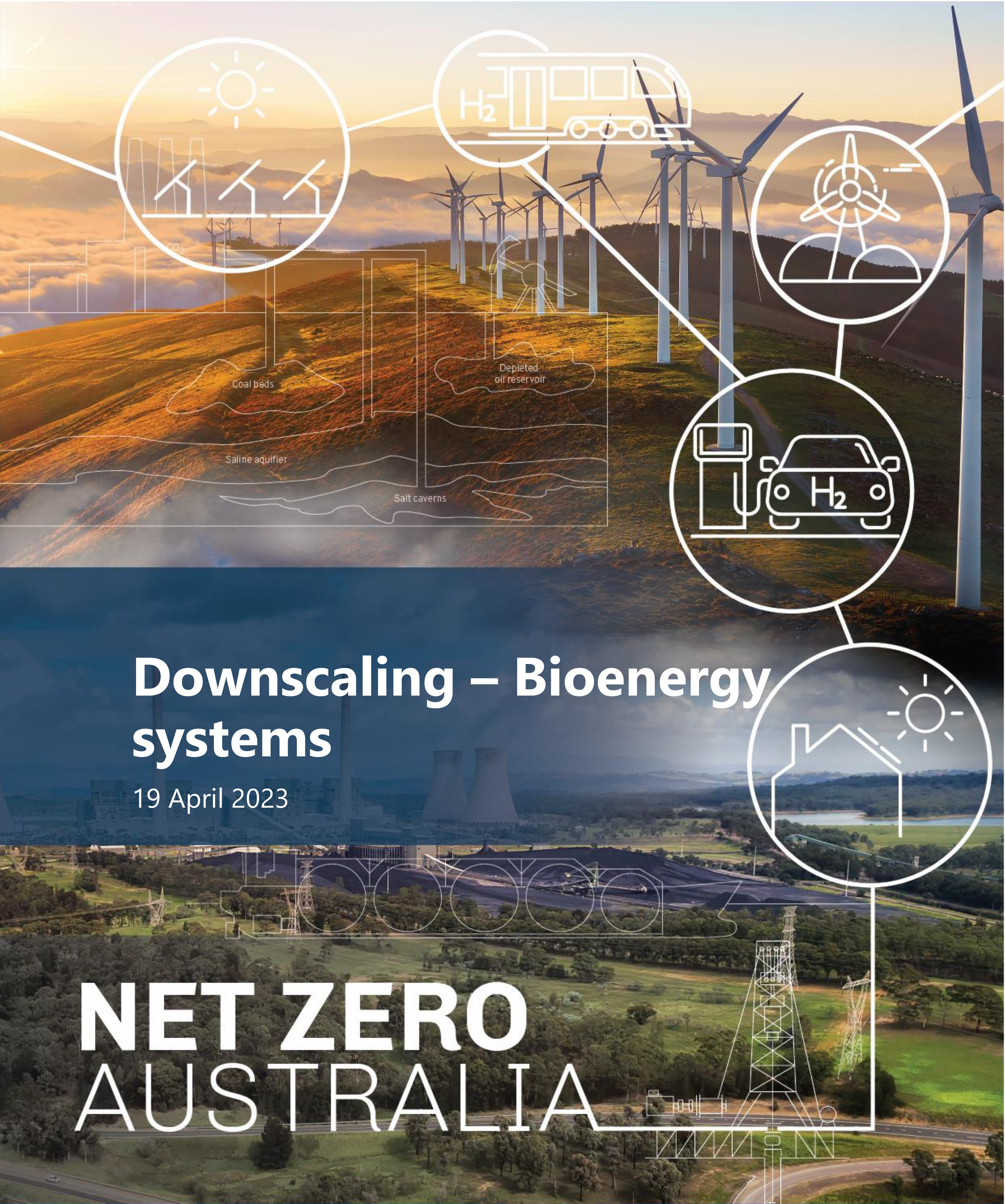

Downscaling – Bioenergy systems

19 April 2023

NET ZERO
AUSTRALIA

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The Net Zero Australia (NZAu) project is a collaborative partnership between the University of Melbourne, The University of Queensland, Princeton University and management consultancy Nous Group. The study examines pathways and detailed infrastructure requirements by which Australia can transition to net zero emissions, and be a major exporter of low emission energy and products.

Net Zero Australia

Downscaling – Bioenergy systems

19 April 2023

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Contents

1 Introduction

Bioenergy can be an important resource for decarbonising our energy systems if the emissions arising from bioenergy consumption are wholly or partly offset by the carbon dioxide sequestered during the growth of the biomass feedstock. Biofuels can then also achieve negative emissions when paired with carbon capture and storage. Nonetheless, the establishment of an Australian bioenergy industry that supplies and processes biomass feedstock from regionally diverse and widespread locations will depend on the technical and economic assessment of the role of bioenergy in a net-zero transition with a spatially granular level of detail. This bioenergy downscaling report therefore provides assessment of the biomass resource, its potential uses, and the need for bioenergy infrastructure investment in the net-zero transition modelled in the *Net Zero Australia* (NZAu) Project.

Evaluation of bioenergy as an option for energy system decarbonisation first requires an assessment of the optimal use of scarce bioenergy resources as a substitute for fossil fuels in electricity generation, in standalone electricity generation, for direct industrial or building heat provision, and through conversion to biofuels of various types. These potential uses span the residential, commercial, industrial and transport sectors of the energy system. *Net Zero Australia*'s macro-scale energy system modelling considers each of these opportunities for bioenergy to contribute to decarbonisation, including the continued use of biomass in industry and buildings sectors and the potential future conversion of biomass to biofuels. We also extend this analysis to provide a finer level of spatial detail around the supply and use of biomass in a future Australian bioenergy industry.

2 Biomass resource supply

Estimates of the Australian biomass resource are documented in the NZAu Methods, Assumptions, Scenarios and Sensitivities (MASS) document (Net Zero Australia Project, 2022), and are informed by CSIRO studies (Crawford et al., 2016; Farine et al., 2012). These estimates incorporate constraints on biomass availability that avoid clearing of native vegetation, minimise impacts on domestic food security, retain a portion of agricultural and forest residues to protect soil, and minimise the impact on local processing industries. The types of biomass resource appraised and used as input to the NZAu modelling are:

- crop stubble;
- native grasses;
- pulpwood and residues (either from forest harvesting or wood processing) from plantation and native forests;
- bagasse; and
- organic municipal solid waste (MSW).

2.1 Biomass availability and cost

The available dry biomass feedstock used in the NZAu macro-scale energy system modelling is shown in Figure 1 by resource type and aggregated by NZAu zone. This dry resource is approximately 1050 PJ/year (79,000 kt/year) by 2030 and is diversified across resource types and across Australia, with resource available in eastern, southern and south-western Australia. These data are sourced from Crawford et al. (2016) by 60 statistical divisions across Australia, and are aggregated to the 15 NZAu zones according to the spatial mapping presented Table 3 in the appendices.

Figure 2 shows the distribution of various biomass resource types across Australia in 2050, with the resource distribution similar in other modelled years. The organic municipal solid waste resource is concentrated in Australia's major population centres, while other resources are more regional. Native grasses are available in Queensland and New South Wales, while crop stubble is in the more southern regions of New South Wales, Victoria, South Australia and Western Australia. Australia's forestry residue resource is also located in the southern regions, with most resource distributed in Victoria and Tasmania. We note that Queensland's and New South Wales' bagasse resource is not presented here since its continued use in heat and power applications within the sugar cane industry is discussed later.

The biomass availability of ~1050 PJ/year is less than the 2600 PJ/year *theoretical* resource potential quoted in the recently published Australian Government Bioenergy Roadmap (ENEA Consulting & Deloitte, 2021). This is because our estimates observe technical and sustainable resource constraints that will naturally preclude a significant portion of *any theoretical* bio-resource appraisal. We also note that Australia's potential sustainable biomass availability (Figure 1) represents a significant difference between the *Net Zero Australia* and the *Net Zero America* (Larson et al., 2021) studies. *Net Zero America* sourced biomass availability and cost data from the U.S. Department of Energy's 2016 *Billion Ton Study* (Langholtz et al., 2016), which provided year-by-year county-level projections of biomass feedstocks potentially available for energy uses with corresponding costs in the U.S. through to 2040. Total resource estimates in the US's Billion Ton Study are *an order of magnitude greater* than the present study. Further, to date, no biomass resource appraisal of comparable detail has been undertaken for Australia.

A supply cost curve for the biomass resource was established by dividing each resource type in each NZAu zone into three bins of equal resource (PJ / year, Figure 1) and assigning a low, medium and high cost to these bins, as presented in Table 1. It should be noted that biomass feedstock used for bioenergy has low density, high moisture content and is typically harvested and transported from diffuse sources, so that the cost of biomass is highly case specific and sensitive to transportation distances. Nevertheless, the simplified supply cost curve used in this work should represent the average conditions for low, medium and high cost biomass feedstocks.

Figure 1 | Annual Australian biomass resource availability by biomass type (left) and NZAu zone (right).

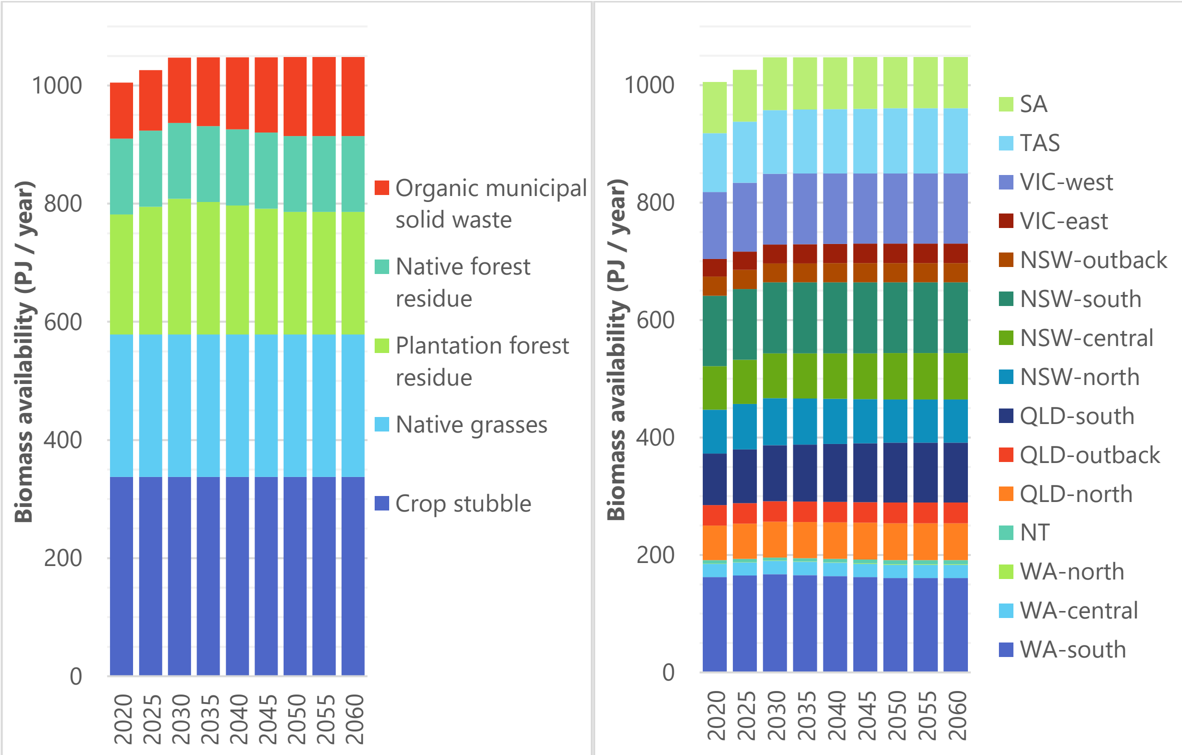
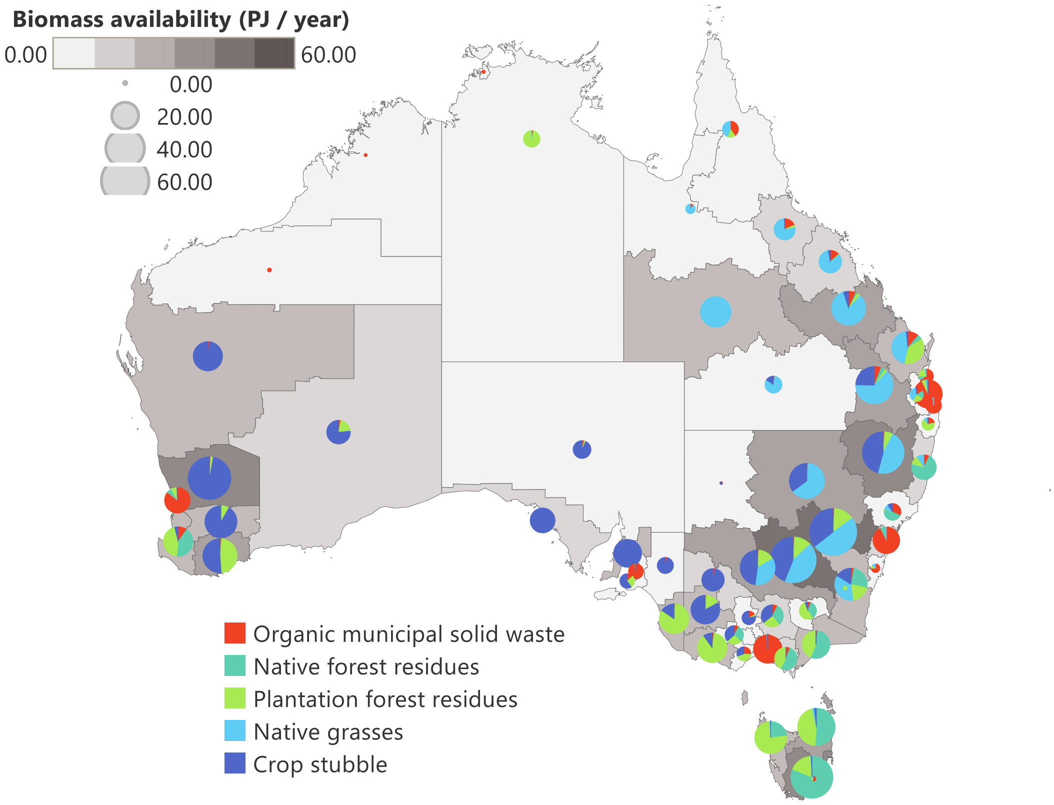


Table 1 | Dry biomass feedstock cost inputs to macro-scale energy system modelling, by resource type and cost bin.

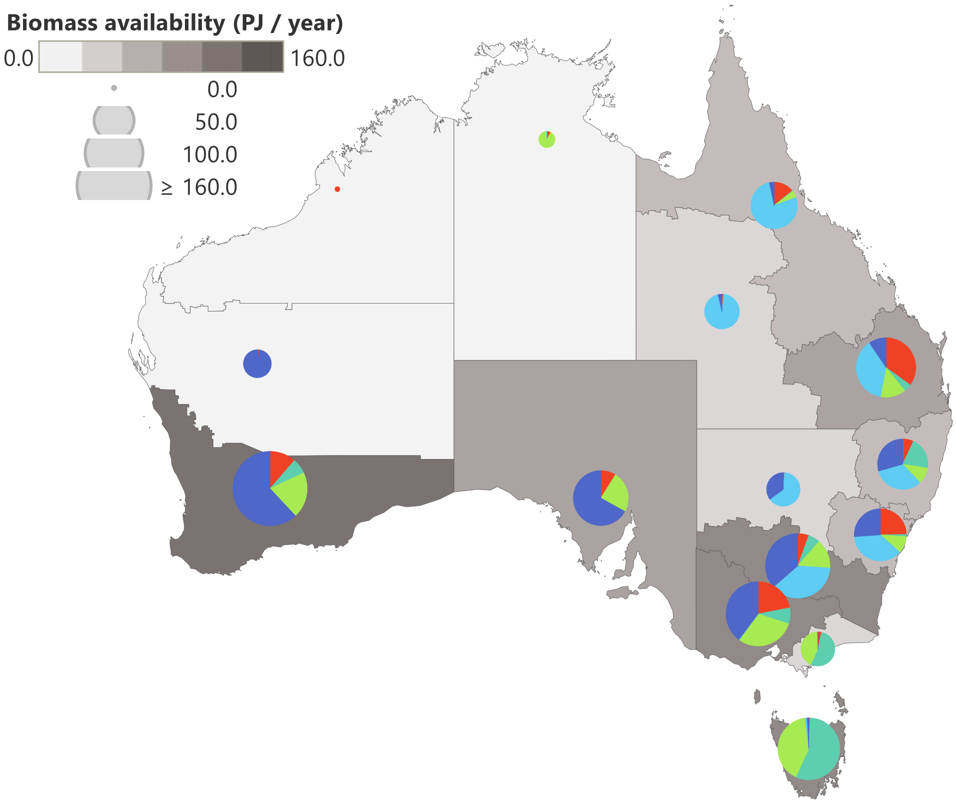
Resource	Dry biomass cost (2020 AU$/GJ)		
	Low cost	Medium cost	High cost
Crop stubble	6	8	10
Native grasses	6	8	10
Plantation forest residue	6	8	10
Native forest residue	6	8	10
Organic municipal solid waste	5	9	12

Figure 2 | 2050 Australian biomass resource availability by resource type, and (a) by ABS statistical division sourced from Crawford et al. (2016); and (b) aggregated to each NZAu macro-energy system modelling zone.

(a) 2050 biomass resource by ABS statistical division



(b) 2050 biomass resource by NZAu zone



3 Summary of regional investment modelling of bioenergy activity

Figure 3 presents a summary of the bioenergy activity output from NZAu's macro-scale energy system modelling for the Reference (REF), E+ and E− Scenarios. The current use of bagasse, MSW and other dry biomass in buildings and industry are projected to continue through to 2060, with energy efficiency improvement in the E+ and E− Scenarios, relative to the REF Scenario. In addition, a biofuels industry is rapidly established between 2030 and 2035 to make use of any available dry biomass and MSW for production of zero-emissions fuels up to the biomass resource limit. Here dry biomass includes the crop stubble, native grasses, and forestry residues.

Figure 3 | (a) The source of the bioenergy feedstock used in the system modelling; and (b) the sectoral use of that bioenergy feedstock, for the whole of Australia and the Reference, E+, E− Scenarios.

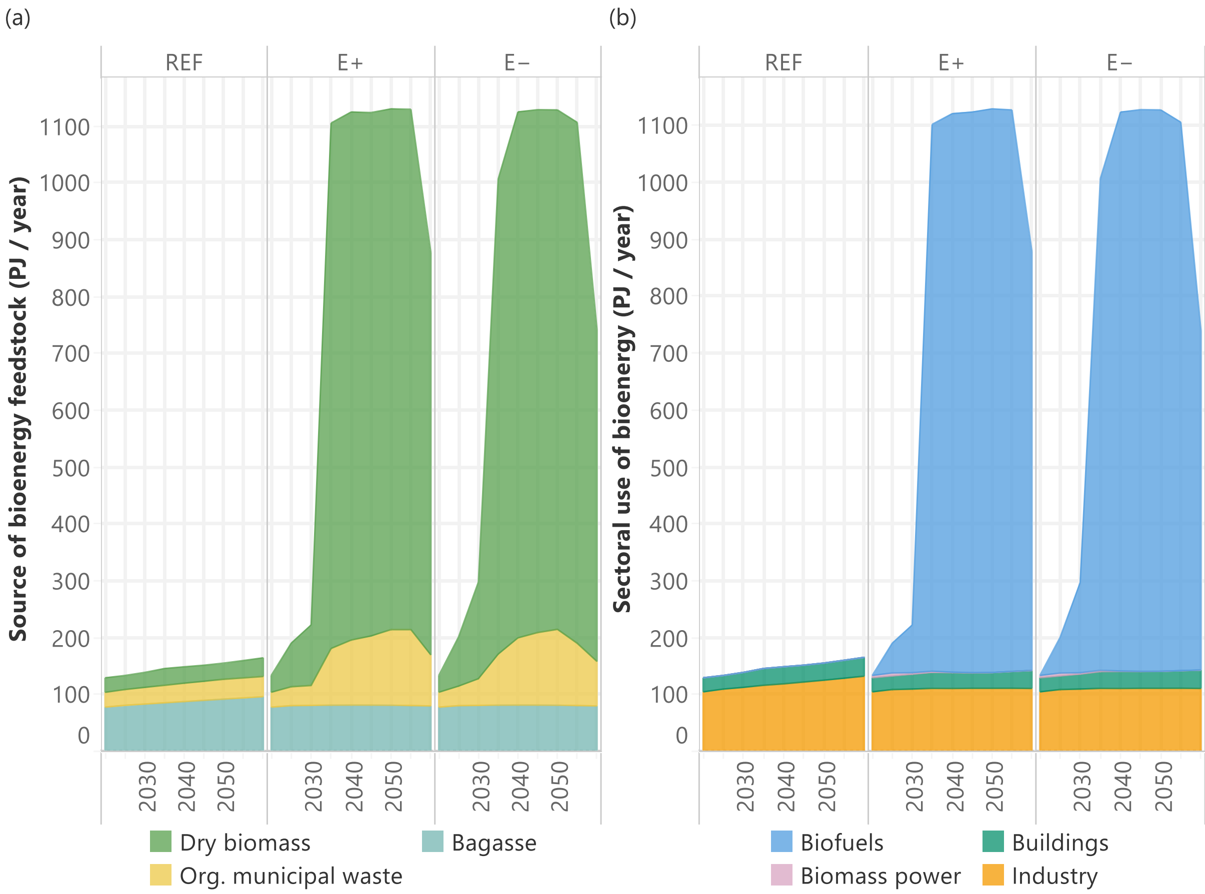
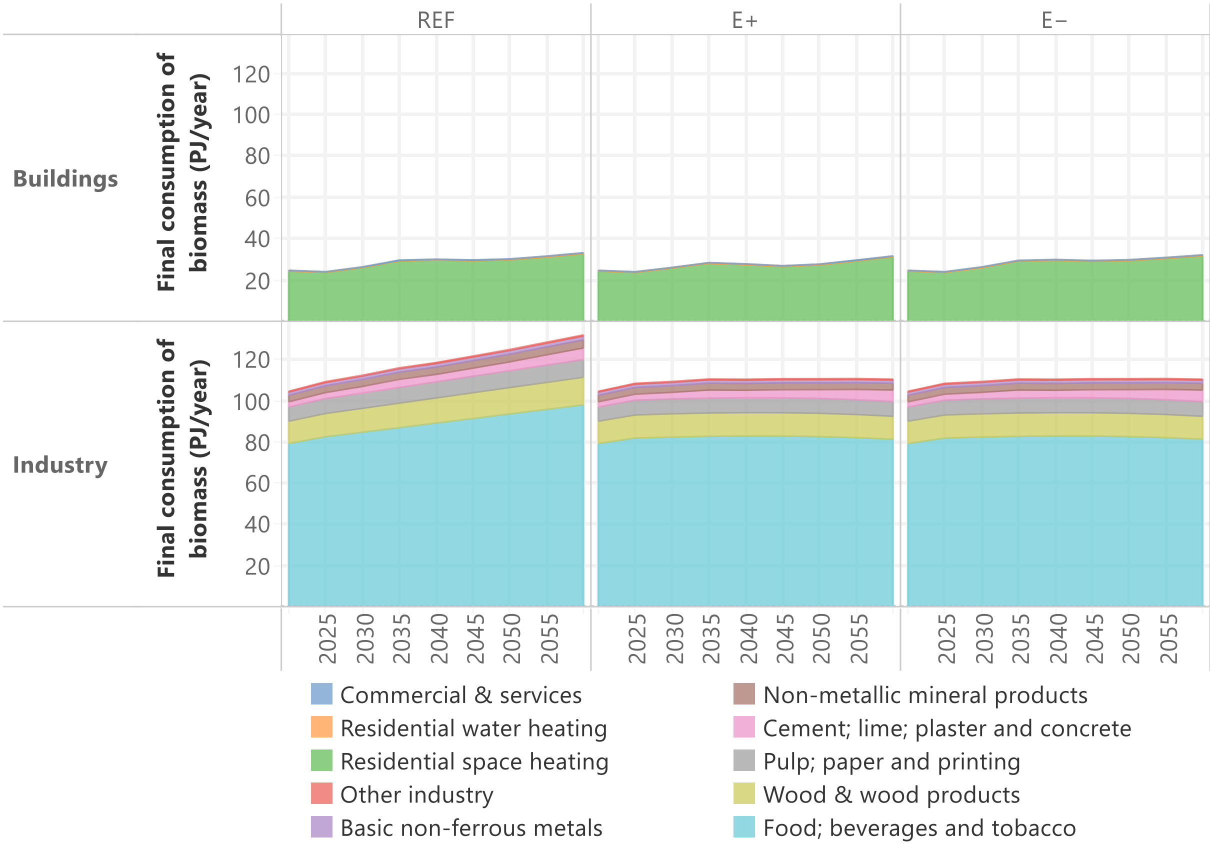


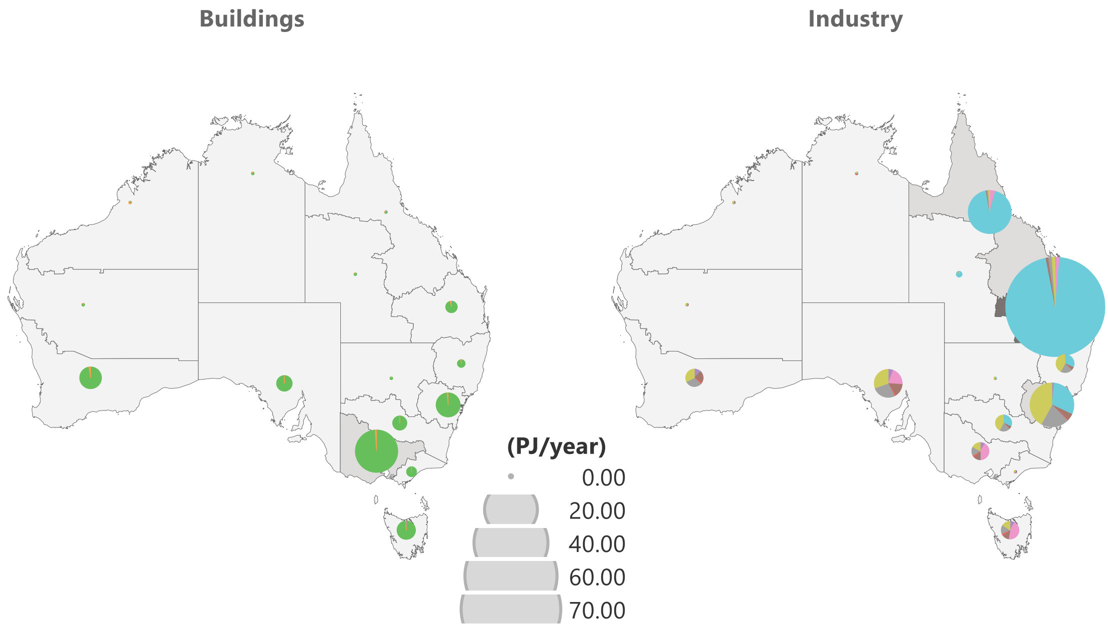
Figure 4 shows the modelled final consumption of biomass (i.e. that not used for biofuel production) in more detail. The largest use of biomass in buildings is ~30 PJ/year for *residential space heating*, which is a continuation of current trends across Australia, and particularly in Victoria and Tasmania. Within the industrial sector, the major use of biomass is the approximately 80 PJ/year in the *food, beverages and tobacco* industry, which incorporates the sugarcane industry, and therefore the continued significant self-use of bagasse for small-scale combined heat and power across Queensland and New South Wales. The results also exhibit continued use of biomass in other industrial subsectors on a scale of approximately 30 PJ/year. The net-zero E+ and E− Scenarios therefore do not identify a significant opportunity for emissions reduction through direct final consumption of biomass, *above* that which already occurs.

Figure 4 | Final consumption of biomass (a) by sector, subsector and for REF, E+ and E−; and (b) by NZAu region, sector and for the E+ Scenario in 2050.

(a)



(b) E+ 2050 final consumption of bioenergy by NZAu zone



All net zero scenarios used dry biomass for biofuels production up to the available resource limit. This is shown in Figure 5 for the E+ and E− Scenarios in which the major biofuel produced is synthetic natural gas (bio-SNG) via biogasification (with or without carbon capture). Figure 5 and Figure 6 show that, for E+ in 2050, the bio-SNG is predominantly produced with carbon capture in QLD and SA, VIC and central WA, as these regions are located closest to the available CO_2 sequestration sites, while in NSW and TAS the majority of bio-SNG is produced without carbon capture.

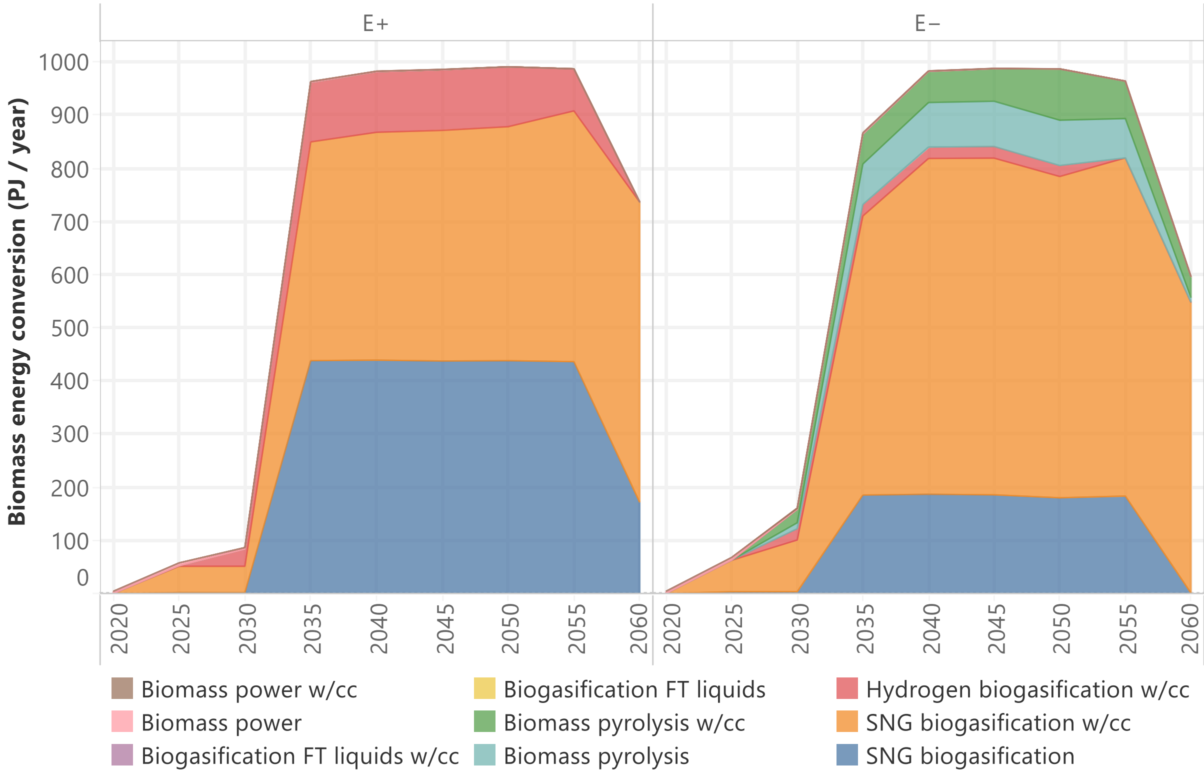
In addition to bio-SNG, the biomass resource is used in E+ to produce hydrogen through biogasification with carbon capture in E+ in eastern VIC, southern QLD and SA. The production of hydrogen from biomass via gasification with carbon capture represents the bioenergy conversion pathway with greatest potential for negative CO_2 emissions, with 81 kg-CO_2/GJ-biomass captured (from the biomass' embodied biogenic 89 kg-CO_2/GJ-biomass). This is significantly greater than the rates of CO_2 withdrawal possible through bio-SNG production via biogasification, 30 kg-CO_2/GJ-biomass. Therefore, we find that H_2 production occurs in regions with a coincidence of biomass resource and CO_2 sequestration potential, to provide both hydrogen as a fuel *and* net negative flows of CO_2.

In the E− Scenario, Figure 5 and Figure 6 show that biomass resources are used to produce bio-SNG, small amount of H_2, as well as liquid biofuels with and without carbon capture via fast pyrolysis of biomass. These liquid biofuels are more prospective in the E− Scenario because they are used to decarbonise solid or liquid fuel use in transportation and industry, which have significant mid-century residual demand for solid and liquid fuels due to the E− Scenario's slower electrification trend. We explore these macro effects elsewhere in this project and focus in the following sections on downscaling these bioenergy activities.

We note that similar results were found in the other core net zero Scenarios modelled, and so this document focusses only on the three scenarios presented in Figure 3, REF, E+ and E−. Appendix B shows the modelled bioenergy conversion for the other core Scenarios.

Figure 5 | Biomass energy conversion with various technologies (a) for the E+ and E− scenario; and (b) by NZAu region for the E+ scenario in 2050.

(a)



(b) E+ 2050 Biomass energy conversion by NZAu zone

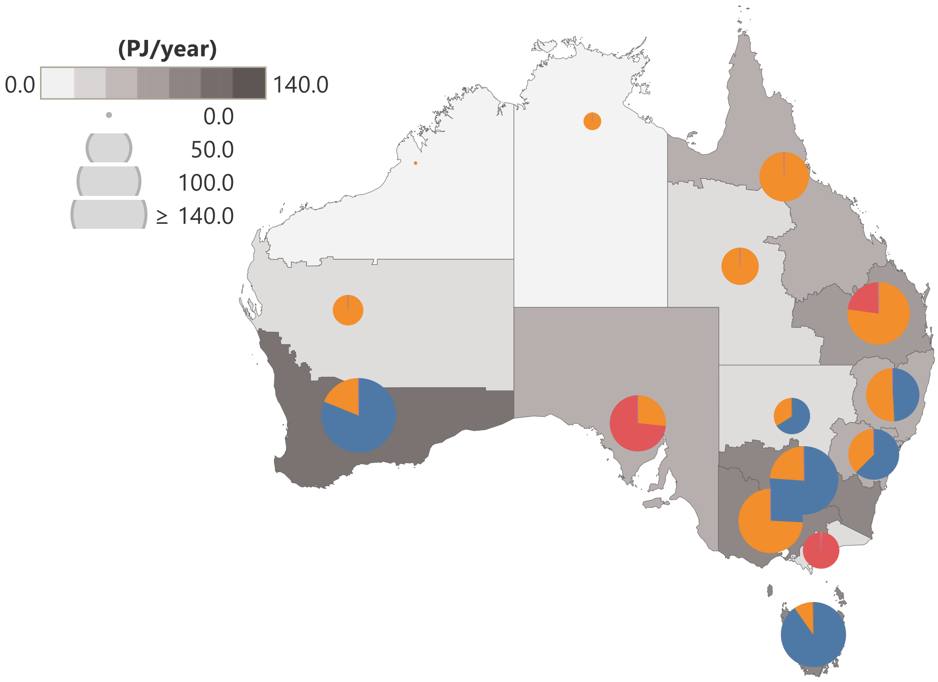
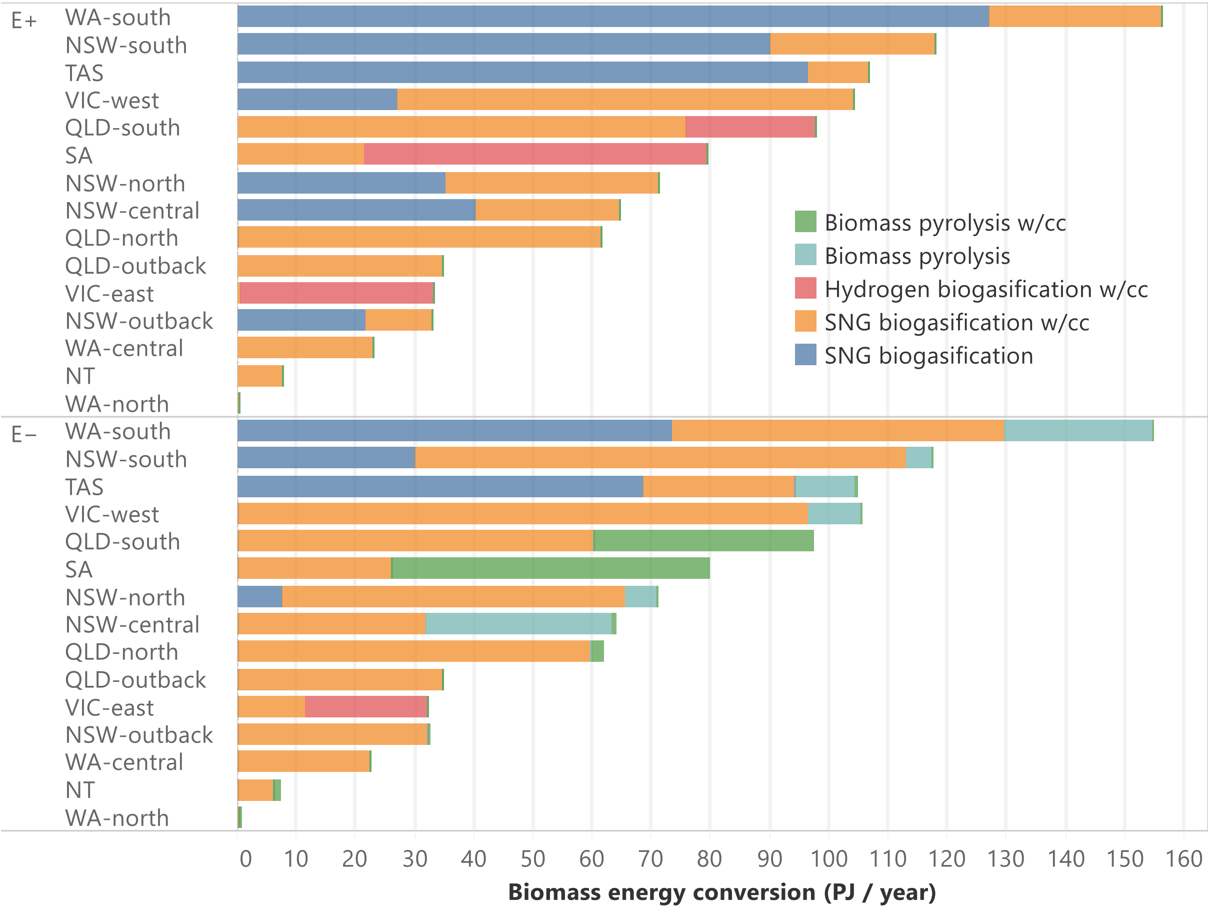


Figure 6 | 2050 biomass energy conversion with various technologies for the E+ and E− Scenarios, by NZAu region



4 Siting biomass conversion facilities

This siting analysis downscales the annual addition of all biomass conversion facilities present in the macro-scale energy system modelling results from the NZAu 15-region level to the 60 statistical divisions that represent the same spatial granularity provided by the biomass resource estimates.

We focus on facilities that convert biomass feedstock into other forms of energy, and do not downscale direct use of biomass in industry/buildings final demand. The specific bioenergy facility types modelled in this work and their primary energy product are shown in Table 2. Here, we site only those facilities that were found to be present in the macro-scale energy system modelling, as outlined in section 3. The biomass feedstock used in each type of biomass conversion facility is not distinguished by source or biomass type but is presented as a mix of biomass types used in each downscaled region. That is, any type of biomass feedstock shown in Figure 1 and Figure 2 can be used in any conversion technology.

Considerations for the siting of biomass conversion facilities include the proximity to any natural gas or hydrogen pipelines for facilities producing those gaseous fuels. Facilities with carbon capture should also be preferentially located near to CO_2 pipelines and geological sequestration sites. Furthermore, it is likely that conversion facilities would be deployed first in those regions with greatest biomass resource density. The procedure for downscaling the 15-region level results and incorporation of these considerations is outlined below in section 4.2.

Table 2 | The candidate biomass conversion technologies modelled in macro-scale energy system modelling.

Biomass conversion technology	Primary energy product(s)	Carbon capture?	Present in macro-scale energy system modelling?
Bio-gasification	**Synthetic natural gas (bio-SNG)**	**No**	**Yes**
Bio-gasification w/cc	**Synthetic natural gas (bio-SNG)**	**Yes**	**Yes**
Bio-gasification w/cc	**Hydrogen**	**Yes**	**Yes**
Bio-gasification Fischer-Tropsch	Synthetic liquid fuels	No	No
Bio-gasification Fischer-Tropsch w/cc	Synthetic liquid fuels	Yes	No
Biomass fast pyrolysis	**Synthetic solid & liquid fuels**	**No**	**Yes**
Biomass fast pyrolysis w/cc	**Synthetic solid & liquid fuels**	**Yes**	**Yes**
Power cycle	Electricity	No	No
Power cycle w/cc	Electricity	Yes	No

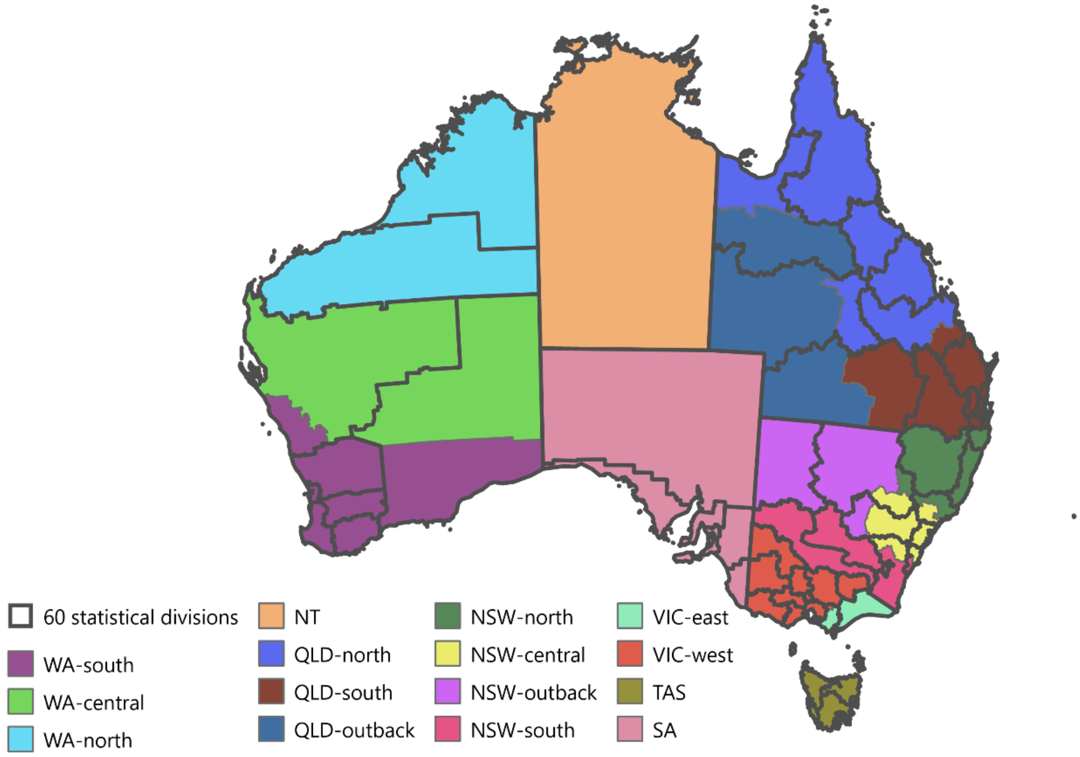
4.1 Spatial basis for downscaling

Biomass used in bioenergy activity typically has low density, high moisture content and is often harvested and transported from diffuse sources, so that the cost of biomass is sensitive to transportation distances. Biomass conversion facilities are thus generally sited relatively close to biomass sources. This downscaling analysis therefore assumes that biomass produced within each downscaling region is used within that region.

The siting of bioenergy conversion facilities is based on the same 60 ABS statistical divisions that were used to estimate the biomass resource, represented in Figure 7 with an underlay of the 15 NZAu zones used in the macro-scale energy system modelling. These 60 statistical divisions represent "relatively homogeneous regions characterised by identifiable social and economic links between the inhabitants and between the economic units within the region, under the unifying influence of one or more major towns or cities" (Australian Bureau of Statistics, 2006).

Where a statistical division straddles two of the modelled NZAu zones, its bioenergy resource and consumption is allocated entirely to the NZAu zone that constitutes the majority of the land area. The mapping of the 60 statistical divisions to 15 NZAu zones is presented in Table 3.

Figure 7 | The spatial basis for bioenergy downscaling is represented by the 60 statistical divisions shown, also with an underlay of the NZAu zones used in macro-scale energy system modelling.



4.2 Downscaling procedure

A resource allocation optimisation model was developed to preferentially allocate the biomass resource used in each NZAu zone and by each bioenergy conversion facility type to the smaller statistical divisions that make up each zone. Overall, downscaling of biomass conversion facilities assumes that facilities would first deploy in areas with highest biomass supply density, and be sited near to storage or CO_2 pipeline networks (for facilities w/cc). This preferential allocation of biomass resource is incorporated in the optimisation model with three factors:

- Biomass resource density (PJ/km^2) of the statistical division;
- The statistical division's proximity to CO_2 sequestration sites; and
- The facility type siting order of preference (hydrogen biogasification w/cc, biomass pyrolysis w/cc, biomass pyrolysis, SNG biogasification w/cc, SNG biogasification).

These three factors are incorporated in the modelling by applying a rank to each statistical division in a NZAu zone for each of the factors. The statistical division rankings for resource density and sequestration proximity are shown in Table 3.

The objective function of the optimisation model minimises the ranked supply of biomass from each statistical division to the encompassing NZAu zone, subject to the constraints:

- a portion of each statistical division's biomass resource is first allocated to the buildings and industrial consumption found by the system modelling for each NZAu zone (Figure 4) in proportion to the resource availability of the statistical division; then
- the sum of remaining biomass supply from all statistical divisions within a given NZAu zone to each bioenergy conversion facility type is equal to the total biomass used in that NZAu zone by that facility type; and
- the sum of biomass supply from a statistical division across the different facility types is less than or equal to the resource availability in that statistical division.

This optimisation is performed for the years 2020 to 2060 in 5-year timesteps and for all Scenarios.

Once all required biomass was allocated in each statistical division to each facility type, an assessment was performed across all 60 statistical divisions of the number of resulting facilities and their capacity. This analysis assumes a nominal bioenergy facility size of 700 dry-kt/year of biomass processing capacity for all facility types. Therefore, the allocated biomass used in each statistical division is converted to annual dry mass used and divided by 700 kt/year to determine the number of individual facilities. Where the biomass used by a certain technology in a statistical division is less than 700 kt/year, the number of facilities sited is 1 with a capacity of the allocated biomass use. Where the biomass used by a facility is more than 700 kt/year the number of facilities is rounded down to the nearest integer, and the average facility size is the total allocated biomass use, divided by the number of facilities. This enables an assessment of the distribution of facility capacities across Australia.

4.3 Siting analysis: E+ and E−

Figure 8 and Figure 9 present the results of the bioenergy downscaling analysis for the E+ and E− Scenarios in 2050, with all other downscaled years shown in Appendix C and D. The spatial distribution of bioenergy conversion, consumption and the number of bioenergy facilities shows a significant opportunity for new bioenergy industry in certain key locations around Australia.

Specifically, synthetic natural gas is produced through biogasification of MSW and crop stubble in southern Western Australia, with some facilities incorporating carbon capture and located in the Perth and Midlands statistical divisions, closer to the northern sequestration sites.

In Queensland, native grasses and organic MSW are used for synthetic natural gas production along the southern coastal statistical divisions, with all facilities incorporating carbon capture due to their proximity to sequestration sites in the Surat Basin.

In NSW, native grasses and forestry residues are used to produce synthetic natural gas with more limited use of carbon capture. Significant bioenergy hubs may be established around the Northern, North-Western, Central-West and Murrumbidgee statistical divisions with 17 downscaled facilities.

In Victoria, forestry residues in the south west are used to produce synthetic natural gas with carbon capture, while crop stubble is used to produce synthetic natural gas without carbon capture along the northern border. In Gippsland, forestry residues are used to produce hydrogen with carbon capture and storage in the nearby offshore Gippsland sequestration site, thereby achieving a significant net withdrawal of atmospheric CO_2. Specifically, in the E+ Scenario, we find approximately 30 PJ/year of biomass consumption across the Gippsland and East Gippsland statistical divisions, producing 15 PJ/year of hydrogen and sequestering 2-3 Mt of biogenic CO_2.

Tasmania's forestry residue resource is used to produce synthetic natural gas through biogasification, with only limited use of carbon capture. The downscaling analysis sites 8 synthetic natural gas facilities in Tasmania by 2050 in E+.

In South Australia, crop stubble from around Adelaide and plantation forestry residues from the south east are used to produce predominantly hydrogen with biogasification and carbon capture. We find that in E+ 2050 ~50 PJ/year of biomass is used to produce ~25 PJ/year of hydrogen and with sequestration of ~4 Mt-CO_2/year. Crop stubble resource in more northern regions of SA are also used to produce synthetic natural gas with carbon capture.

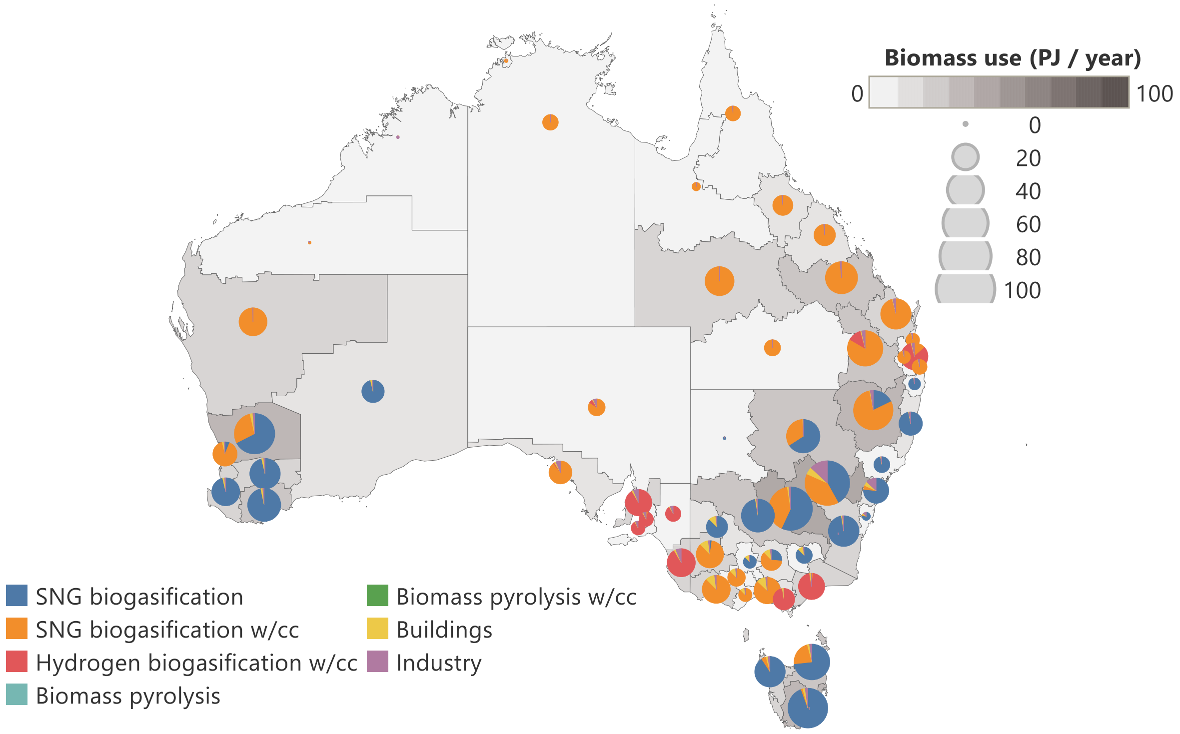
Similar themes are observed in the E− scenario but with some biomass pyrolysis sited instead of hydrogen production. Pyrolysis facilities are sited in statistical divisions with high resource density, and these are generally located in regions surrounding large population centres. A mix of pyrolysis facilities with and without carbon capture are sited, with carbon capture facilities preferentially sited in regions with sequestration potential, such as South Australia and Southern Queensland. Pyrolysis is used without carbon capture in New South Wales, southern Western Australia and Tasmania.

Limited opportunity for bioenergy facilities is observed in northern Australia, due to the limited available resource and lower domestic demand for decarbonised fuels.

Figure 10 presents the number of bioenergy conversion facilities sited in 2050, showing 97 and 103 sited facilities for the E+ and E− Scenarios, respectively. In both Scenarios, the majority of these facilities are for synthetic natural gas production, with some incorporating carbon capture. Figure 11 shows the capacity distribution of these facilities, displaying that while the majority of facilities are sized close to the nominal capacity of 700 kt/year, a significant proportion are smaller. Nonetheless, facilities with a processing capacity of at least 700 dry-kt/year account for more than 80% of all biomass used across the country.

Figure 8 | Bioenergy activity downscaled for the E+ Scenario in 2050, showing (a) the amount of biomass used in various conversion technologies across the 60 statistical division, and (b) the number of bioenergy conversion facilities of each facility type.

(a) Bioenergy conversion and consumption in E+, 2050



(b) Number of bioenergy conversion facilities in E+, 2050

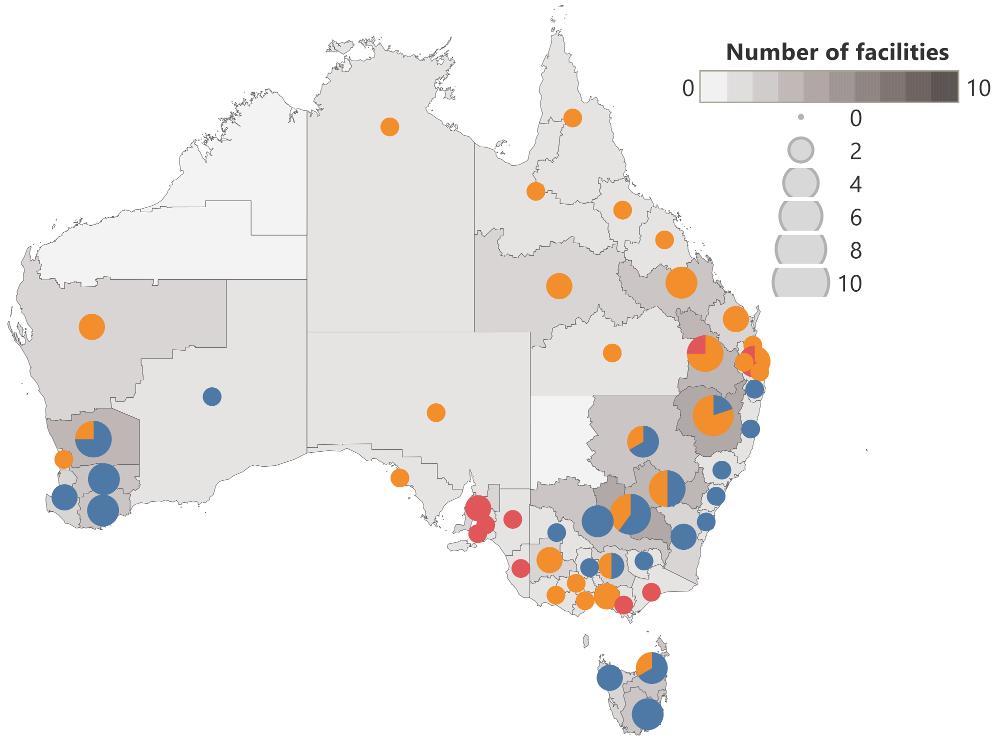
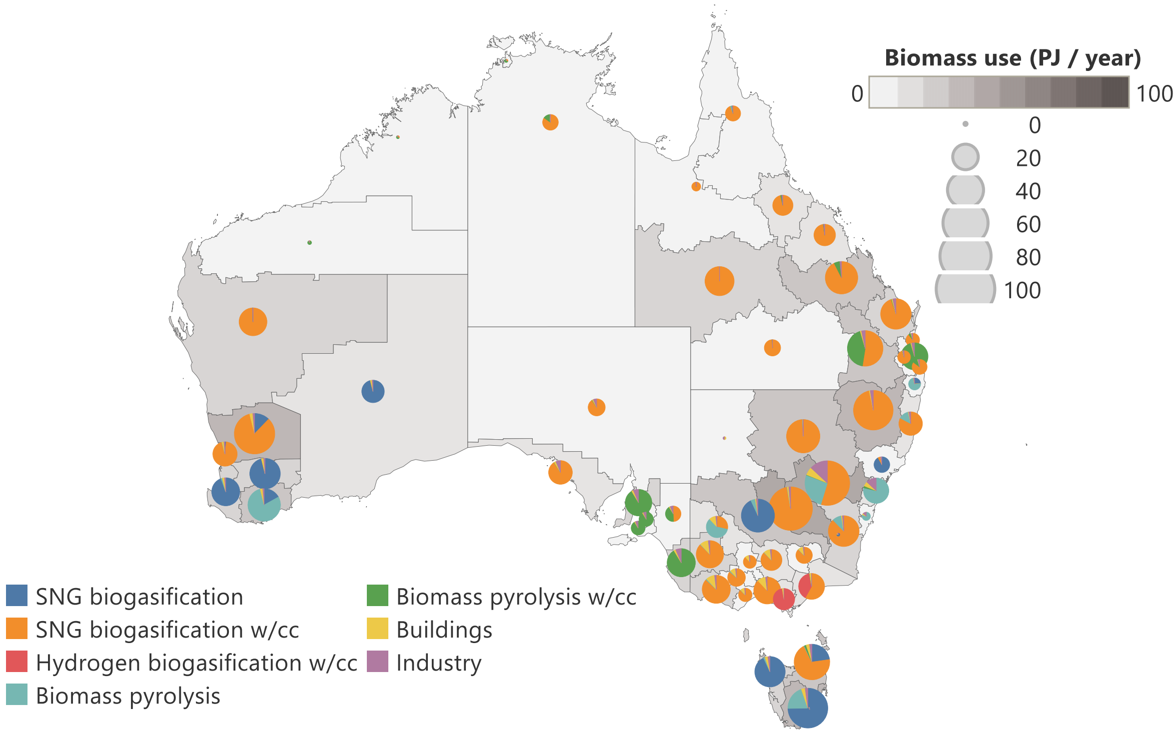


Figure 9 | Bioenergy activity downscaled for the E− Scenario in 2050, showing (a) the amount of biomass used in various conversion technologies across the 60 statistical division, and (b) the number of bioenergy conversion facilities of each facility type.

(a) Bioenergy conversion and consumption in E−, 2050



(b) Number of bioenergy conversion facilities in E−, 2050

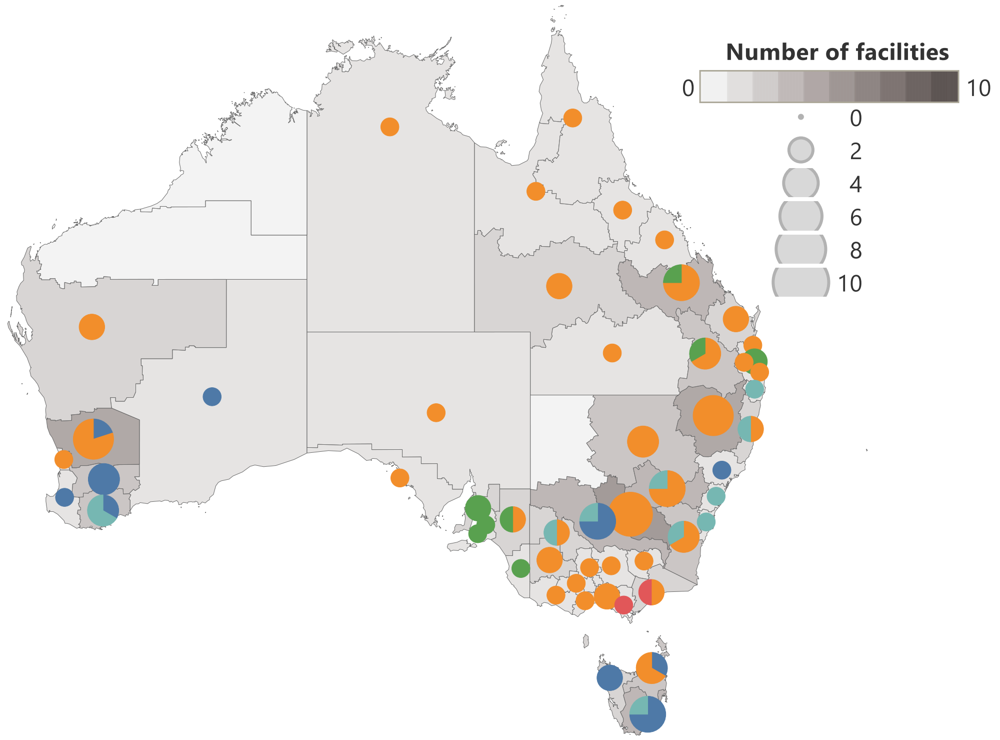


Figure 10 | Number of downscaled bioenergy conversion facilities in 2050, by facility type and scenario.

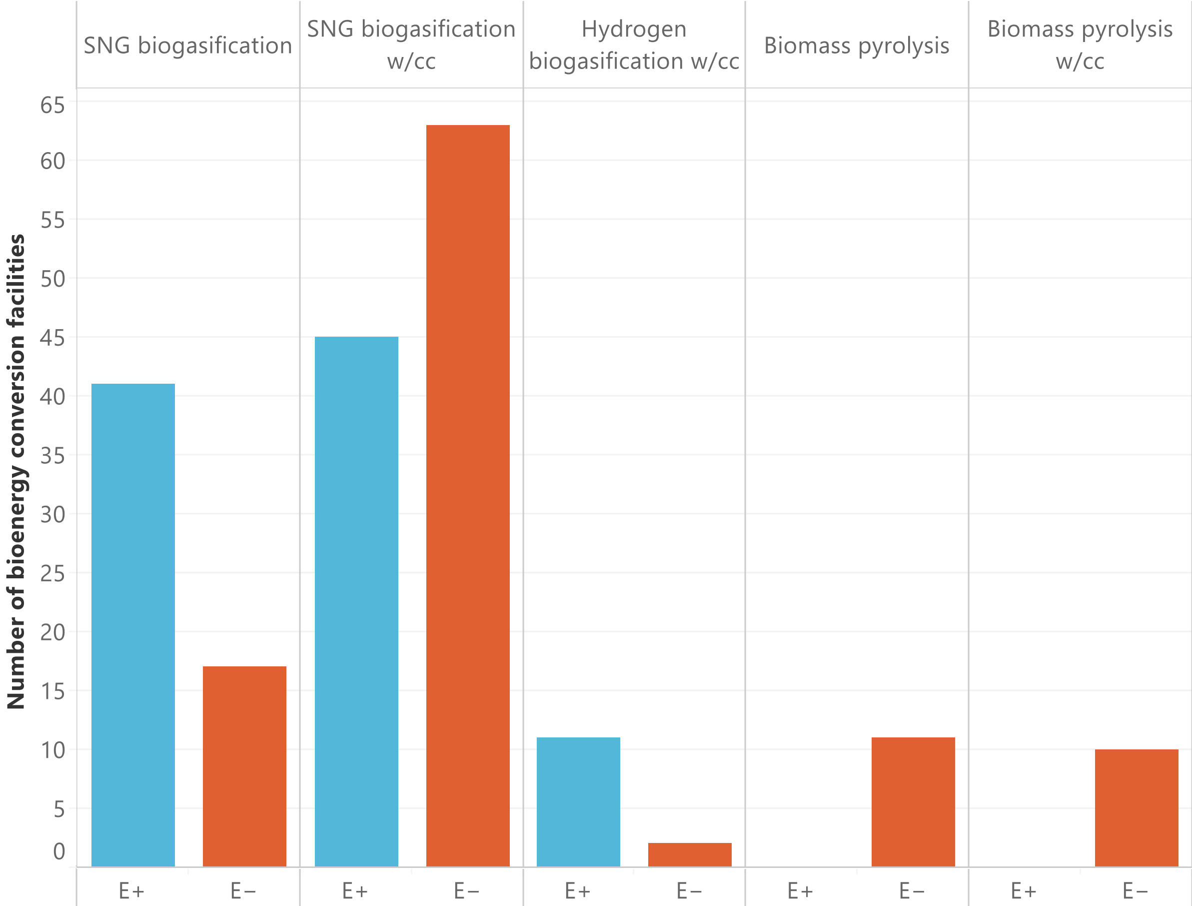
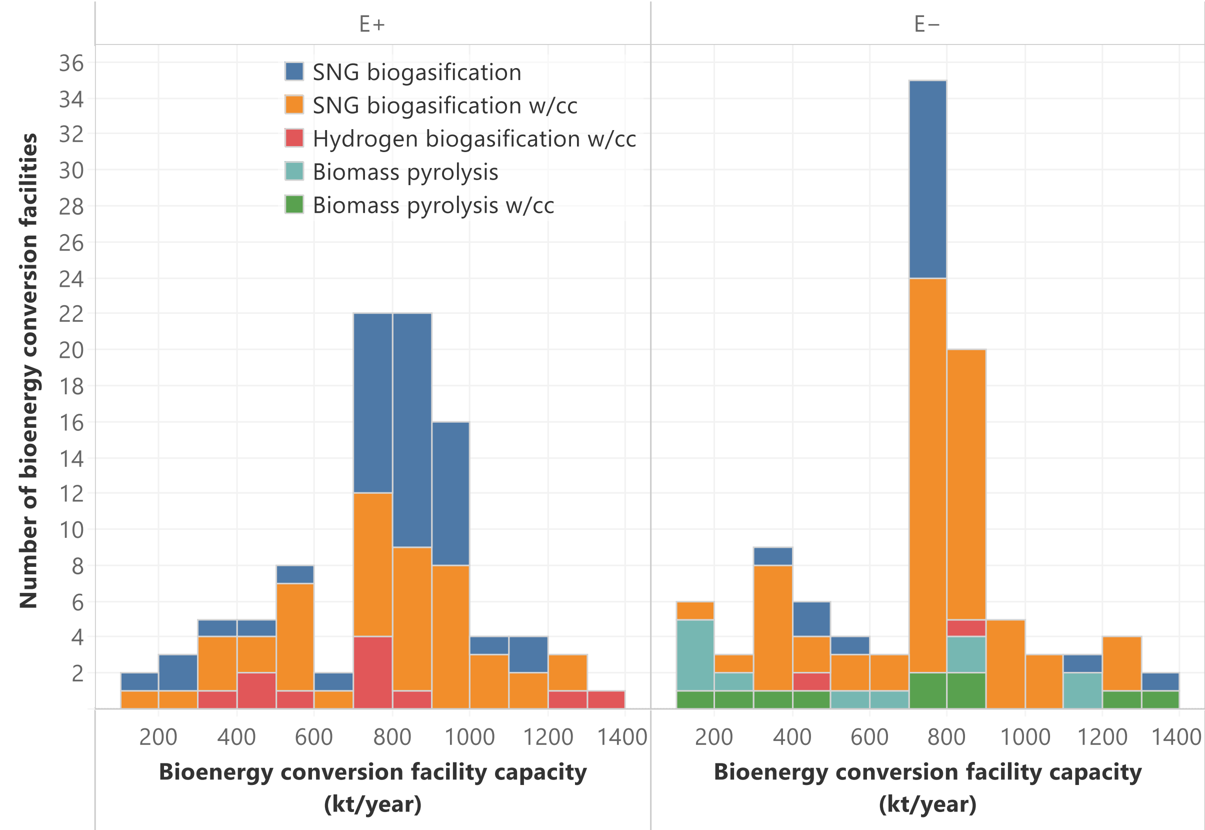


Figure 11 | Bioenergy conversion facility capacity distribution in 2050, by facility type and scenario. Capacities are presented in terms of annual dry biomass throughput.



4.4 Integration of bioenergy with national CO_2 infrastructure

Many of the bioenergy plants sited above are built with carbon capture, which represents a means of achieving net withdrawal of atmospheric CO_2 when the bioenergy conversion process emissions are captured and permanently sequestered in geologic formations. The NZAu macro-scale energy system modelling has shown that bioenergy plants with CO_2 capture are a source of 20-30 Mt-CO_2/year from 2035 across all Core Scenarios, accounting for 2-3% of total CO_2 supply in E+RE− and 20-30% in E+RE−. Figure 12 shows this CO_2 supply for the two Scenarios of focus in this report, E+ and and E−, demonstrating the role that bioenergy with carbon capture plays as part of a system of CO_2 capture, transmission and sequestration infrastructure.

The choice to build bioenergy with carbon capture is made by macro-scale energy system optimisation across 15 regions, given a biomass and sequestration resource at that 15-region level and with potential interconnection between regions. However, we have shown that Australia's biomass resource is in fact diffusely distributed across many smaller disaggregated regions, each characterised by different agricultural, forestry and other biomass-producing activities. This implies that bioenergy plants – which each act as point sources of CO_2 when paired with carbon capture – would also be diffusely distributed across the country. This is demonstrated in Figure 13, which presents the regional (60 statistical division level) distribution of annual CO_2 captured in downscaled bioenergy plants with carbon capture in 2050 for the E+ and E− Scenarios. The point sources of CO_2 are relatively concentrated in parts of WA, VIC and SA, but are more widely spread in NSW and QLD.

Practical planning of a potential new bioenergy industry that both provides low-emissions biofuels and net withdrawal of CO_2 through the use of carbon capture and sequestration would then further require consideration of:

- The available CO_2 transport infrastructure;
- The trade off between transport of low energy density raw biomass feedstock via road with transport of captured compressed CO_2 via pipelines from the bioenergy plant to CO_2 transmission infrastructure; and
- The relative merits of alternative means achieving net withdrawal of atmospheric CO_2, such as direct air CO_2 capture undertaken near to sequestration sites to avoid long-distance transmission of captured CO_2 from bioenergy plants.

Furthermore, the design of national CO_2 transmission and sequestration infrastructure will be influenced by the geographic locations of other point sources of CO_2, which are determined by downscaling in other areas of the NZAu project, such as thermal power plants, cement plants, direct air capture.

Figure 12 | Supply of CO_2 by different sources, for the NZAu E+ and E− Core Scenarios.

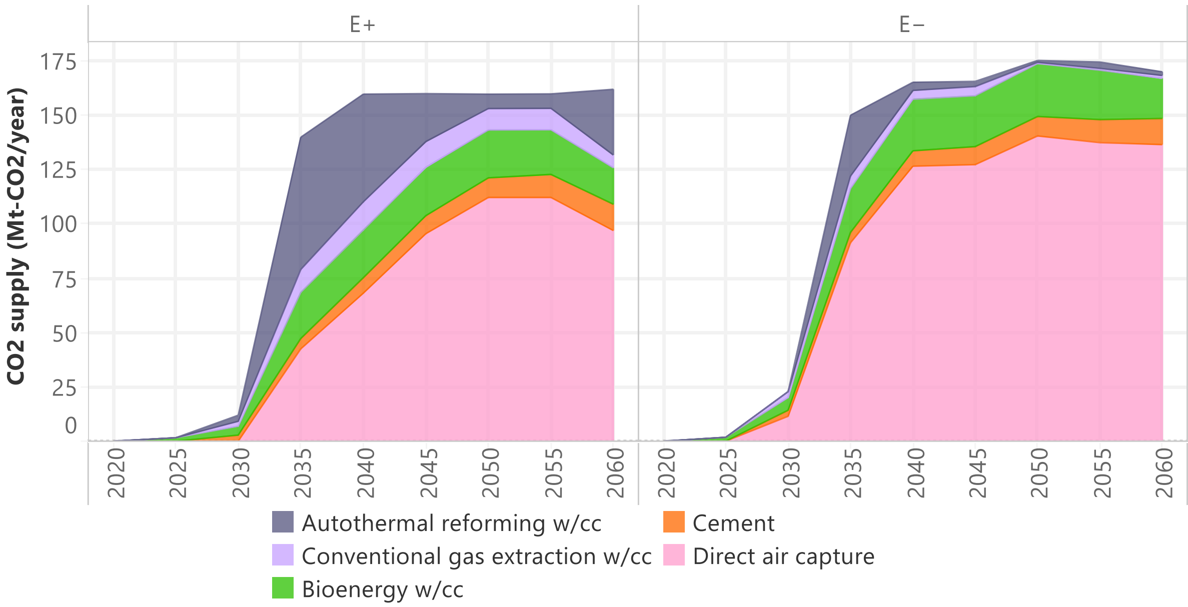
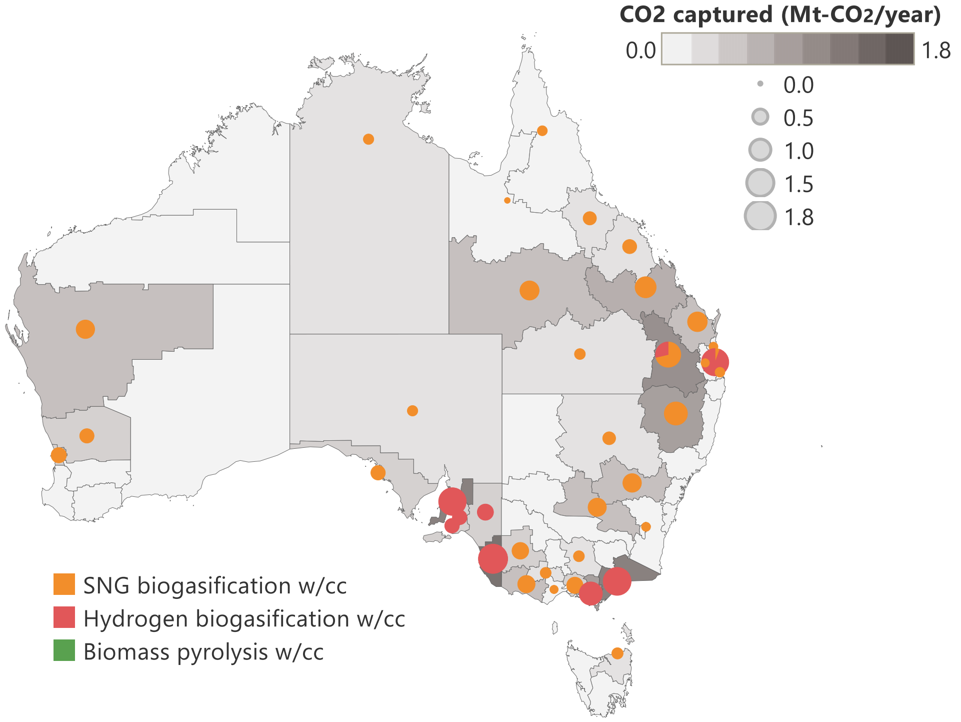


Figure 13 | CO_2 captured from the bioenergy plants downscaled to the 60 statistical divisions in 2050, for: (a) the E+ Scenario; and (b) the E– Scenario.

(a) E+, 2050



(b) E–, 2050

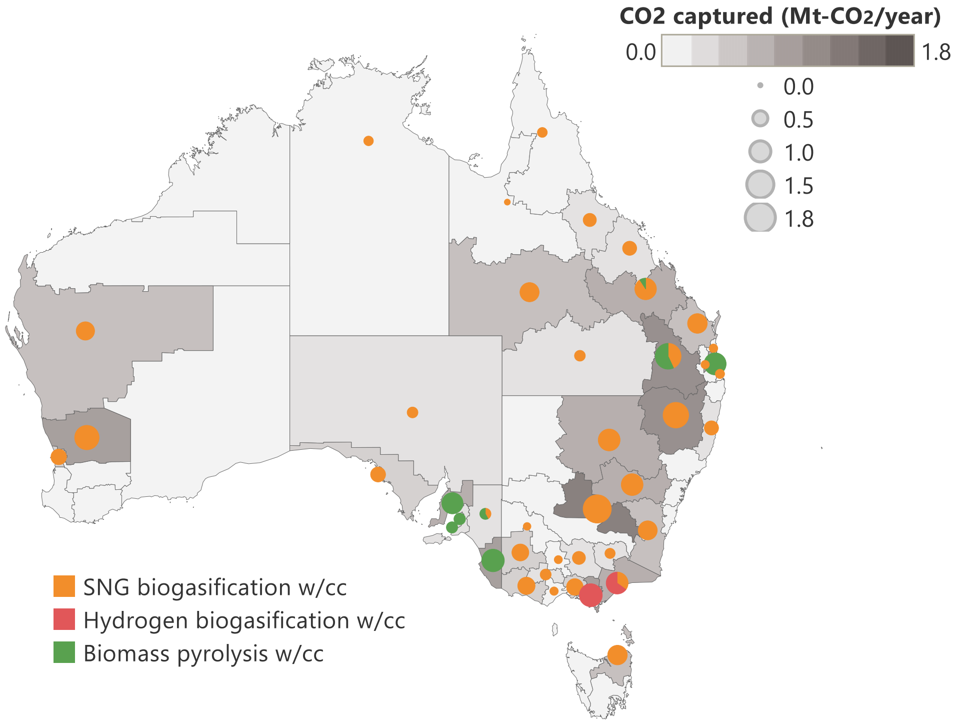
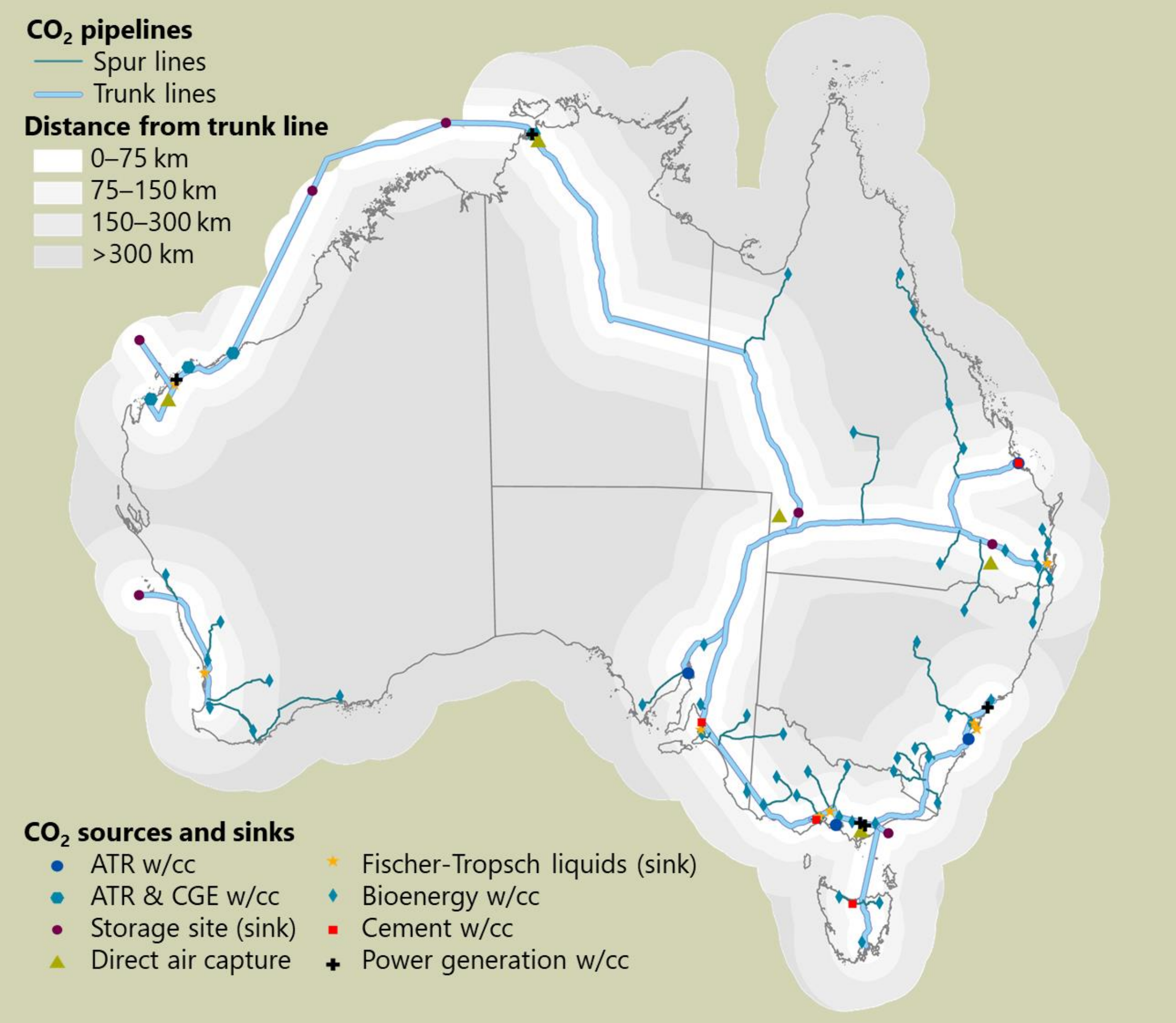


Figure 14 presents a notional map of *candidate* Australian CO_2 infrastructure, showing all potential downscaled trunk and spur CO_2 pipelines, and point sources and sinks of CO_2, as modelled in the Net Zero Australia project. The locations shown for potential bioenergy facilities are based on locations of biomass resource included in the *Australian Renewable Energy Mapping Infrastructure Project* (ARENA, 2021), with one location shown for each of the 60 statistical divisions considered in this report. Of particular note here are the spur lines connecting those bioenergy facilities with CO_2 transmission trunklines. Such spur lines are typically routed by determining the minimum distance from CO_2 point sources to CO_2 transmission lines, given existing rights of way and other land use constraints.

Previous work downscaling similar CO_2 infrastructure in the USA for the Net Zero America study suggested CO_2 sources should be located within 200km of transmission lines (Greig et al., 2021). However, a number of the spur lines shown in Figure 14 have distances significantly greater than this threshold, e.g. those in southern WA, northern QLD and regional NSW. This suggests that there may be least-cost alternatives to installing carbon capture with those regional bioenergy plants and requiring long-distance spur line CO_2 transport facilities, such as additional direct air capture at sites close to sequestration. Further detail on the downscaling of CO_2 infrastructure and these relevant trade offs in the NZAu project is available in the companion downscaling report *Downscaling – CO_2 capture, transmission, use & storage*.

Figure 14 | Notional map of Australian CO_2 infrastructure, showing all downscaled candidate trunk and spur CO_2 pipelines, and point sources and sinks of CO_2, as modelled in the Net Zero Australia project. Further detail on the downscaling of CO_2 infrastructure is available in the companion downscaling report *CO_2 capture, transmission, use & storage*.



5 Investment cost analysis

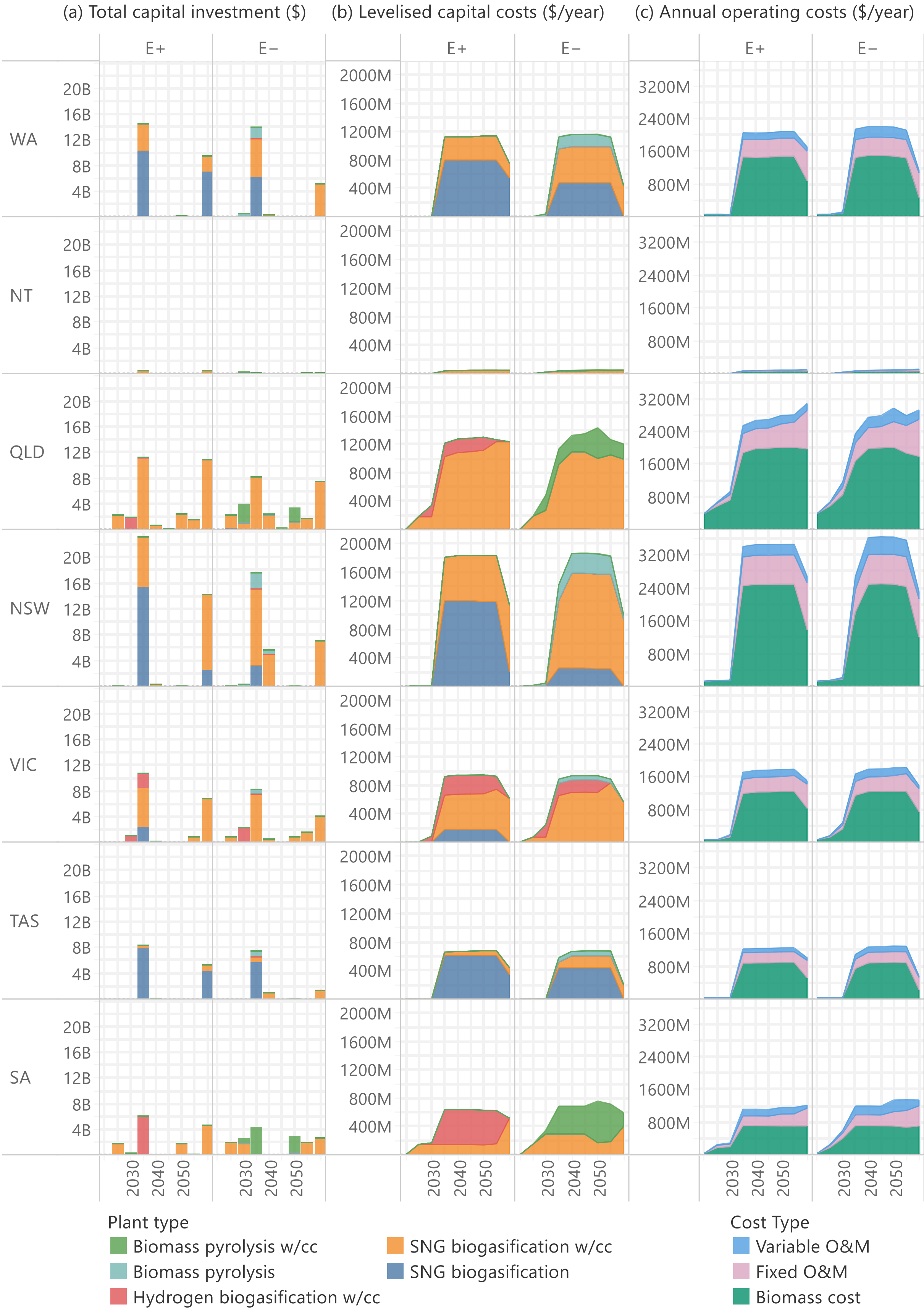
Bioenergy conversion facilities deployed in the years to 2060 represent a considerable investment of capital in a new industry. Figure 15 shows this investment across Australia, by year of required total capital investment, and ongoing levelised capital and operating costs. This shows that there are two timeframes for the required capital investment. The first is associated with initial establishment of the bioenergy industry, in which 80–90 $B of capital investment occurs between 2025 and 2040. This is levied as a roughly 6–7 $B ongoing levelised capital cost. The second investment time frame shown in Figure 15 is associated with the bioenergy facilities sited in around 2035 and coming to end of life in 2055-2060. At this point some investment is required for refurbishment of existing facilities, or construction of new facilities.

In addition to capital investment, the bioenergy industry will incur significant ongoing expenditure on the biomass feedstock used in the various bioenergy facilities, as well as operating costs. It is found that the ongoing operating costs of the bioenergy industry modelled here account for around ~13 $B of annual expenditure, the large majority of which is the biomass feedstock.

Figure 16 presents these same costs, disaggregated by Australian state. The investment costs required to establish the modelled bioenergy industry are approximately in proportion to the available resource, with the biggest investment found in New South Wales, Queensland and Western Australia. These costs are also presented in Appendix D, disaggregated by NZAu zone.

Figure 15 | Bioenergy industry investment cost results for Australia.

Figure 16 | Bioenergy industry investment cost results for each Australian state or territory.



6 Prospects for biomethane

The Net Zero Australia MASS document (Net Zero Australia Project, 2022) provides estimates of the biogas availability in Australia, with particular focus on that available from the wet waste streams of urban waste, livestock residues and food processing residues. Biogas is a biogenic mixture of mainly methane and carbon dioxide derived from the anaerobic digestion of biomass, which is either directly used in applications that can tolerate carbon dioxide, or is upgraded to biomethane (IEA Bioenergy, 2022). Biogas produced from wet waste streams is likely to have lower cost and better suitability to biogas production through anaerobic digestion than the drier, agricultural crop and forestry biomass residues considered above.

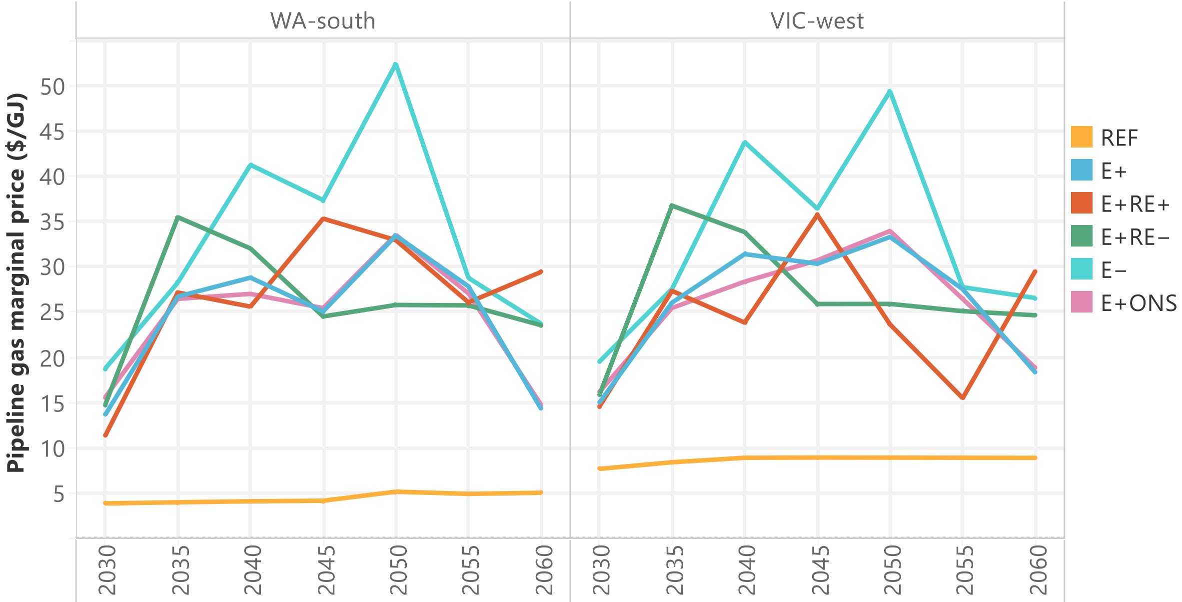
The MASS document uses an available biogas resource estimate of 50 PJ/year, which is a small resource, relative to current annual gas consumption and even relative to the dry biomass resource assessed above. This estimate also aligns with recent assessments of biomethane availability made by the Future Fuels CRC, whose suitability analysis found ~50 PJ/year of biomethane could be available across a range of sites (Culley et al., 2022). This 50 PJ/year biogas resource was not included as an available resource in NZAu's macro-scale energy system modelling with RIO. However, here we assess the prospects of any future available biogas, by reference to the energy system optimised with RIO in NZAu's Core Scenarios.

Figure 17 presents the marginal price for pipeline gas (methane) derived from NZAu's energy system supply-side optimisation, across the modelled horizon, Core Scenarios and for representative west- and east-coast regions. These marginal prices reflect the modelled cost of supplying an additional increment of gas. Figure 17 shows that the marginal price of gas increases relative to the REF Scenario with the application of the system-wide emissions constraint, reflecting the cost of producing one more unit of zero-net-emissions gas (via synthetic or bio- processes), or similarly, the cost of using fossil natural gas and the associated cost of offsetting the fossil fuel combustion emissions.

The implication of the marginal prices shown in Figure 17 is that any future biogas resource that can be sustainably produced and upgraded to biomethane and grid injected at a total cost of <20 $/GJ would be likely to displace the supply of gas from other sources in the modelled energy system after 2030.

A recent FFCRC report performed suitability analysis of different Australian region for hosting biogas production facilities and presented levelised costs of energy (LCOEs) for biomethane produced across the country with wet waste streams (Culley et al., 2022). The LCOEs of biomethane were found to be in the range 10–25 $/GJ, with the most commercially viable locations near to major cities (Culley et al., 2022). This suggests that any such biomethane upgraded from biogas produced in facilities near to cities and their greater density of waste resources would be a prospective alternative to fossil natural gas, bio-SNG, and synthetic natural gas consumption in NZAu's Core Scenarios. Significantly also, it was found that the LCOE of biomethane is lowest when produced in a facility with consistent biomass feedstock availability throughout the year (Culley et al., 2022). This highlights the potential of biogas produced from wet urban, livestock and food processing waste streams, which are characterised by a constant seasonal availability.

Figure 17 | Pipeline gas (methane) marginal prices from NZAu's macro-scale energy system modelling, by Core Scenario and for representative west- and east-coast regions.



7 Summary

This work has examined the potential future emergence of a bioenergy industry, as modelled in Net Zero Australia's Core Scenarios. We find the rapid deployment of bioenergy plants from 2035 to 2040, which process approximately 80 million dry tonnes per annum of available biomass waste and residues (~1000 PJ/year), to produce approximately 600 PJ/year of zero-emissions gaseous and liquid fuels. Across the modelled Core Scenarios, synthetic natural gas is the dominant biofuel produced via biogasification, with hydrogen via biogasification and liquid fuels via pyrolysis also produced to lesser extents. The Core Scenarios also deploy significant capacity to capture bioenergy conversion process CO_2 emissions (bioenergy with carbon capture & storage, BECCS), which represents a means of achieving net atmospheric CO_2 withdrawal of 20-30 Mt-CO_2/year that is largely sequestered in geological formations.

Downscaling of this modelled bioenergy activity sited approximately 100 bioenergy facilities across Australia, with those facilities concentrated in regions of greater biomass resource density. Furthermore, facilities that are paired with carbon capture were preferentially sited near to CO_2 transmission infrastructure.

In total, the establishment of this bioenergy industry would require 80–90 $B of capital investment between 2025 and 2040, levied as a roughly 6–7 $B ongoing levelised capital cost. In addition ongoing expenditure on the biomass feedstock and operating costs would account for around ~13 $B per annum.

The practical establishment of a new bioenergy industry as part of Australia's national pathway to net zero GHG emissions would require, among other things:

- studies that characterise the availability of biomass feedstock for bioenergy conversion, incorporating evaluations of biomass supply sustainability, economic potential, and competition with food and feed crops;
- analysis and optimisation of biomass feedstock supply chains, from growth to harvest and aggregation at bioenergy plants or hubs;
- research and development to bring the prospective bioenergy conversion technologies assessed here (biogasification, pyrolysis and carbon capture) to high levels of commercial readiness, particularly with respect to enabling the use of heterogeneous biomass feedstock in a particular bioenergy conversion facility; and
- The administering of regulations and standards that permit the substitution of biofuels (produced from biomass feedstock) for currently used conventional (fossil) fuels.

The use of biomass residues and waste feedstocks, as considered in this work, will need to be sustainably harvested to minimise impact on existing agriculture and forestry industries. However, the establishment of a bioenergy industry and new revenue streams may also be complementary to those industries. Nevertheless, any energy policy that seeks to incentivise the use of waste biomass and organic matter should also carefully consider the impacts of those incentives on the production of primary agricultural and forestry products.

Appendices

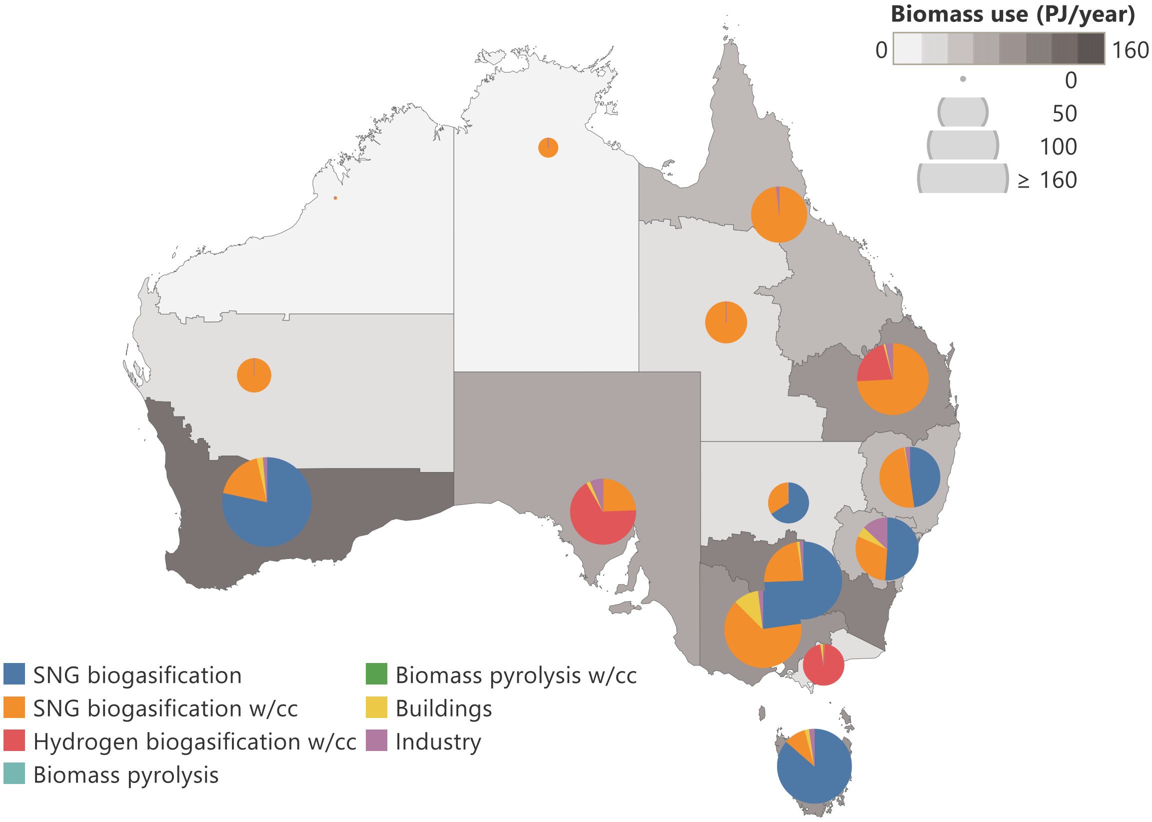
Appendix A: Mapping of biomass resource and consumption

Table 3 | Mapping of ABS statistical division (SD) to NZAu zone, as well as the resource density and CO_2 sequestration proximity ranking for each SD.

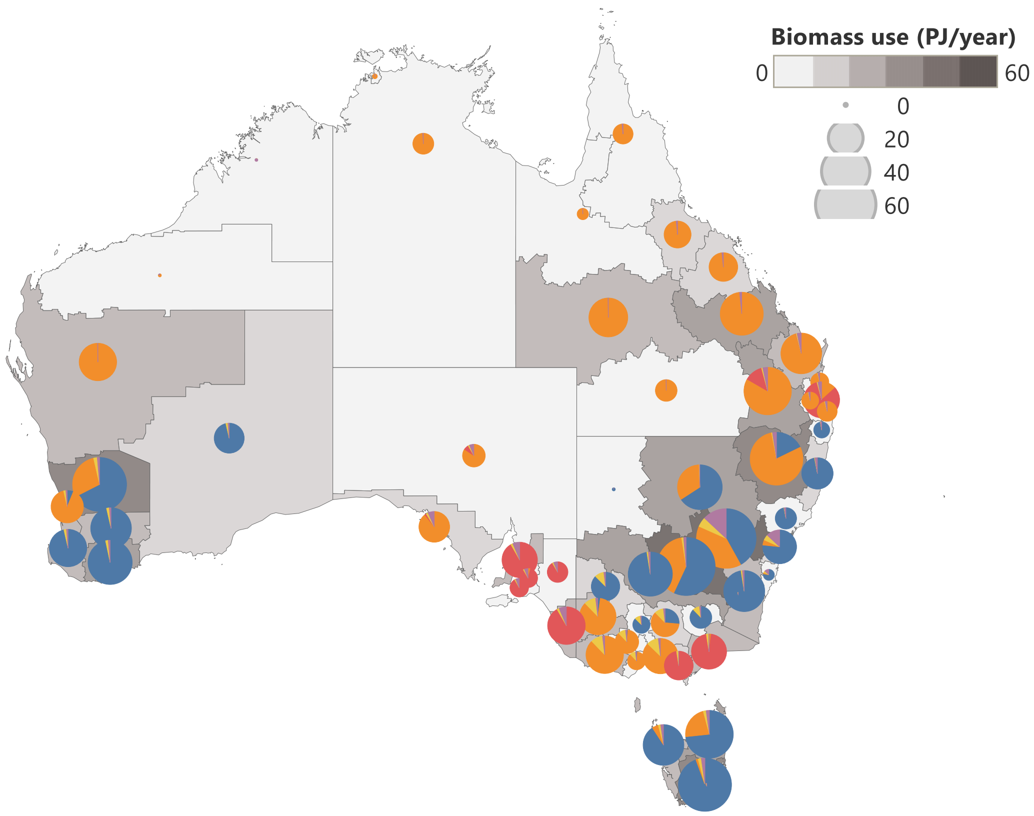
SD ID	SD Name	NZAu zone	Resource density rank	CO2 sequestration proximity rank
105	Sydney	NSW-central	1	2
110	Hunter	NSW-north	4	2
115	Illawarra	NSW-central	3	2
120	Richmond-Tweed	NSW-north	2	3
125	Mid-North Coast	NSW-north	1	3
130	Northern	NSW-north	3	1
135	North Western	NSW-outback	1	1
140	Central West	NSW-central	2	1
145	South Eastern	NSW-south	3	2
150	Murrumbidgee	NSW-south	2	2
155	Murray	NSW-south	4	3
160	Far West	NSW-outback	2	1
205	Melbourne	VIC-west	1	2
210	Barwon	VIC-west	5	2
215	Western District	VIC-west	2	2
220	Central Highlands	VIC-west	3	2
225	Wimmera	VIC-west	4	2
230	Mallee	VIC-west	9	3
235	Loddon	VIC-west	8	2
240	Goulburn	VIC-west	6	2
245	Ovens-Murray	VIC-west	7	2
250	East Gippsland	VIC-east	2	1
255	Gippsland	VIC-east	1	1
305	Brisbane	QLD-south	1	3
307	Gold Coast	QLD-south	2	4
309	Sunshine Coast	QLD-south	3	3
312	West Moreton	QLD-south	5	2
315	Wide Bay-Burnett	QLD-south	4	2
320	Darling Downs	QLD-south	6	1
325	South West	QLD-outback	2	2
330	Fitzroy	QLD-north	1	1

SD ID	SD Name	NZAu zone	Resource density rank	CO2 sequestration proximity rank
335	Central West	QLD-outback	1	1
340	Mackay	QLD-north	2	2
345	Northern	QLD-north	3	3
350	Far North	QLD-north	4	3
355	North West	QLD-outback	3	3
405	Adelaide	SA	1	2
410	Outer Adelaide	SA	4	2
415	Yorke and Lower North	SA	3	3
420	Murray Lands	SA	6	2
425	South East	SA	2	3
430	Eyre	SA	5	3
435	Northern	SA	7	2
505	Perth	WA-south	1	2
510	South West	WA-south	3	5
515	Lower Great Southern	WA-south	2	6
520	Upper Great Southern	WA-south	4	3
525	Midlands	WA-south	5	1
530	South Eastern	WA-south	6	4
535	Central	WA-central	1	2
540	Pilbara	WA-north	1	1
545	Kimberley	WA-north	2	2
605	Greater Hobart	TAS	4	2
610	Southern	TAS	1	2
615	Northern	TAS	2	2
620	Mersey-Lyell	TAS	3	2
705	Darwin	NT	1	1
710	Northern Territory - Bal	NT	2	2
805	Canberra	NSW-south	1	2
810	Australian Capital Territory - Bal	NSW-south	5	2

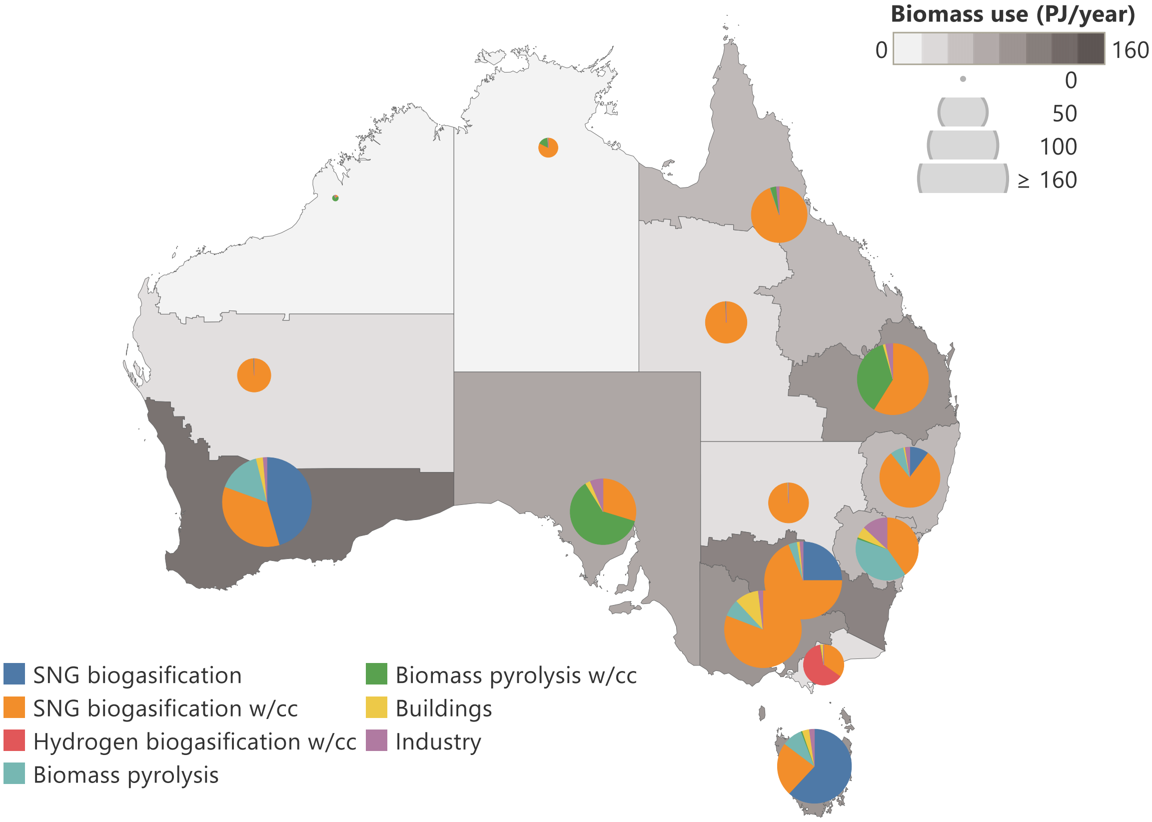
(a) E+ 2050 biomass use by NZAu zone



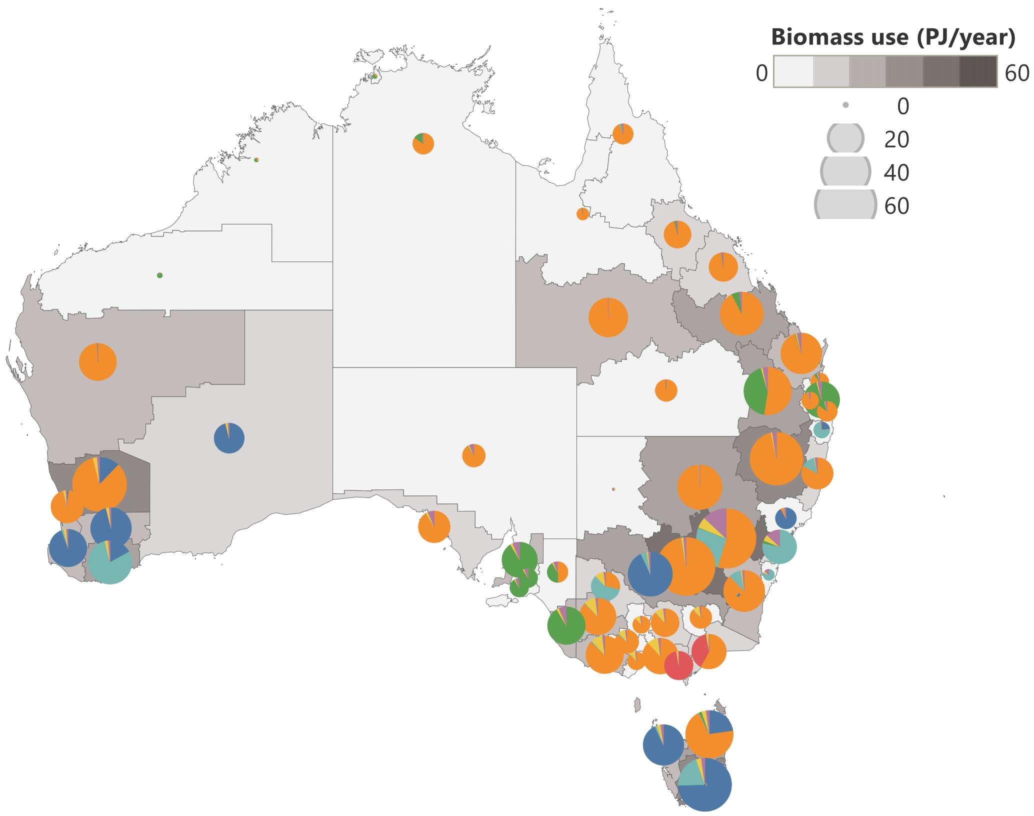
(b) E+ 2050 biomass use by ABS statistical division



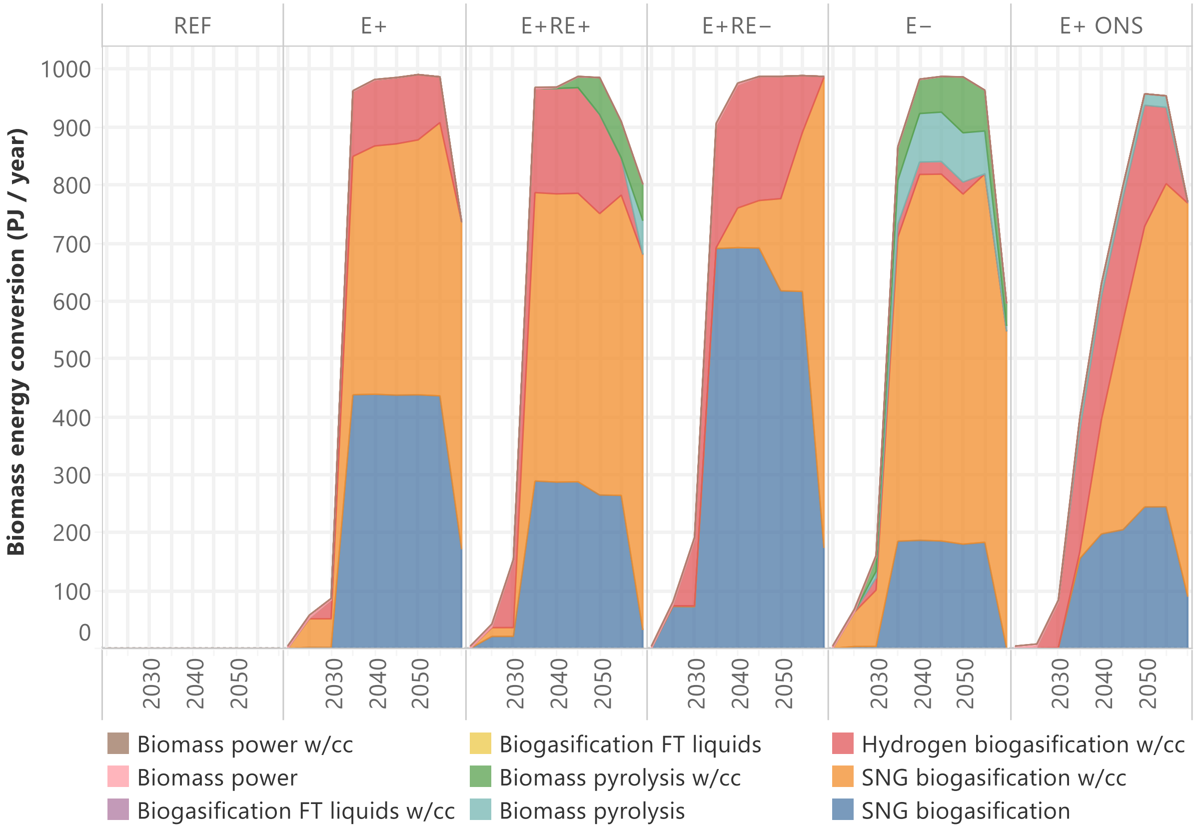
(a) E− 2050 biomass use by NZAu zone



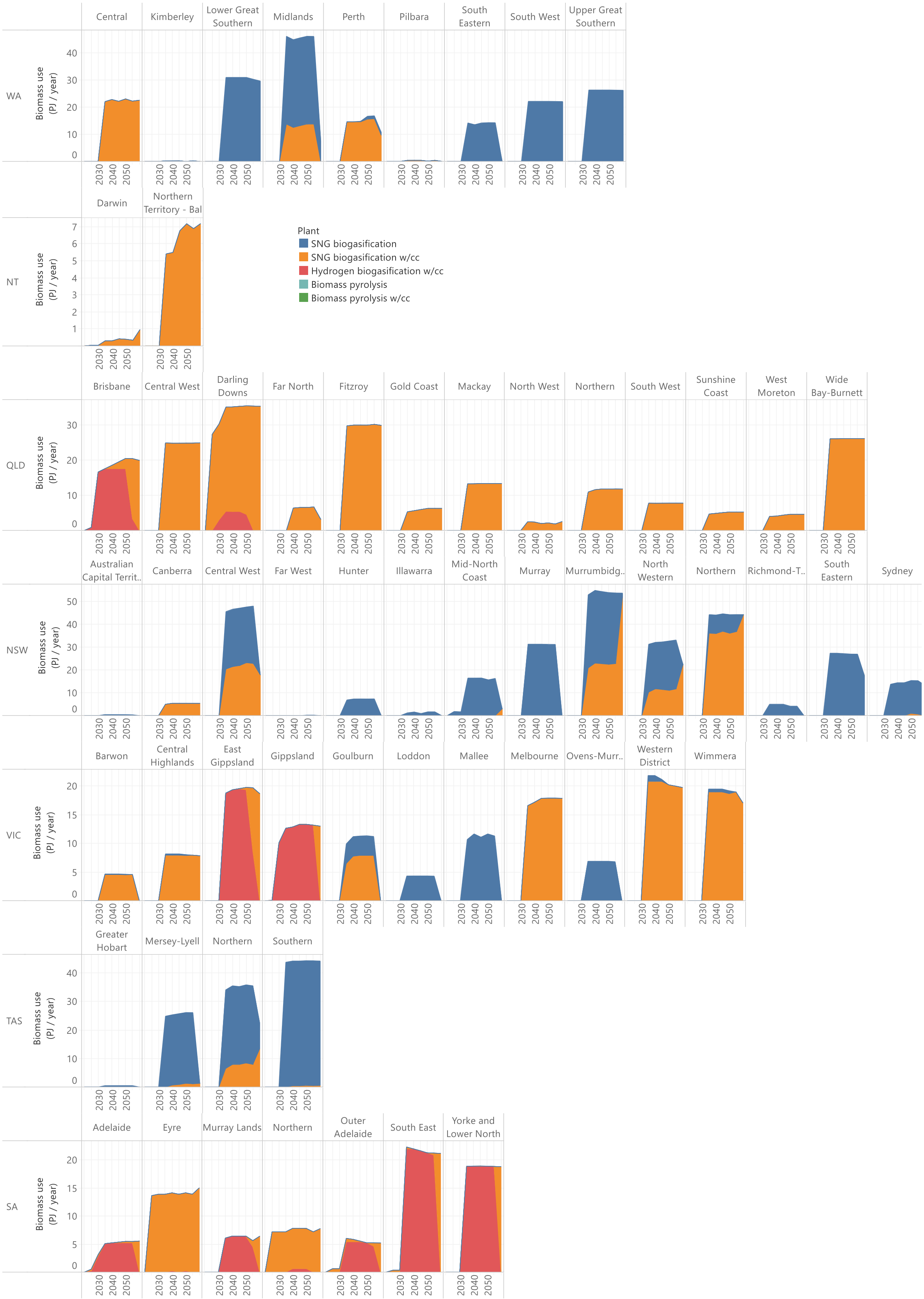
(b) E− 2050 biomass use by ABS statistical division



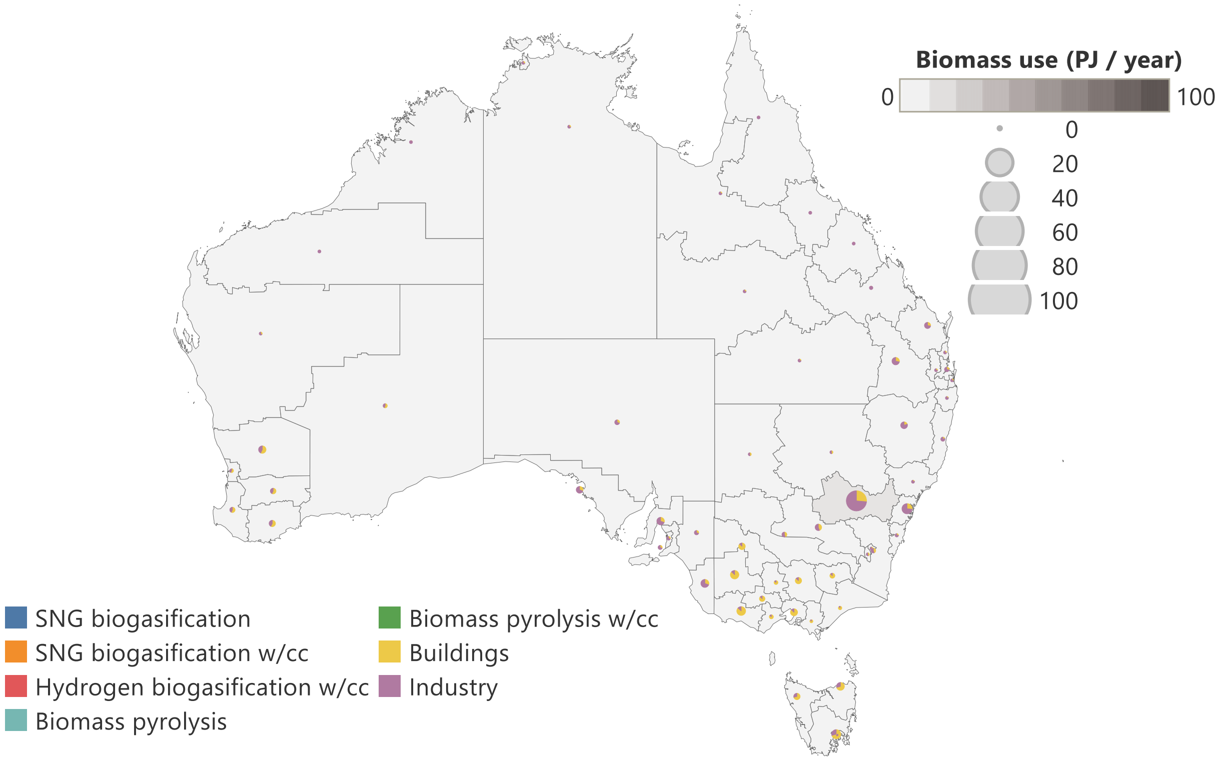
Appendix B: Modelled bioenergy conversion for all core Scenarios



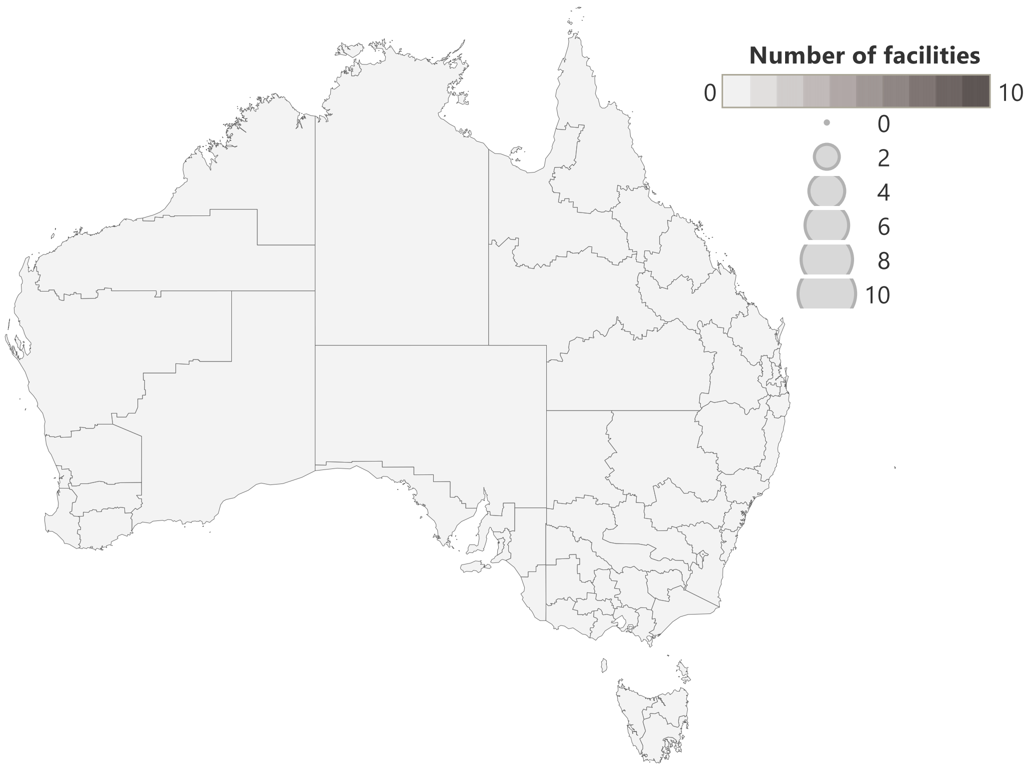
Appendix C: Geospatial evolution of bioconversion facilities: E+



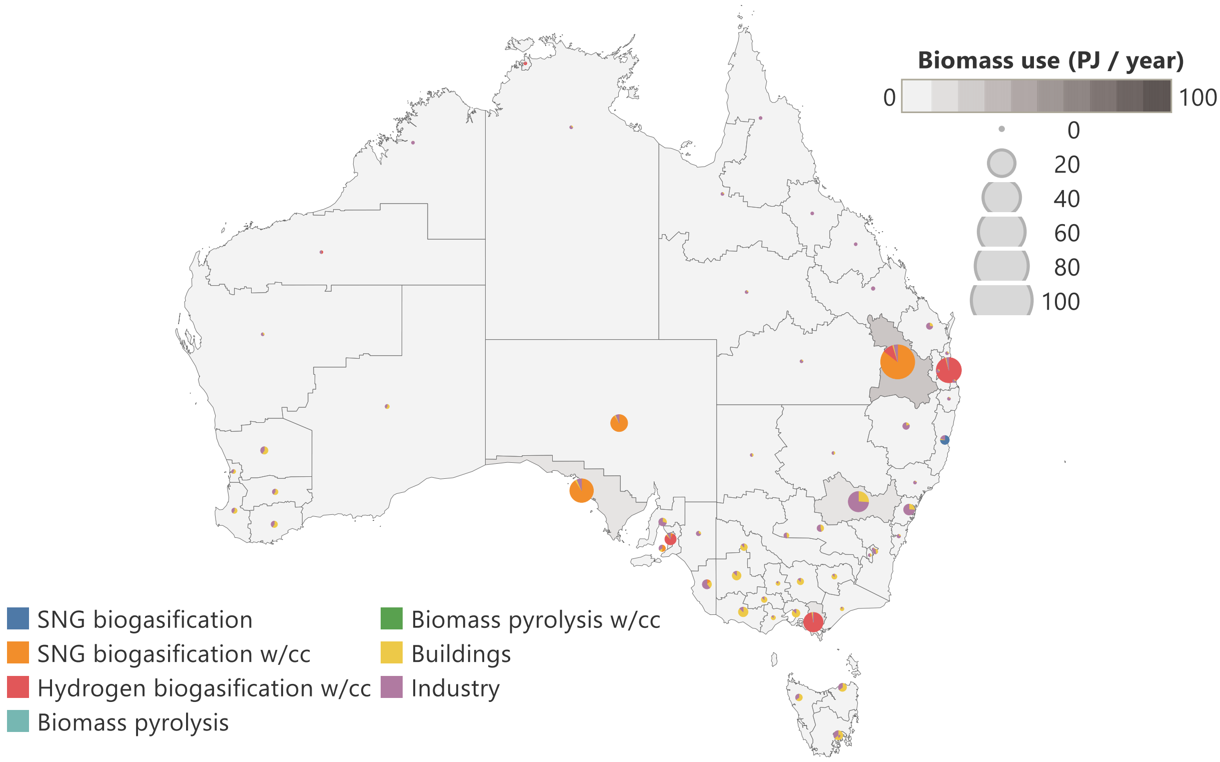
(a) Bioenergy conversion and consumption in E+, 2020



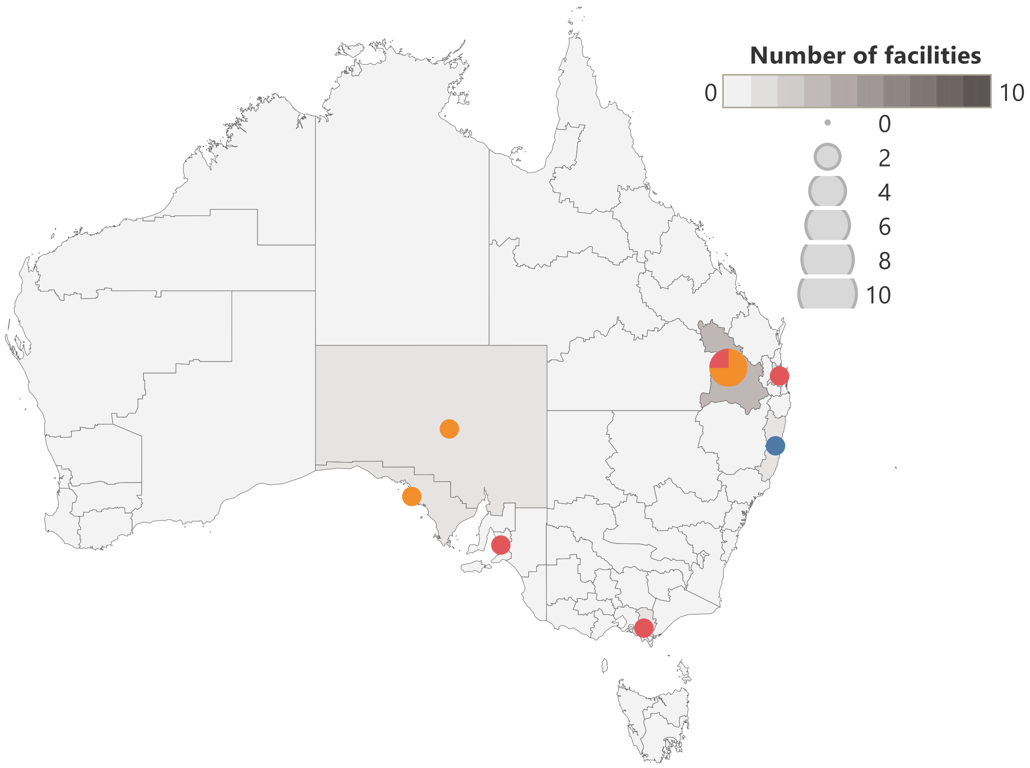
(b) Number of bioenergy conversion facilities in E+, 2020



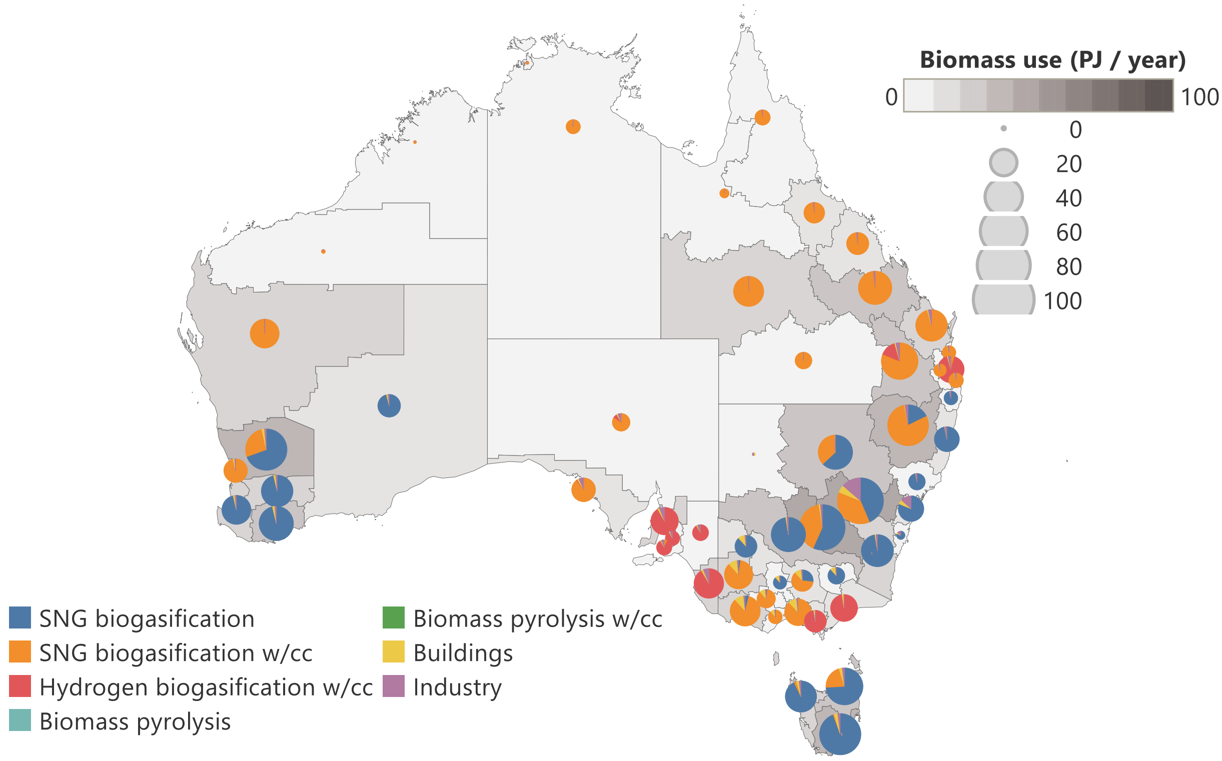
(a) Bioenergy conversion and consumption in E+, 2030



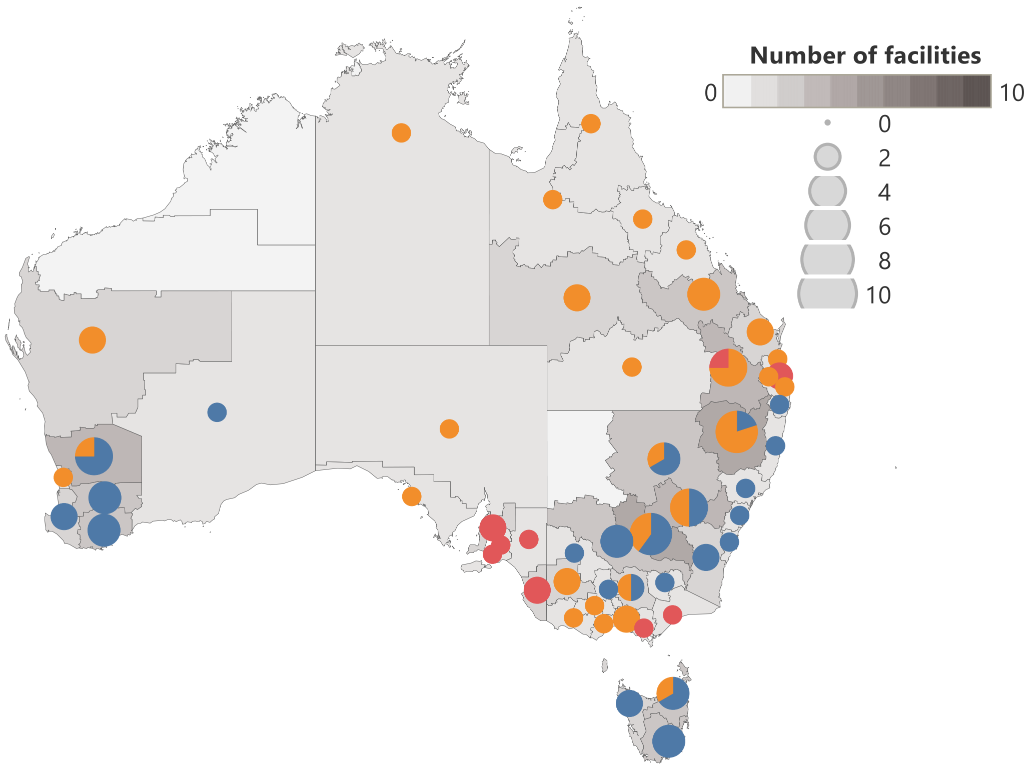
(b) Number of bioenergy conversion facilities in E+, 2030



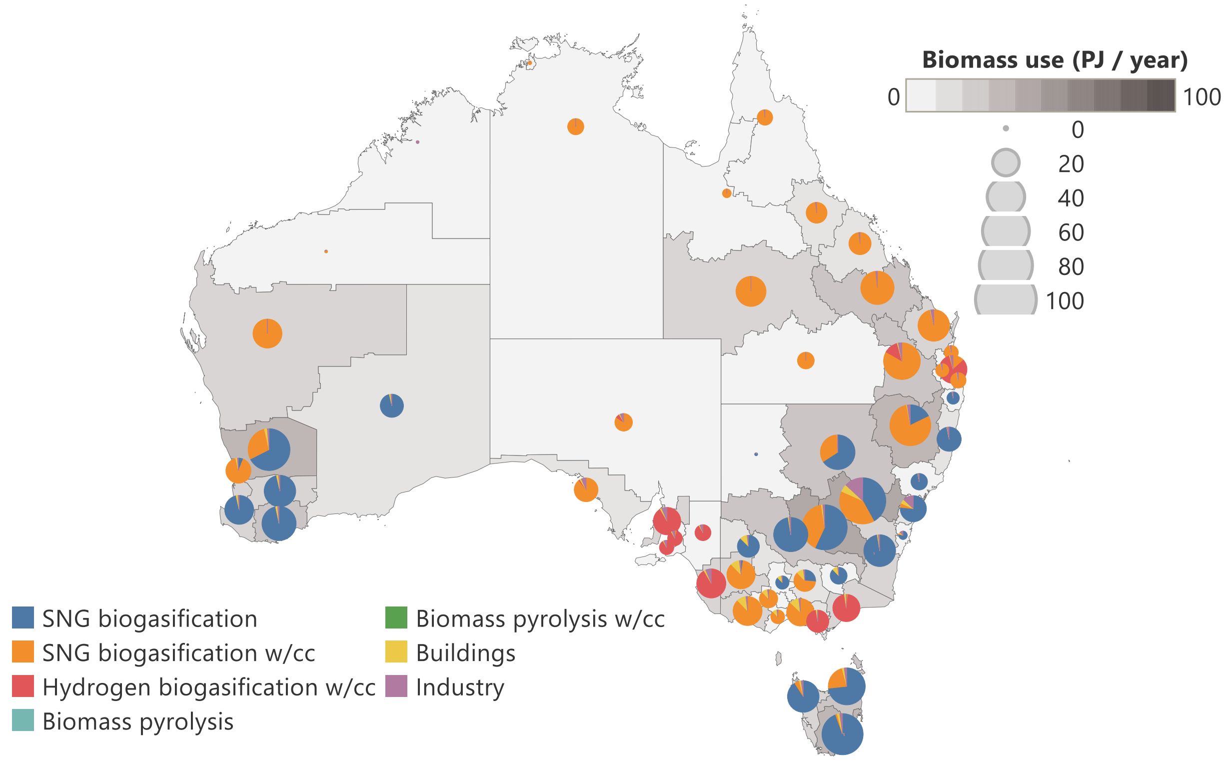
(a) Bioenergy conversion and consumption in E+, 2040



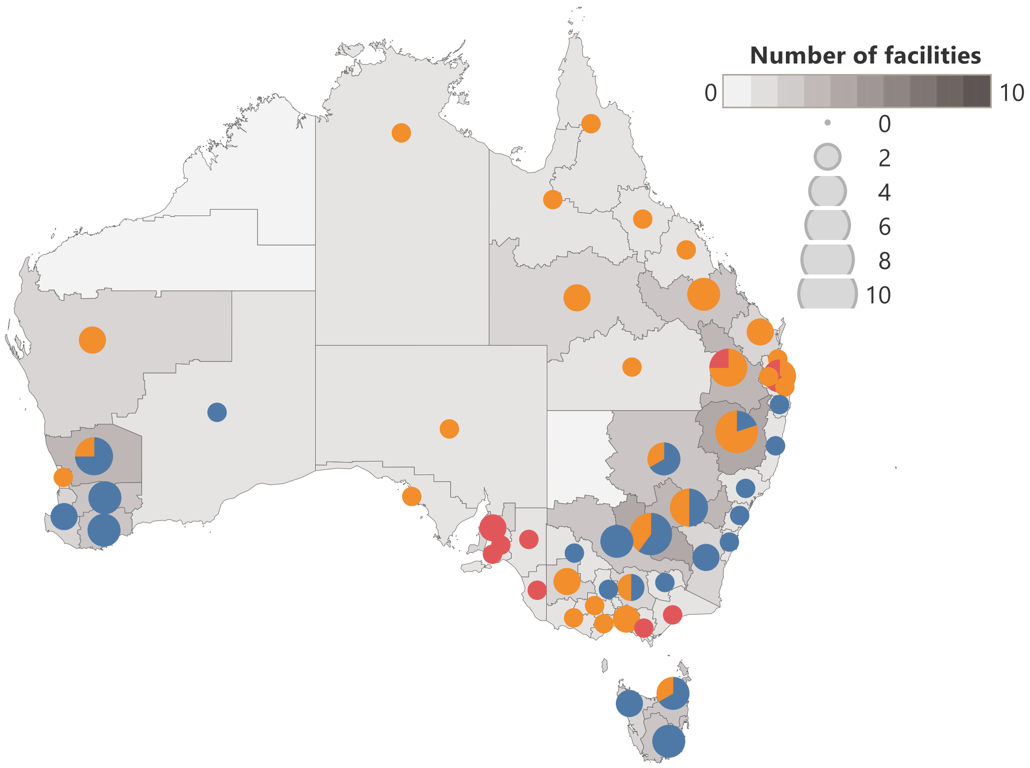
(b) Number of bioenergy conversion facilities in E+, 2040



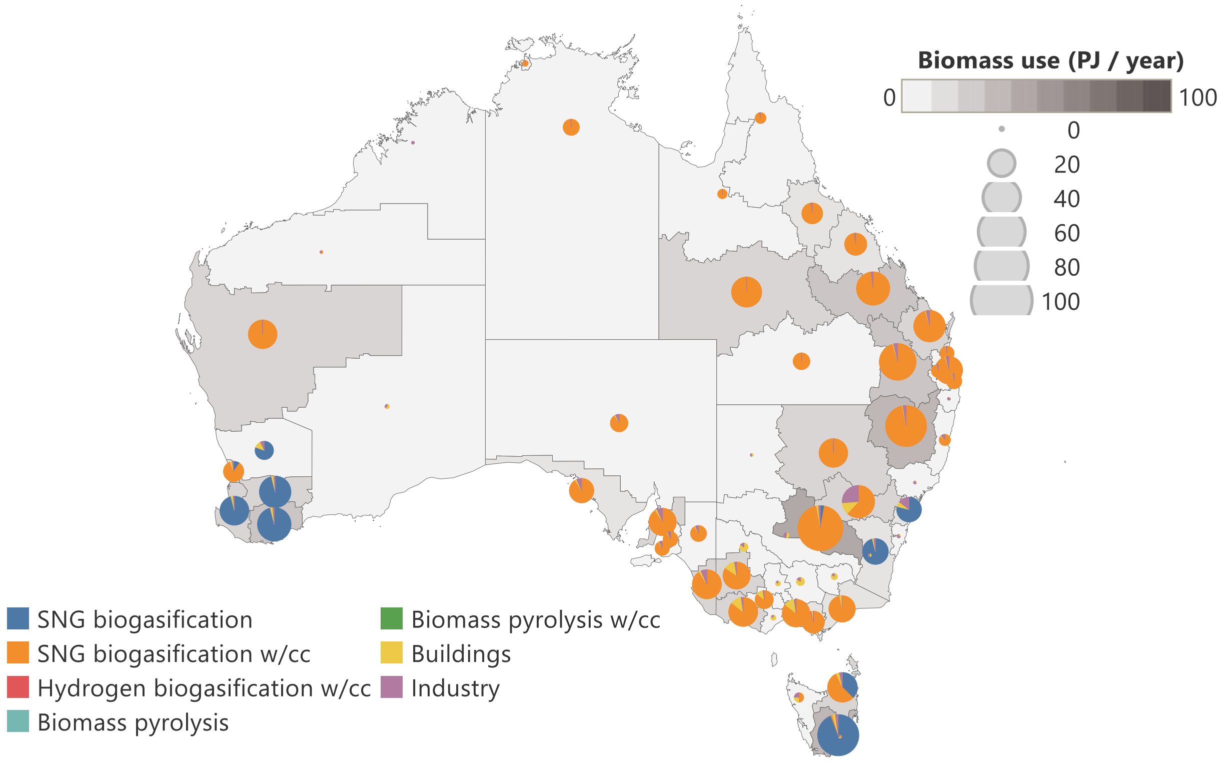
(a) Bioenergy conversion and consumption in E+, 2050



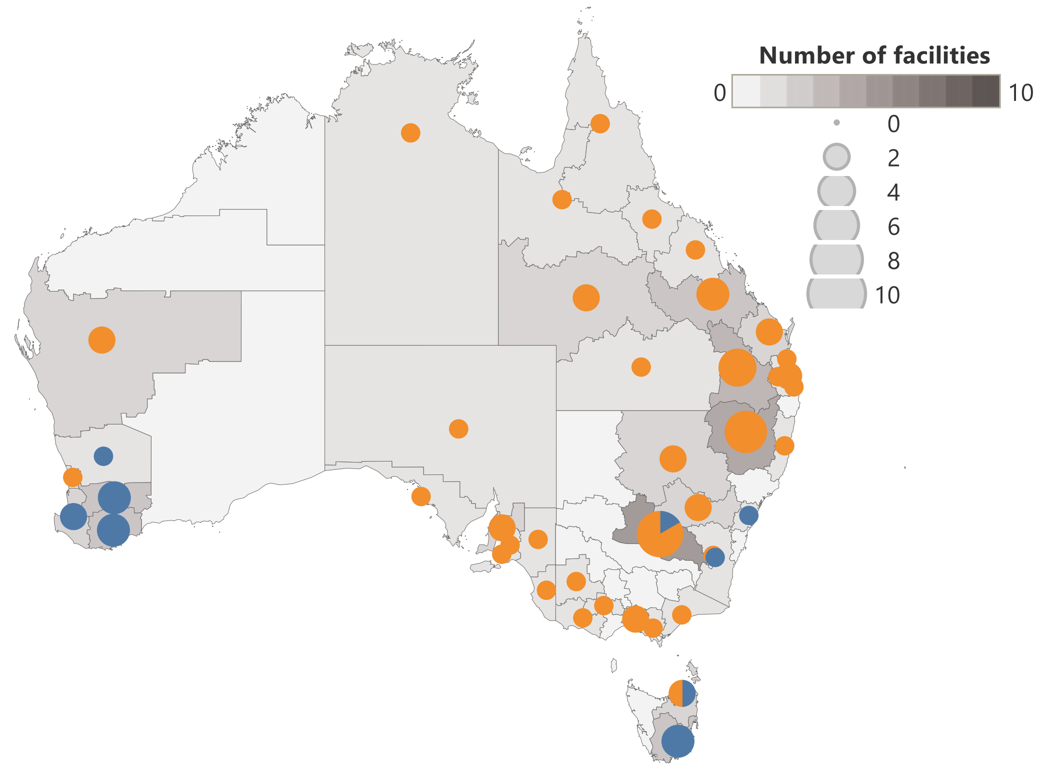
(b) Number of bioenergy conversion facilities in E+, 2050



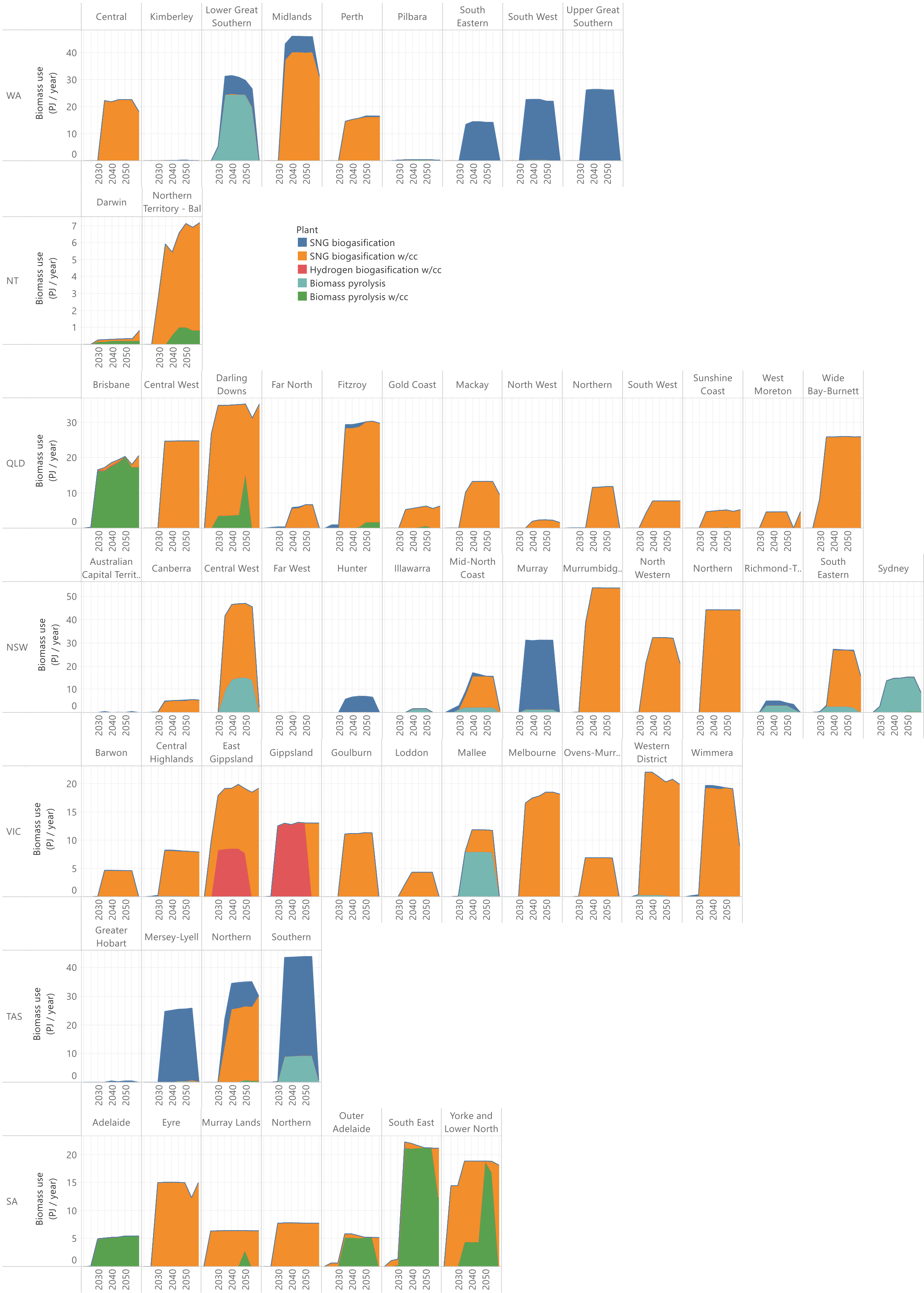
(a) Bioenergy conversion and consumption in E+, 2060



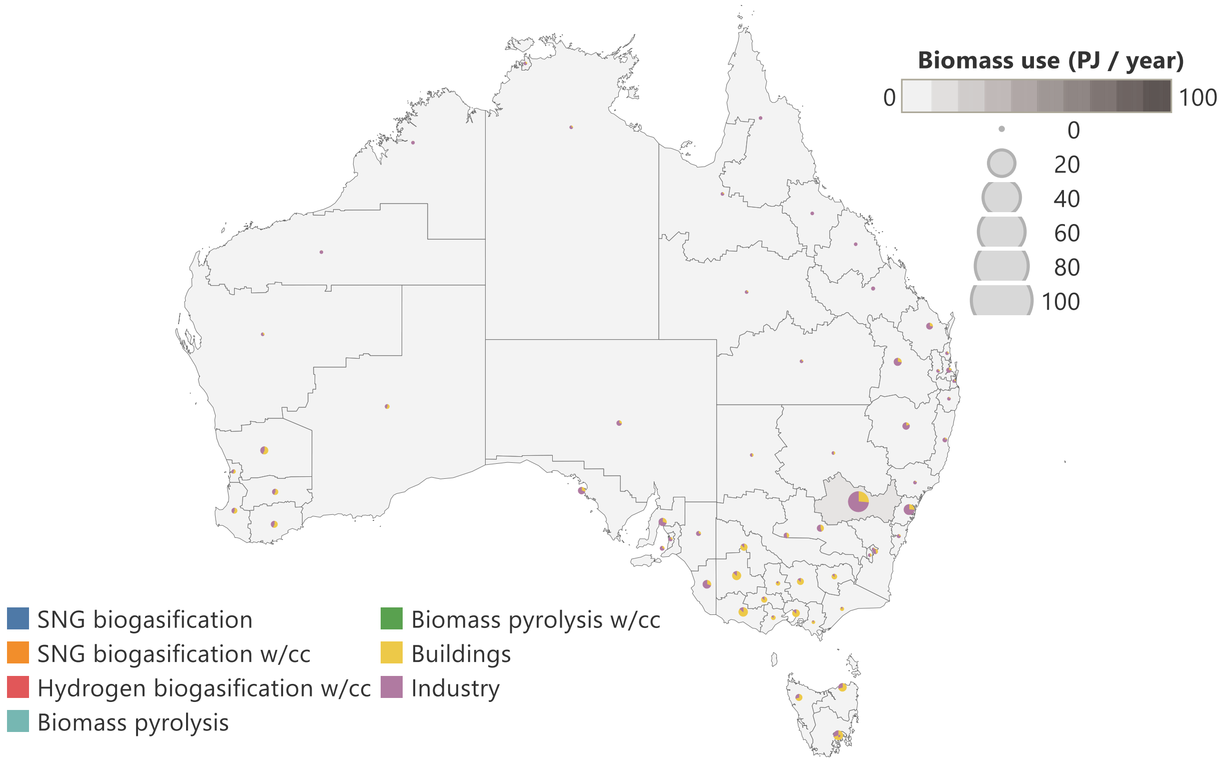
(b) Number of bioenergy conversion facilities in E+, 2060



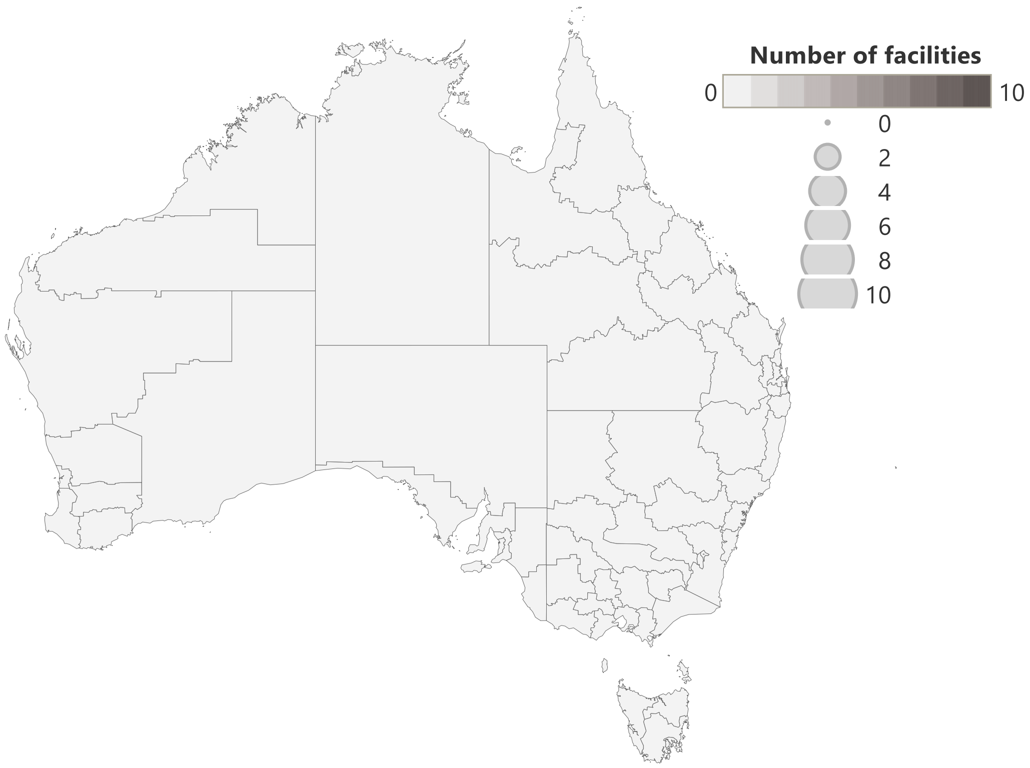
Appendix D Geospatial evolution of bioconversion facilities: E–



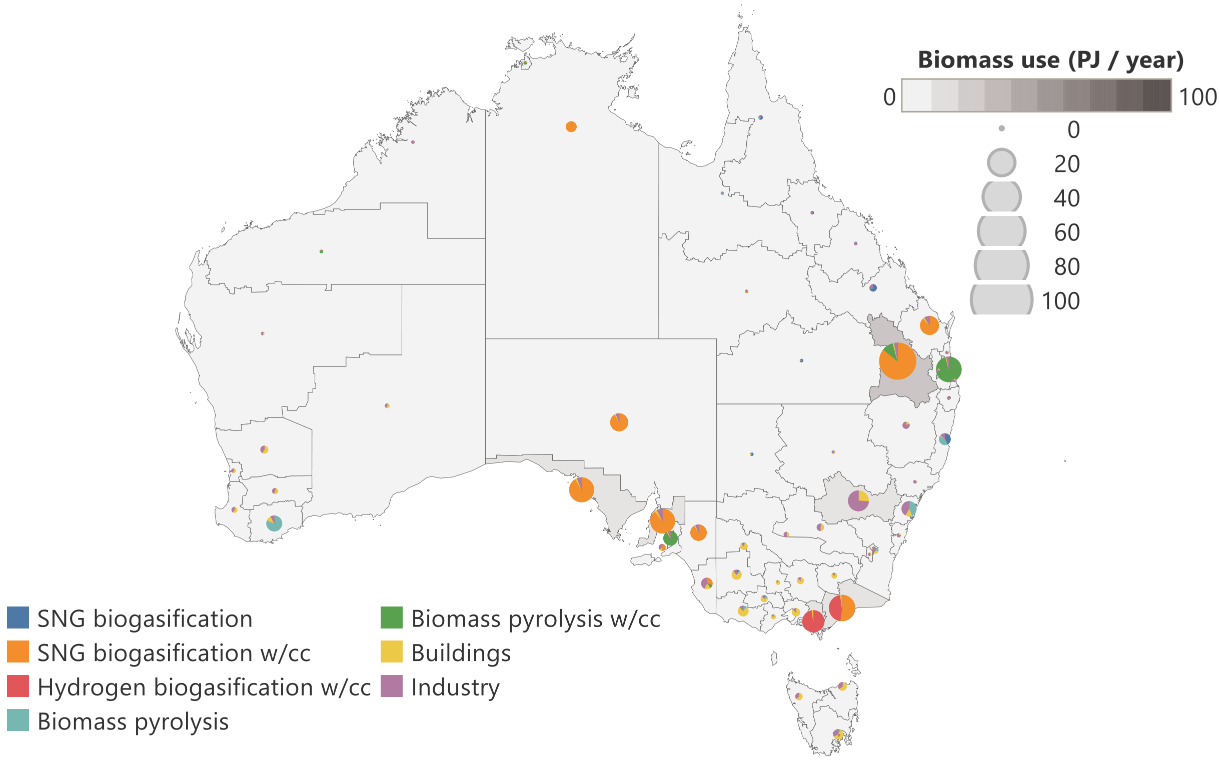
(a) Bioenergy conversion and consumption in E−, 2020



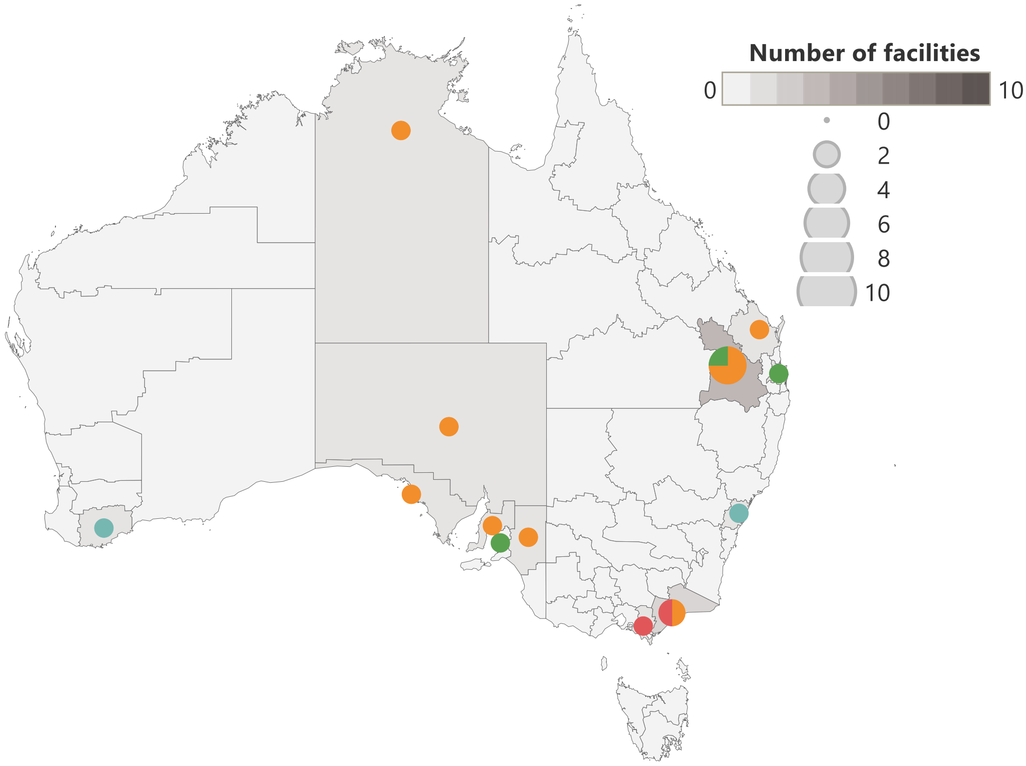
(b) Number of bioenergy conversion facilities in E−, 2020



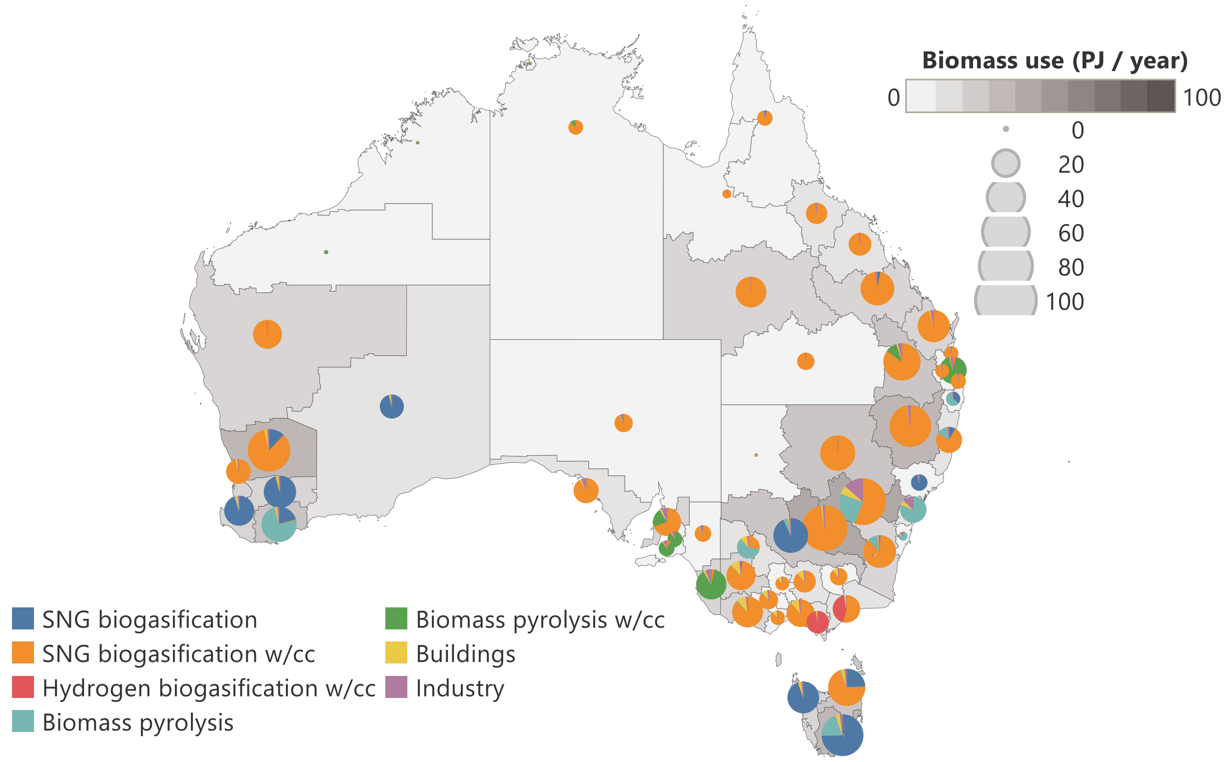
(a) Bioenergy conversion and consumption in E−, 2030



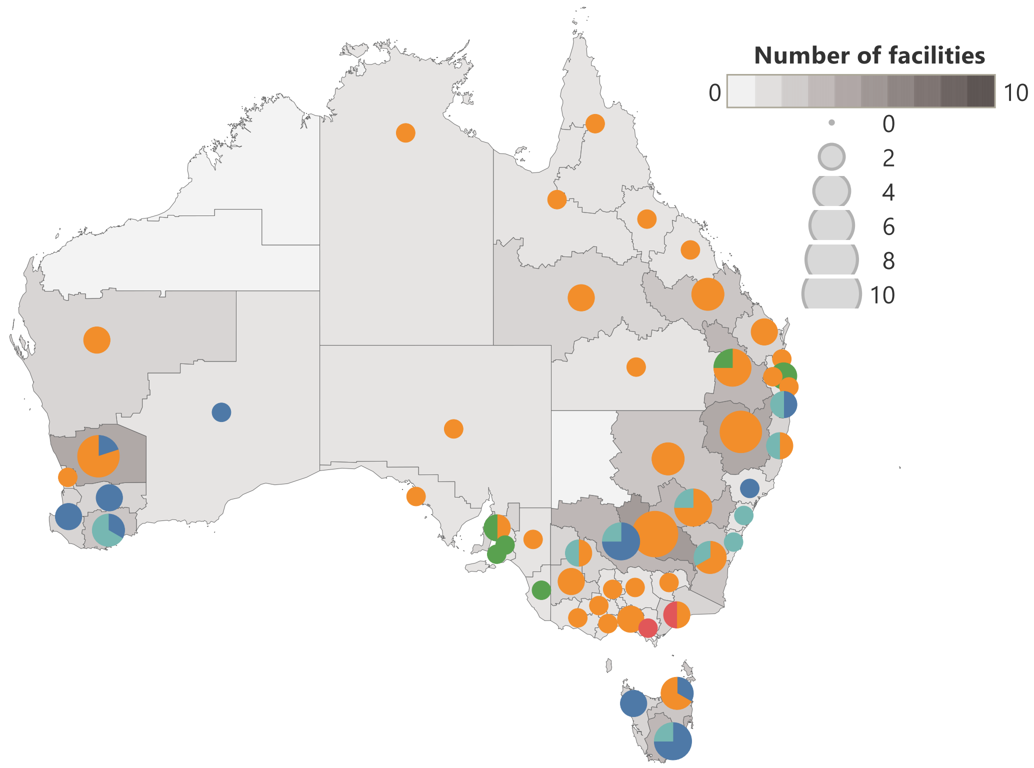
(b) Number of bioenergy conversion facilities in E−, 2030



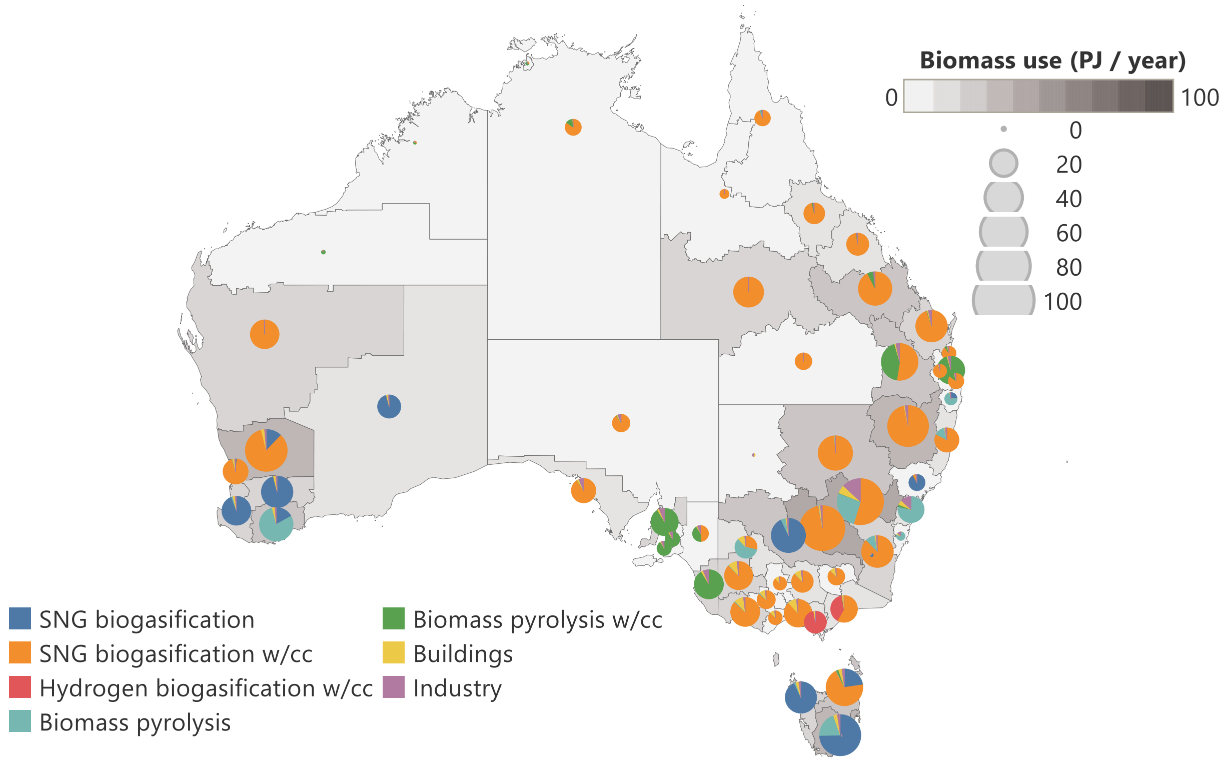
(a) Bioenergy conversion and consumption in E−, 2040



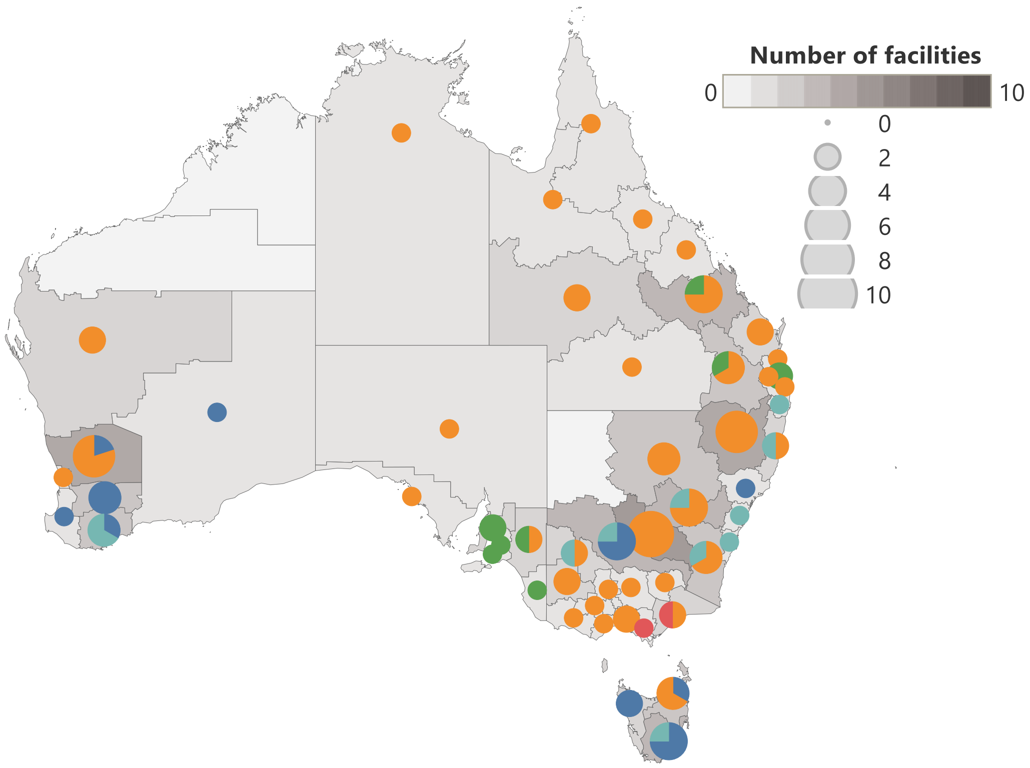
(b) Number of bioenergy conversion facilities in E−, 2040



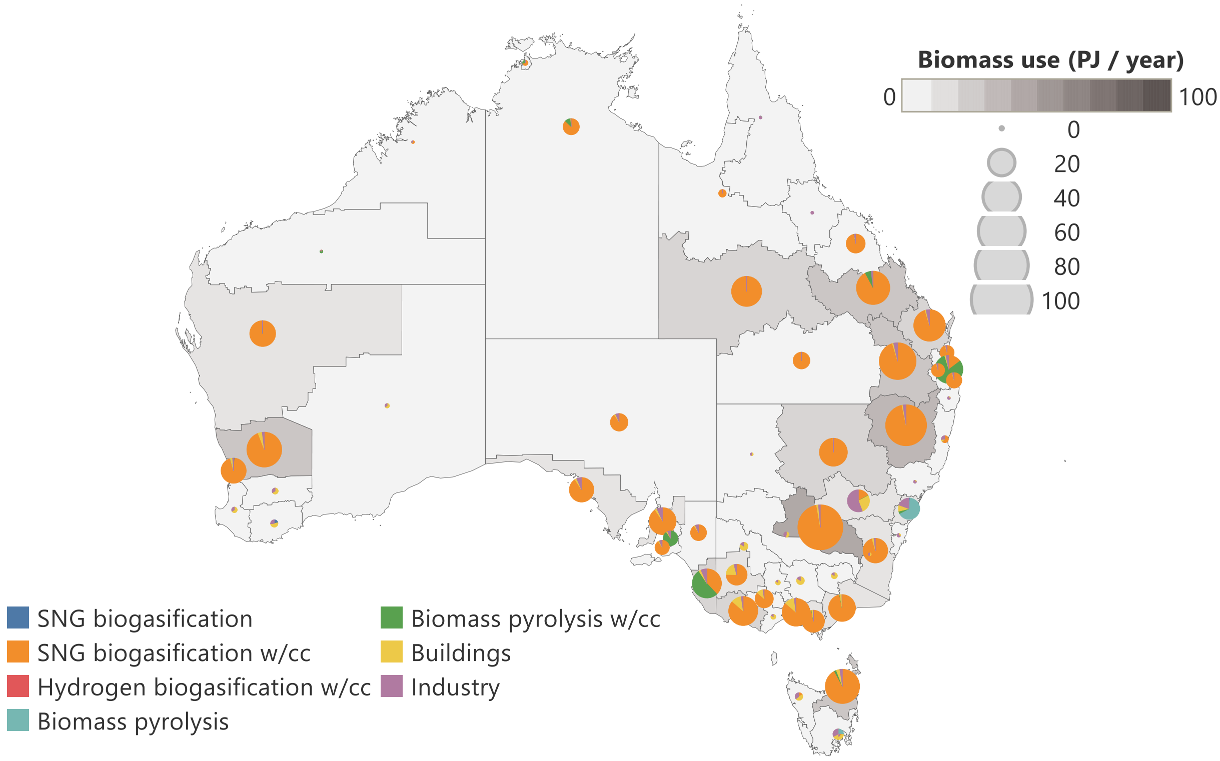
(a) Bioenergy conversion and consumption in E−, 2050



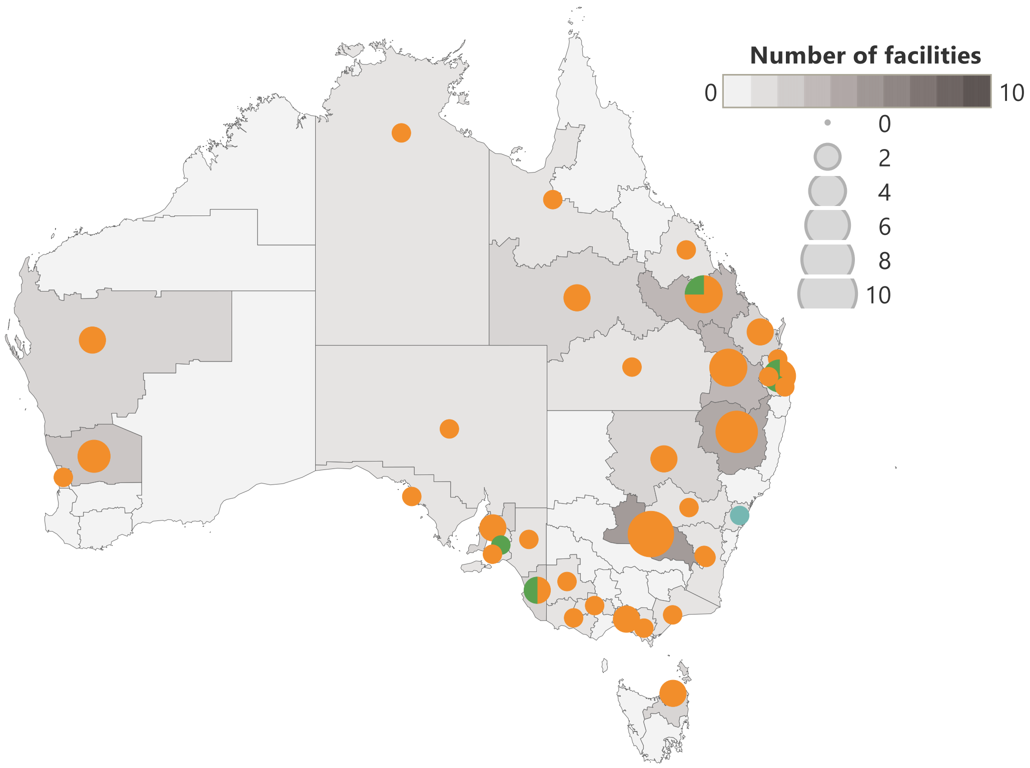
(b) Number of bioenergy conversion facilities in E−, 2050



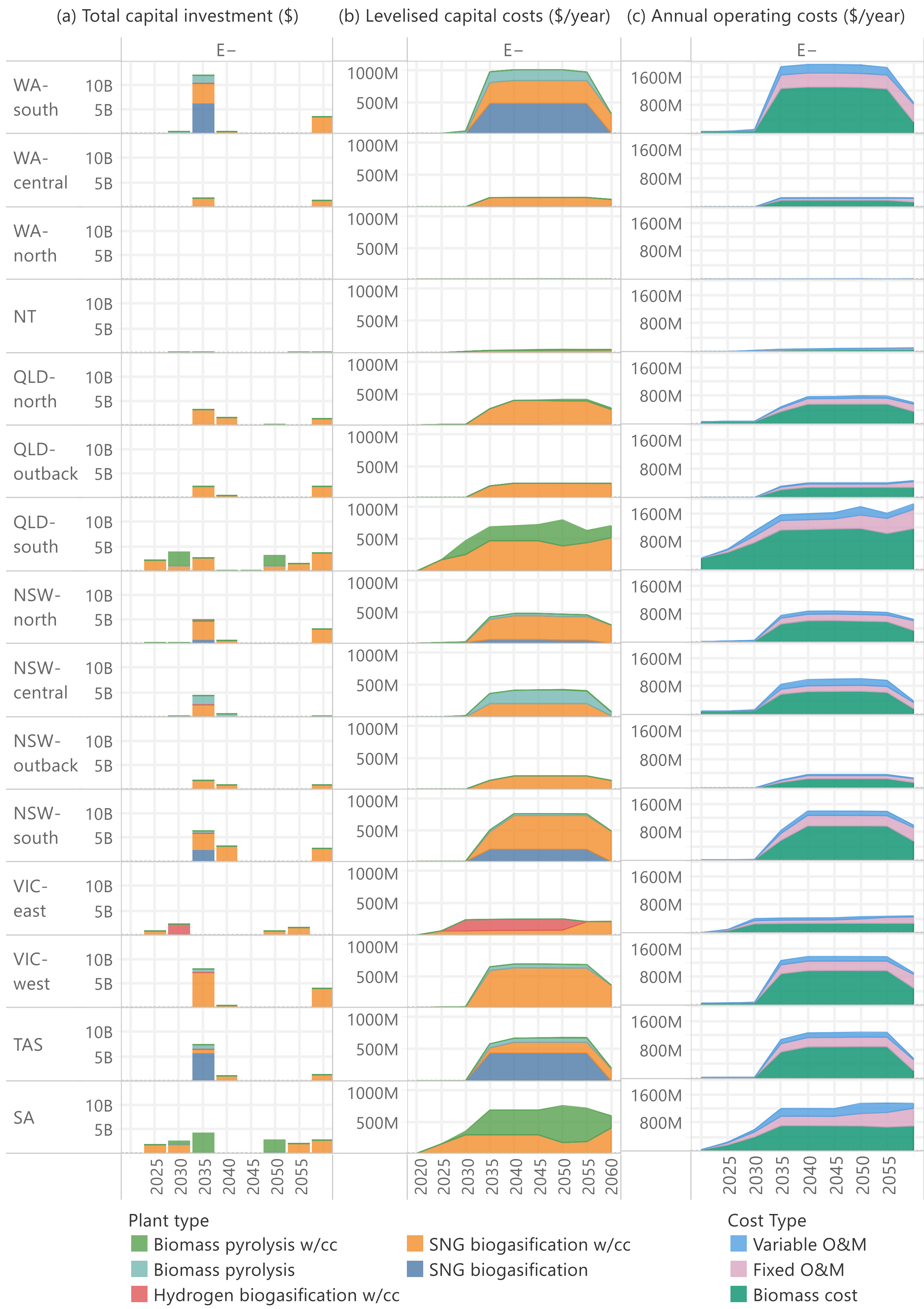
(a) Bioenergy conversion and consumption in E−, 2060



(b) Number of bioenergy conversion facilities in E−, 2060



Appendix E Investment cost by NZAu zone


(a) Total capital investment ($)
(b) Levelised capital costs ($/year)
(c) Annual operating costs ($/year)
E–
WA-south
WA-central
WA-north
NT
QLD-north
QLD-outback
QLD-south
NSW-north
NSW-central
NSW-outback
NSW-south
VIC-east
VIC-west
TAS
SA
10B
5B
1000M
500M
1600M
800M
2025 2030 2035 2040 2045 2050 2055
2020 2025 2030 2035 2040 2045 2050 2055 2060
Plant type
Biomass pyrolysis w/cc
Biomass pyrolysis
Hydrogen biogasification w/cc
SNG biogasification w/cc
SNG biogasification
Cost Type
Variable O&M
Fixed O&M
Biomass cost

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