent renewables when they are combined with battery storage (see Figure 4).

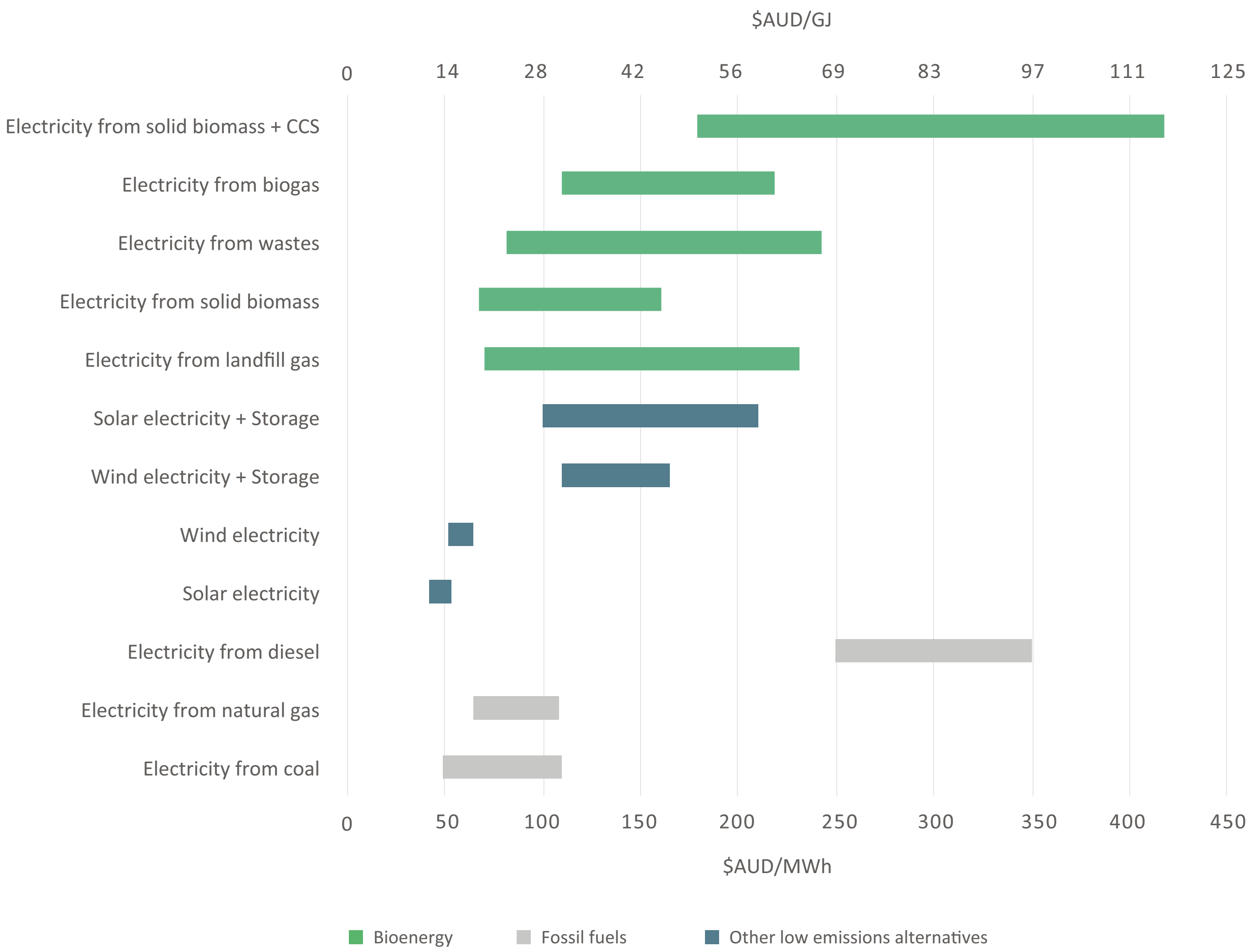
Bioelectricity generation starts being cost-competitive with solar PV and wind combined with battery storage from six hours of storage duration [10].

In addition to using biogas produced through anaerobic digestion, electricity may also be generated from landfill gas, the gas produced during the uncontrolled decomposition of organic waste that has been disposed in landfill. The LCOE of landfill gas is approximately $75/MWh, which is more competitive than other forms of bioelectricity [11].

Off-grid bioelectricity generation, particularly from biogas and solid biomass, is less expensive than off-grid diesel generation.

Bioenergy can thus affordably reduce emissions in off-grid electricity generation where it is currently reliant on diesel, provided there are locally accessible resources.

Figure 4 – Levelised cost of electricity



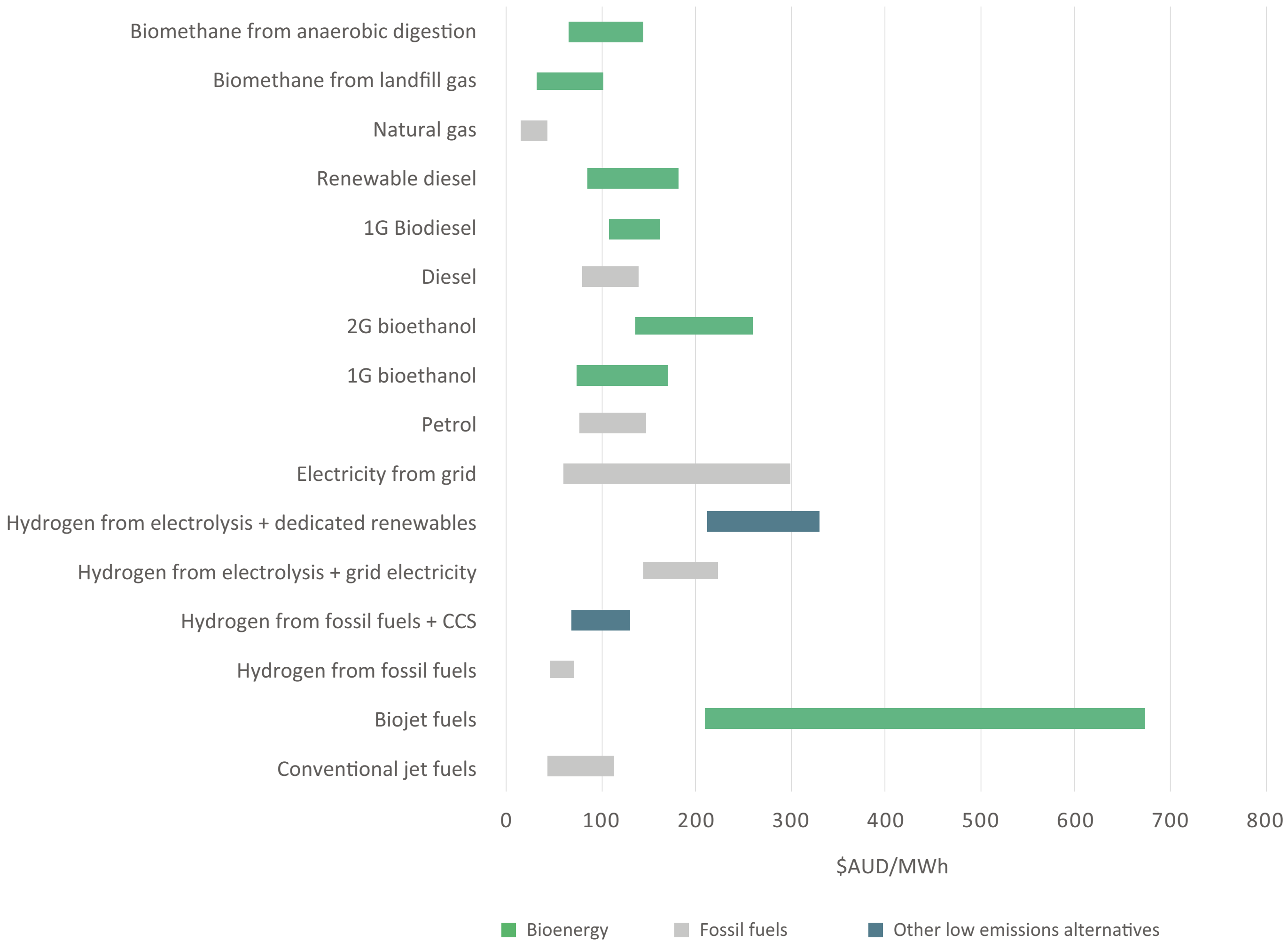
Note: *These LCOEs are based on Enea's analysis of different sources including CSIRO 2019, 'GenCost 2019-20 - Preliminary results for stakeholder review' [12] ; ITP Energised Group 2018, 'Comparison of dispatchable renewable electricity options - Technologies for an orderly transition' [10]; Lazard 2020, 'Levelised cost of energy and levelised cost of storage [13]'; IEA 2019, 'World Energy Outlook' [14]; US Department of Energy 2019, 'Waste to energy from MSW' [15]; IRENA 2020, 'Renewable power generation costs in 2019' [16]. Two to six-hour li-ion batteries are assumed for both wind and solar electricity coupled with storage. For non-intermittent energy sources, base load applications are considered (capacity factors typically between 40 and 80 per cent).*

Levelised cost of fuels and total cost of ownership

Although biofuels are generally more expensive than fossil fuel alternatives, some transport market segments have limited options for emissions reduction (such as long-haul road transport and aviation):

- Figure 5 shows that while 1G bioethanol is cost-competitive with petrol, 2G bioethanol is currently nearly double the cost.
- 1G biodiesel is also more expensive than diesel although the LCOE range for renewable diesel shows that, at times, it can be cost-competitive.
- The cost of biojet fuels would need to more than halved to be cost-competitive with fossil jet fuel.

Figure 5 – Levelised cost of fuel



Notes:

These LCOEs are based on Enea's analysis of different sources incl. IEA 2020, 'Advanced biofuels – Potential for cost reduction' [17]; IRENA 2017, 'Biofuels for Aviation - Technology Brief' [18]; The International Council on Clean Transportation 2019, 'The cost of supporting alternative jet fuels in the European Union' [19]; ARENA and CEFC 2019, 'Biofuels and transport - an Australian Opportunity' [20]; IEA 2020, 'Aviation fuels - Are they ready to take off?' [21]; Australian Government 2014, 'Australian liquid fuels technology assessment' [22]; CSIRO 2018, 'National Hydrogen Roadmap' [23]; AIP 2020, 'Terminal Gate Prices - Historical Averages for Petrol and Diesel' [24].

These LCOE are based on fuel production costs only and exclude downstream components such as fuel transport, compression stations (for gaseous fuels) and refuelling infrastructure. Downstream costs can be significant, especially for fuels that cannot rely on existing infrastructure (e.g. hydrogen or CNG). For gaseous and liquid fuels, costs are based on low heating values.

Diesel and petrol LCOEs are based on Australia's Terminal Gate Prices over a period of two years (2018-2020) to account for oil price fluctuations.

The LCOE of hydrogen from grid electricity is based on an electricity price of $60/MWh (CSIRO's assumption for base case hydrogen costs). This price is considered at the lower end of grid electricity LCOEs displayed on the graph. The higher end of grid electricity LCOEs considers residential retail prices ($300/MWh).

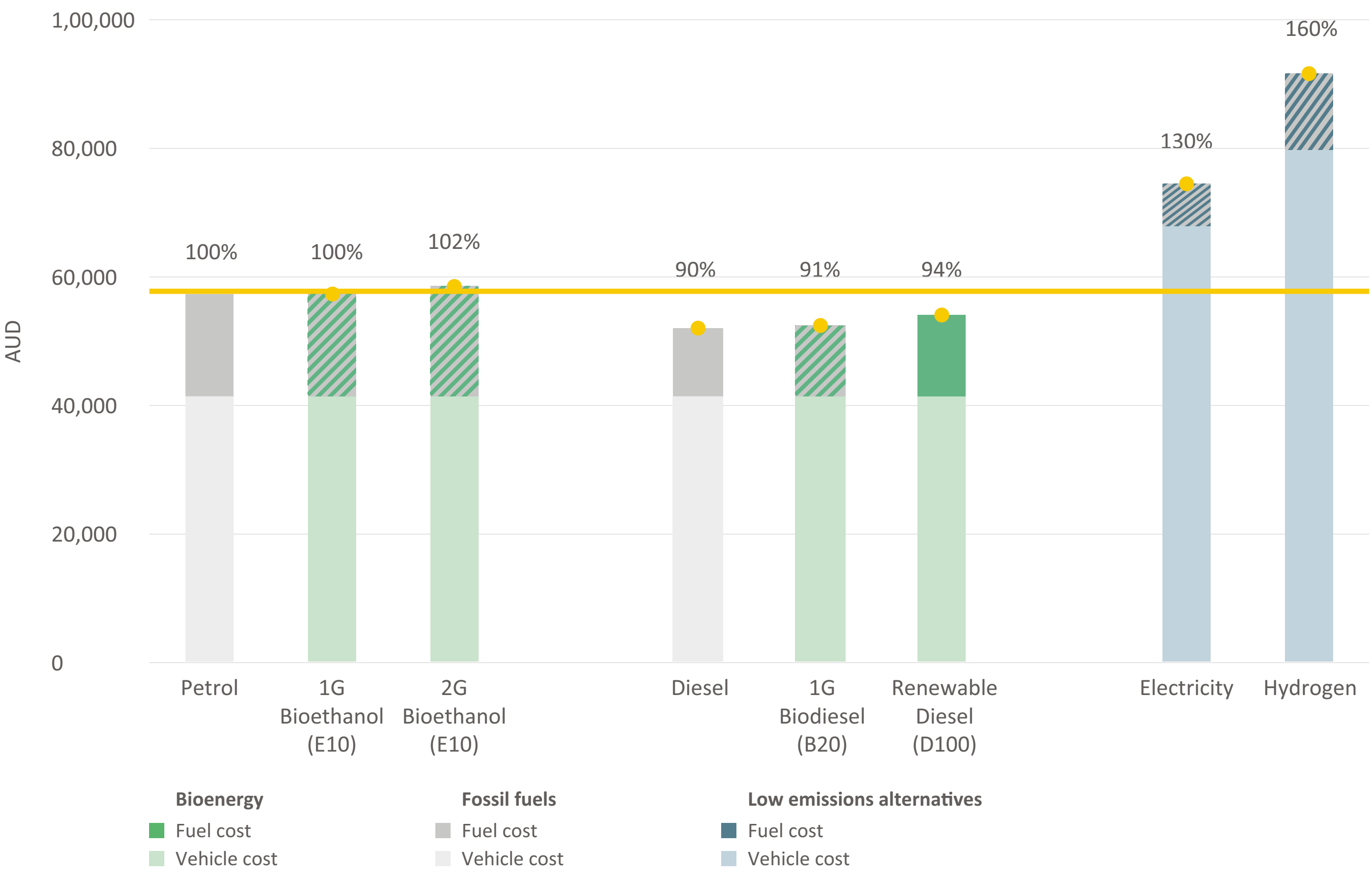
The LCOE in this case, however, has limitations. It only assesses the production cost of fuels and excludes vehicle cost and efficiency. A better comparison of costs across the different alternatives would be based on the total cost of ownership, including these two aspects.

For biofuels, purchasing a new vehicle is not required because of the fuel compatibility with existing engines. In the longer term, it is likely that the cost of electric vehicles and hydrogen vehicles will decline, which would reduce their total cost of ownership.

On a total cost of ownership basis for light-duty vehicles (passenger cars), 1G bioethanol (10 per cent petrol blends), 1G biodiesel (20 per cent petrol blends) and renewable diesel are cost-competitive with petrol and diesel, respectively (see Figure 6).

2G bioethanol vehicles have a similar cost to petrol vehicles. This is mainly due to the low level of blending (10 per cent). Regarding low carbon alternatives, despite higher engine efficiencies and thus lower fuel consumption, electric and hydrogen vehicle are currently not competitive, due to higher vehicle costs (between 1.75 and 2 times the cost of petrol cars).

Figure 6 – Total cost of ownership of light-duty vehicles



Sources: Enea analysis and [25] [26]

Note: *These total costs of ownership are based on Enea analysis. They include vehicles purchase costs and fuel consumption costs. Other vehicles costs such as insurance, licence and registration, maintenance and repairs are excluded. Fuel costs include fuel production LCOEs only (see Figure 5), downstream components such as fuel transport, compression stations (for gaseous fuels) and refuelling infrastructure are excluded. Fuel consumptions are based on typical efficiencies for petrol and diesel engines, electric powertrains and hydrogen fuel cells. The use of grid electricity and hydrogen from grid electricity is assumed for electric and hydrogen vehicles respectively. A 10-year period of planned ownership is considered for fuel consumption.*

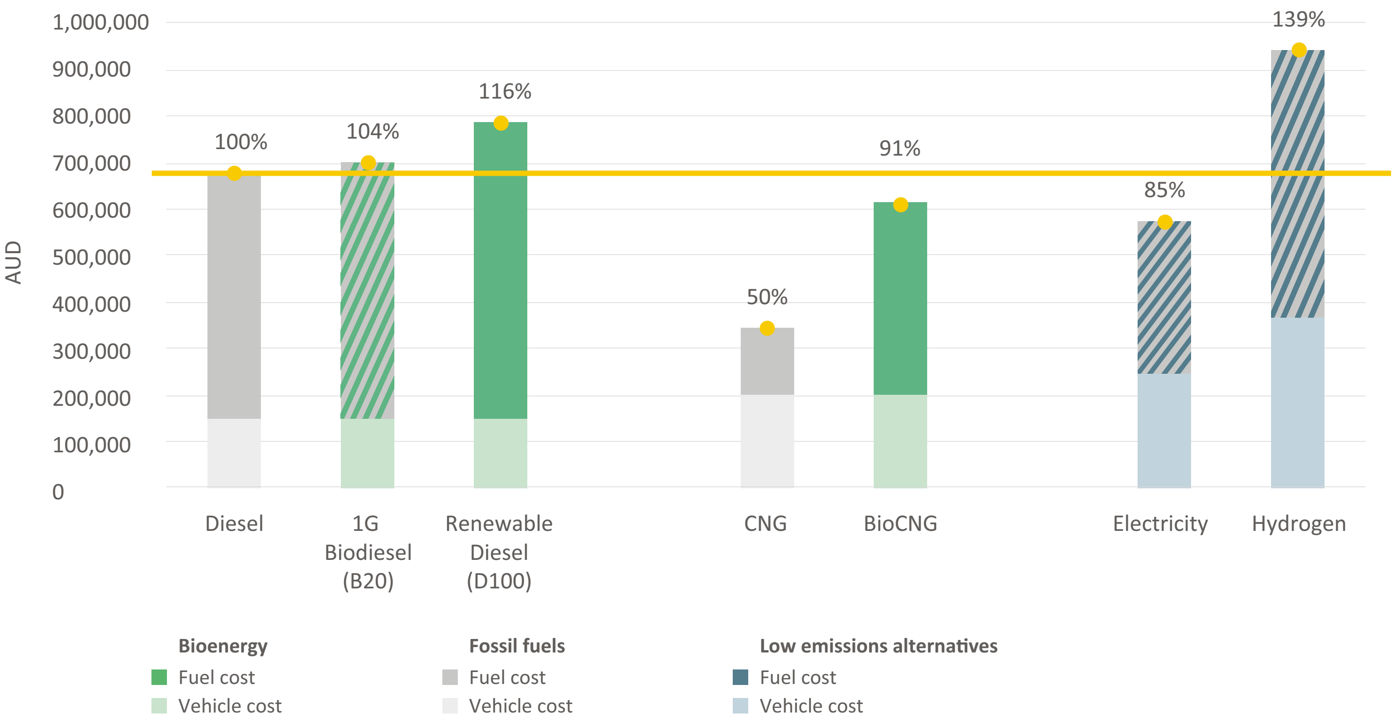
For heavy-duty vehicles (heavy-duty trucks), 1G biodiesel and renewable diesel result in higher costs compared to diesel (7 per cent and 19 per cent higher cost respectively). This cost comparison is however very sensitive to relative feedstock and oil prices.

Despite higher vehicle costs, bioCNG can be competitive with diesel. However, similar to 1G biodiesel and renewable diesel, bioCNG is highly sensitive to relative feedstock and oil prices. In addition, fuels costs do not include fuel transport and refuelling station infrastructure, which can be more expensive for bioCNG compared to other biofuels.

Regarding low carbon alternatives, despite higher vehicle costs, electric vehicles can be more cost-competitive than biofuels, due to lower fuel costs over the 10 years of planned ownership.

However, it must be noted that electric vehicles are technically challenging due to driving range limitations especially for heavy-duty applications. Hydrogen vehicles are currently not cost-competitive due to significant vehicle costs.

Figure 7 – Total cost of ownership of heavy-duty vehicles



Sources: Enea analysis from [25] [26]

Note: *These total costs of ownership are based on Enea's analysis. They include vehicles purchase costs and fuel consumption costs. Other vehicles costs such as insurance, licence and registration, maintenance and repairs are excluded. Fuel costs include fuel production LCOEs only (see Figure 5), downstream components such as fuel transport, compression stations (for gaseous fuels) and refuelling infrastructure are excluded. Fuel consumptions are based on typical efficiencies for diesel and CNG engines, electric powertrains and hydrogen fuel cells. The use of grid electricity and hydrogen from grid electricity is assumed for electric and hydrogen vehicles respectively. A 10-year period of planned ownership is considered for fuel consumption.*

Levelised cost of gas

Landfill gas could offer early opportunities for bioenergy thanks to relatively low production costs compared to low carbon alternatives.

The production costs of biomethane from landfill gas are close to natural gas prices, meaning this pathway could offer an early opportunity for bioenergy, though this is limited by resource constraints.

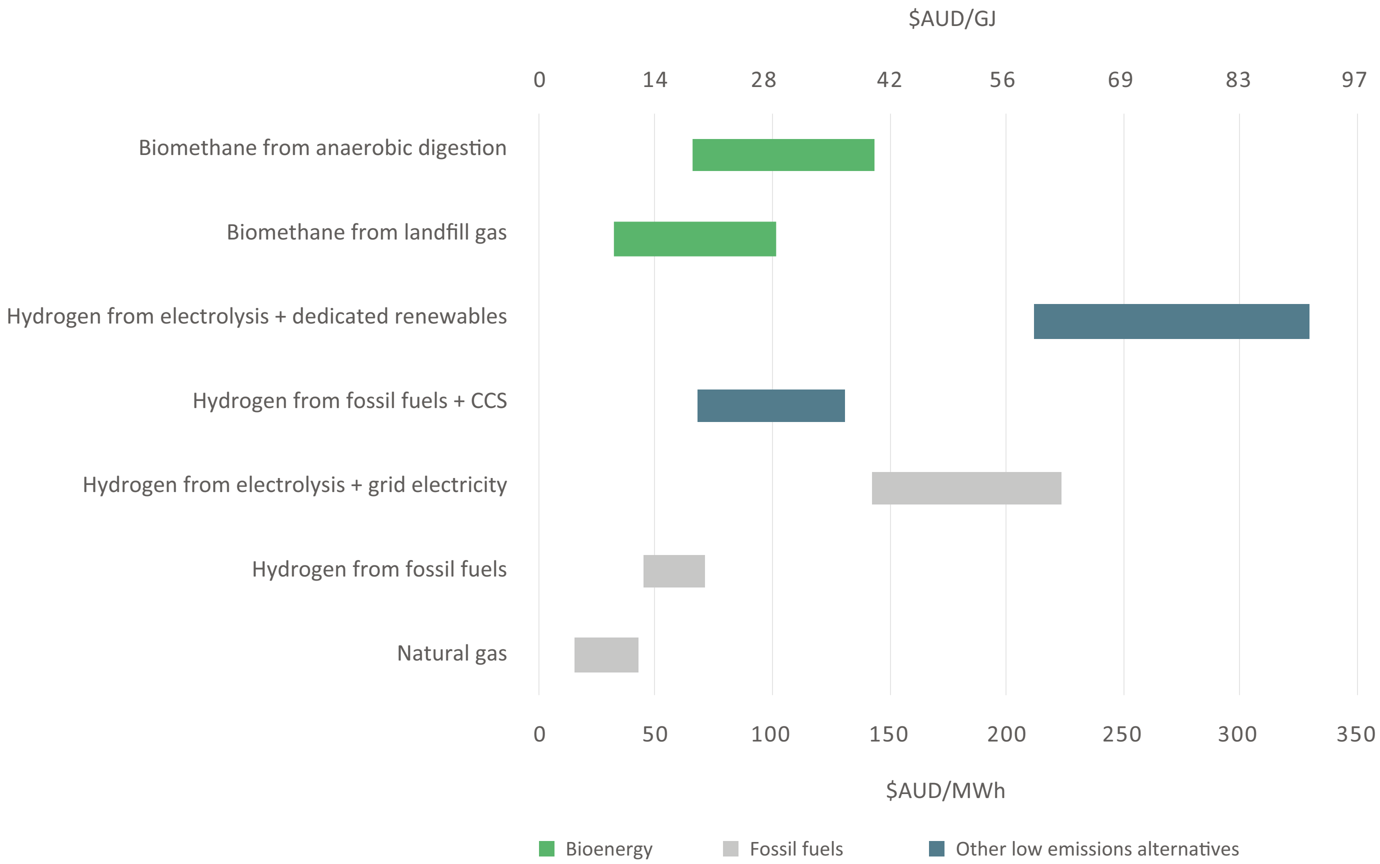
Indeed, landfill gas production is expected to level off in the future due to the reduced amount of waste deposited in landfills [27].

In addition, biomethane from anaerobic digestion is currently less expensive than low emissions alternatives such as hydrogen produced from electrolysis (see Figure 8).

Most cost-competitive projects that are operational globally deliver biomethane at a cost similar to the Australian Government’s economic ‘stretch’ goal of $2 per kg of hydrogen. This is equivalent to $17 per GJ for biomethane production.

In addition, unlike hydrogen, biomethane can be used without requiring upgrading of existing gas infrastructure or customer appliances.

Figure 8 – Levelised cost of gas



Costs are based on low heating values

Note: *These LCOEs are based on Enea's analysis of different sources incl. CSIRO 2018, 'National Hydrogen Roadmap' [23]; IEA 2020, 'Advanced biofuels – Potential for cost reduction' [17]; IEA 2020, 'Outlook for biogas and biomethane - Prospects for organic growth' [9]; Enea 2019, 'Biogas opportunities for Australia' [8]; PWZ 2020, ‘Embracing clean hydrogen for Australia’ [28].*

Cost reductions

Cost reductions for bioenergy pathways may be achieved through [17]:

- reduction in resource production, collection and transport costs and delivery of resources with consistent quality
- improvements to technology performance
- increased plant capacity to realise economies of scale
- increased experience in building and operating large-scale bioenergy plants
- reduction in capital and financing costs
- co-location of resources, bioenergy plants and existing infrastructure.

There are cost-reduction opportunities for markets that benefit from less mature technologies, such as aviation, or less commercial maturity in Australia. Supply chain improvements can also contribute to cost reductions, for instance through biohubs.

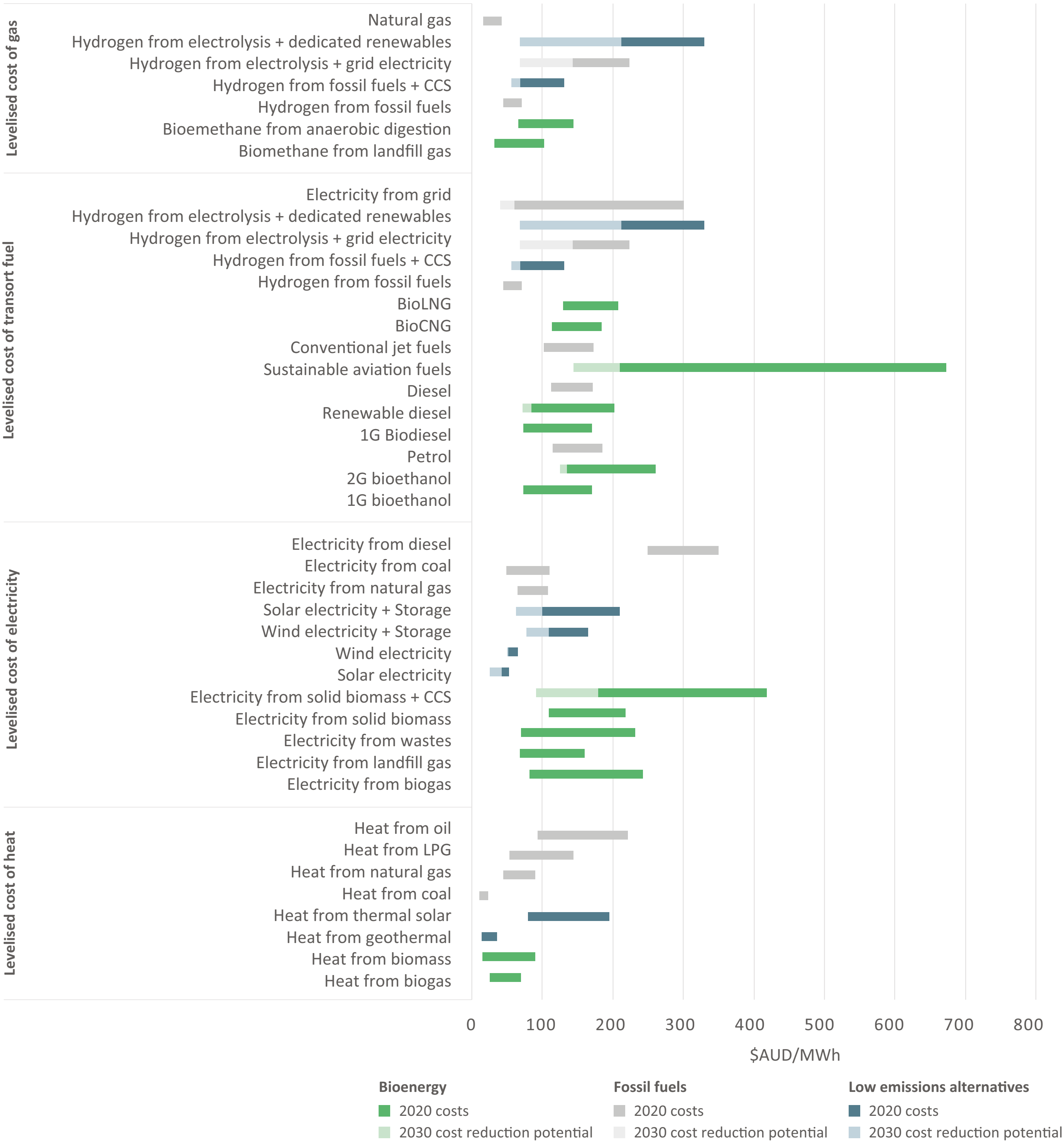
However, cost reductions for bioenergy may be limited compared to other forms of energy. This is due to the maturity of most processing technologies and the dispersed nature of bioenergy resources that require collection and transport. Though possible, cost reductions may not be significant enough to make all bioenergy pathways cost-competitive with fossil-based alternatives (such as biojet fuels) in all cases. Though supply chain improvements can result in lower costs, collection and transport of dispersed resources will still be required, impacting the size of bioenergy projects, and thus potential economies of scale.

The potential for cost reductions will vary between bioenergy pathways, depending on their maturity and commerciality in Australia (see Table 4 and Figure 9).

Table 4 – Summary of potential cost reductions per market

Market	Potential cost reductions
Heat	• There are limited opportunities for cost reductions given the maturity of bioheat generation pathways. • By 2030 solar thermal may be cost-competitive with high-cost heat from biomass, and for low-temperature applications.
Electricity	• Bioelectricity generation pathways have limited opportunities for cost reductions, except when combined with CO_2 capture and storage technology. • Battery storage cost reductions mean that solar PV and wind combined with batteries are likely to become competitive with bioelectricity for longer storage durations.
Transport	• While costs for conventional biofuels are not expected to decline significantly, the costs of advanced biofuels are expected to decline between 18 to 25 per cent by 2030. • Experience gained through demonstration and commercial scale-up has the potential to reduce costs. Equally, integrated biorefineries may present cost reduction opportunities. • Although biojet fuels costs are expected to decline strongly, they are not forecast to be competitive with conventional jet fuel by 2030.
Gas grid injection	• Biomethane production is mature and costs are not expected to decline significantly over the next decade. However, although mature overseas, there is currently no commercial application in Australia, meaning there may be scope for costs to decline as the industry grows. • With significant advances in hydrogen production technologies, biomethane and hydrogen produced from renewable electricity may reach similar levels of cost-competitiveness. This is however unlikely to happen before 2030. In addition, this does not consider the costs of upgrading infrastructure and appliances for hydrogen.

Figure 9 – Cost reduction potential in 2030 of bioenergy pathways



Notes:

These LCOEs are based on Enea's analysis of different sources incl. IEA 2020, 'Advanced biofuels – Potential for cost reduction' [17]; CSIRO 2019, 'GenCost 2019-20 - Preliminary results for stakeholder review' [12]; ITP Energised Group 2018, 'Comparison of dispatchable renewable electricity options - Technologies for an orderly transition' [10]; ITP Thermal 2019, 'Renewable Energy Options for Industrial Process Heat' [6]; Enea 2019, 'Biogas opportunities for Australia' [8]; IEA 2020, 'Outlook for biogas and biomethane - Prospects for organic growth' [9]; The International Council on Clean Transportation 2019, 'The cost of supporting alternative jet fuels in the European Union' [19]

Solid bars indicate current cost ranges, while shaded bars indicated expected cost reductions in 2030. Note that the cost reductions are only for production (LCOE) and do not show reduction in factors such as transportation and storage or upgrades of existing infrastructure. For gaseous and liquid fuels, costs are based on low heating values.

7. Technological advantages of bioenergy pathways

Bioenergy pathways offer certain technological benefits over alternative energy sources across all end-uses. These benefits are mainly due to bioenergy end-products such as biofuels or biomethane usually having similar characteristics to conventional fossil fuels.

Bioenergy can address most industrial heat requirements.

Other low emissions alternatives such as solar thermal and geothermal can be used for industrial heat applications below 400 degrees Celsius. Bioenergy is one of the few options able to meet high-temperature heat demand cost-effectively in the short term, up to 1,200 degrees Celsius.

Some industries can use wastes for heat without needing pre-treatment. For example, cement and lime kilns are particularly suited to using a wide variety of wastes since the ash and impurities that exist in wastes end up as part of the final product [6].

Electricity generation from bioenergy is dispatchable. It can be used to complement other sources of renewable energy such as intermittent solar PV and wind, and reduce emissions in existing dispatchable generation.

Solar PV and wind cannot generate electricity on demand and require electricity storage facilities to be dispatchable.

Like traditional fossil fuels, bioenergy can generate electricity when it is required. Bioenergy can be used for co-firing with existing coal-fired power stations. This is a 'low-hanging fruit' for emissions reduction given it can be applied with limited upgrading of power plants, offering immediate opportunities to reduce the emissions intensity of coal-fired power stations.

Also, existing coal-fired and gas-fired power stations can be converted to use bioenergy exclusively. For example, coal-fired power stations can be converted to use solid biomass such as wood pellets. In the United Kingdom, Drax Power station has converted four of its six generating units to biomass with a capacity of 2.6 GW[3]. Biogas too may be used in existing gas-fired generators [10].

Some biofuels can be blended into petroleum-derived fuels or act as a direct substitute without upgrading existing infrastructure or engines.

The first-generation biofuels 1G bioethanol and 1G biodiesel are chemically different to petrol and diesel. This means they cannot be fully utilised in existing infrastructure or engines but may be blended to a certain extent. Aside from cars that have been adapted to take both petrol and ethanol, ethanol can be blended with petrol up to 10 per cent for regular vehicles and 1G biodiesel can be blended up to 20 per cent with diesel [29].

Advanced or 'drop-in' biofuels such as renewable diesel are chemically similar to conventional fuels and are therefore compatible to petrol, diesel and jet fuel and so minimise compatibility issues with existing engines and infrastructure. This means that advanced biofuels are also suitable for long-haul transport (e.g. renewable diesel) and aviation (e.g. biojet fuels). Sustainable aviation fuels have a maximum blend level of 50 per cent [30].

Biomethane can be injected into existing gas networks without infrastructure and customer appliance upgrades.

Biomethane's very close chemical composition to natural gas makes it a suitable renewable substitute for natural gas. In contrast, due to the different chemical properties of hydrogen, it may only be blended up to 10 to 15 per cent before requiring upgrades to infrastructure and appliances [31]. This poses specific integration challenges for hydrogen compared to biomethane at larger blending ratios.

3. As a comparison, Victoria's Hazelwood power station had a capacity of 1.6 GW.

8. Emissions reduction potential

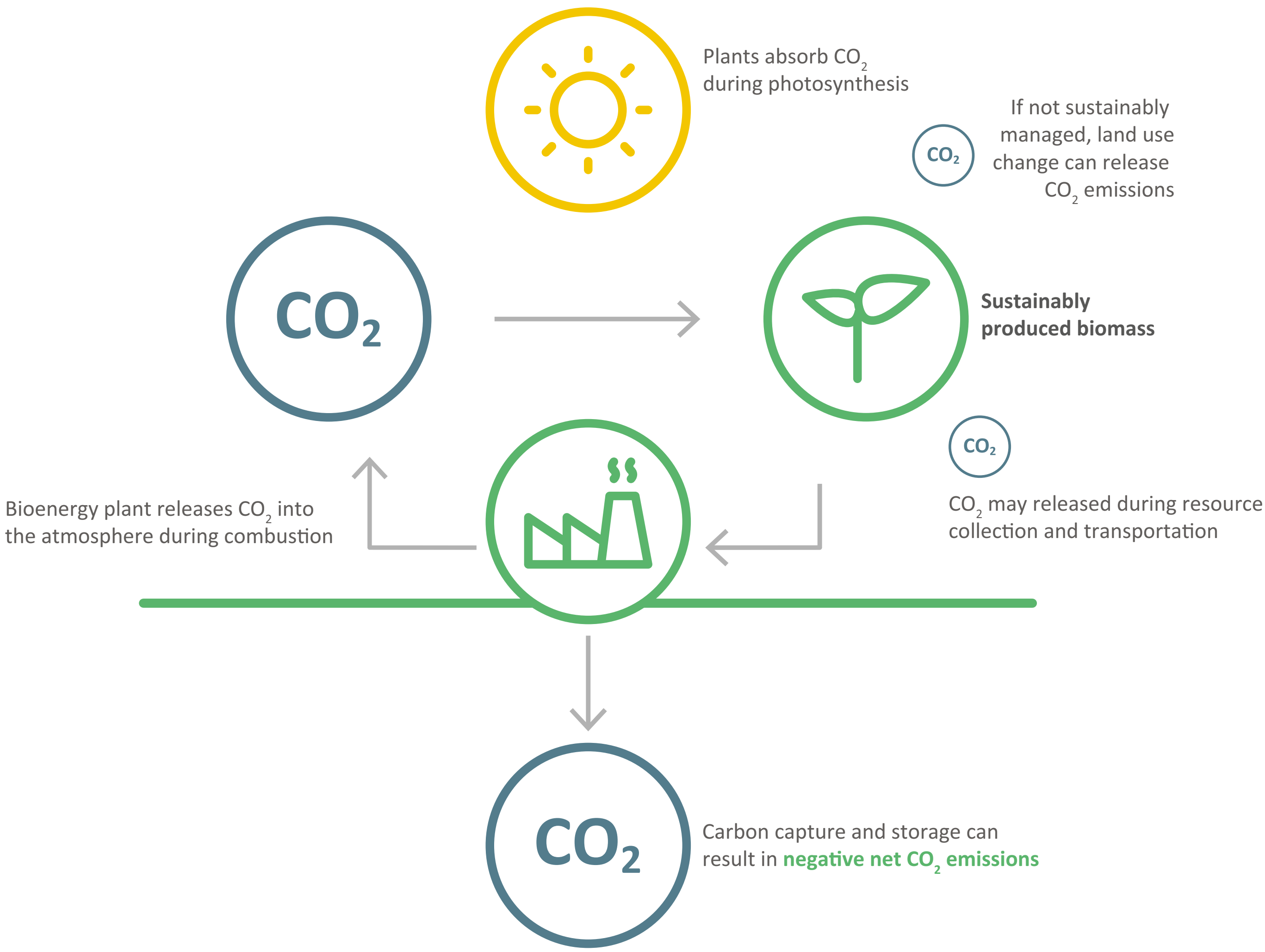
Lifecycle greenhouse gas emissions are important to assessing a bioenergy pathway's emissions reduction potential.

The lifecycle emissions of bioenergy depend on how bioenergy resources are produced and the energy consumption of upstream processing, such as biorefining. Indirect greenhouse gas emissions are primarily associated with conventional biofuels that use food crops, such as sugars, starches and oils, due to land use change. For example, clearing forests for energy cropping will reduce carbon sinks and negatively impact greenhouse gas emissions.

This highlights the importance of sustainability frameworks for bioenergy, including the sustainable management of resources. If managed sustainably, bioenergy can be considered to have marginal lifecycle emissions. That is, if the carbon released during consumption has been previously captured through photosynthesis by biomass as they grow [32] (see Figure 10).

By reducing the amount of waste sent to landfill, waste to energy (WtE) projects, and, more generally, bioenergy pathways that use waste resources, can avoid methane emissions from the degradation of wastes in landfills. This can result in negative lifecycle emissions by crediting avoided methane emissions to these pathways.

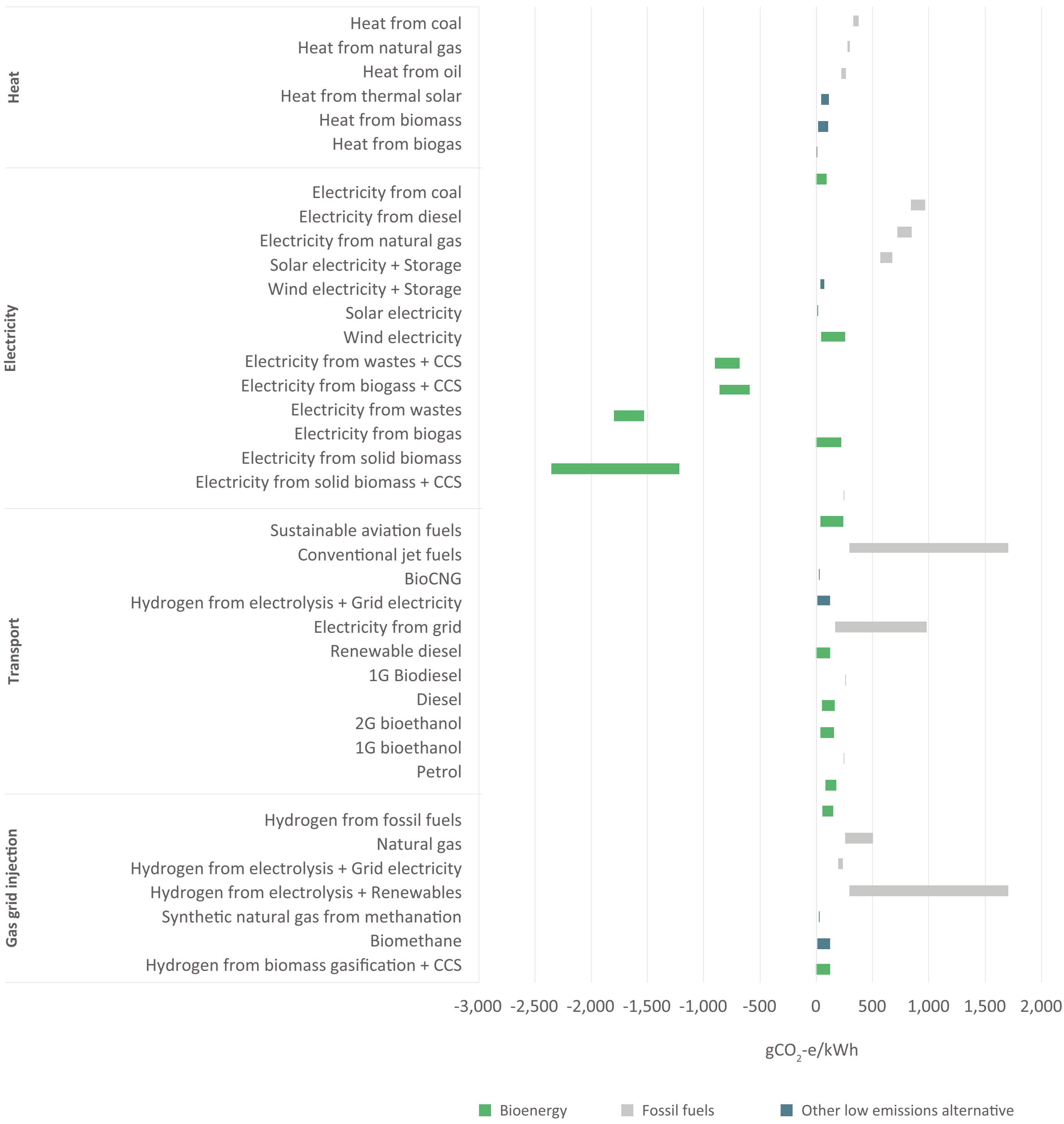
Figure 10 – Illustration of lifecycle emissions from bioenergy



Bioenergy has the potential to reduce greenhouse gas emission across all end-use markets.

The following lifecycle assessment calculates the direct and indirect greenhouse gas emissions associated with all stages of the bioenergy pathway (including production, transport and consumption) presented as grams of greenhouse gas emissions (gCO_2-e) per unit of energy (see Figure 11).

Figure 11 – Comparison of lifecycle emissions of bioenergy and alternative low emissions pathways



Note: *These estimates are based on Enea's analysis of different sources incl. Australian Government - Department of Industry, Science Energy and Resources 2020, 'National Greenhouse Accounts Factors' [33] ; COAG Energy Council, 'Australia's National Hydrogen Strategy' [34]; CSIRO 2019, 'National Hydrogen Roadmap' [23]; Official Journal of the European Union 2018, 'Directive (EU) 2018/2001 of the European parliament and of the council of 11 December 2018 on the promotion of the use of energy from renewable sources' [35]; Ramboll 2018, 'Kwinana waste to energy project - ARENA Life Cycle Assessment' [36]; NREL 2014, 'Life Cycle Assessment Harmonisation' [37]; IEA 2013, 'Using a Life Cycle Assessment Approach to Estimate the Net Greenhouse Gas Emissions of Bioenergy' [38].*

Bioenergy is also capable of delivering significant lifecycle greenhouse gas emissions savings compared to fossil fuel alternatives (see Figure 11)**.**

However, in some end-use markets, alternative low emissions technologies can also offer significant emissions reductions. These include wind and solar PV for electricity generation and hydrogen production via electrolysis (compared to biomethane).

Bioenergy can have great emissions reduction potential in end-use market segments where there is no low emissions alternative, such as aviation.

The emissions reduction potential of bioenergy production pathways heavily depends on the type of resource used. In some instances, negative lifecycle emissions can be achieved by bioenergy.

Indirect land use change can increase lifecycle emissions of certain bioenergy pathways such as conventional biofuels. On the other hand, avoiding methane emissions from waste going to landfill can result in negative emissions for pathways using wastes, such as bioelectricity generation from wastes or biogas pathways.

When combined with CCS, bioenergy can achieve negative net emissions across heat, electricity and gas uses.

In addition to greenhouse gas emissions, bioenergy can also improve air quality through reduced carbon monoxide (CO), nitrous oxides (NO_x) and particulate matter.

Biofuels can result in less particulate matter compared to fossil fuel alternatives such as diesel. As Australia adopts tighter Fuel Quality Standards, biofuels may be further incentivised.

While the combustion of biomass for heat and electricity can result in particulate matters, these can be managed through the implementation of strict standards. Overseas standards, such as those in the EU, could be used for Australia.

Image: Southern Oil

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