Downscaling – Fossil fuel industries

19 April 2023

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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.

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Net Zero Australia

Downscaling – Fossil Fuel Industries

Scenarios considered: E+, E−, E+ RE+, E+ RE−

19 April 2023

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1 Context and scope

1.1 Introduction

This document explores the net-zero transition for fossil fuel (FF) industries modelled by the Net Zero Australia (NZAu) Project, as well as the effect that such a transition may have on the industrial sectors heavily reliant on fossil fuels. Themes covered include the evolution of FF demand across both domestic Australian consumption and exports, as compared to historical trends, together with the effect on this evolution on commodity import and export. Additionally, we consider the depletion of total demonstrated resources at FF extraction basins and evaluate the future change in use of extraction sites that are currently in operation.

Fossil fuels accounted for about 92% of the primary energy production in Australia in 2020 [1]. Overall, 21.9 EJ of primary energy from fossil fuels was supplied to Australian consumers and exporters, including imports of 2.1 EJ of refined fossil fuels and 0.4 EJ of crude oil. About 5.2 EJ of this energy served domestic demand and 16.7 EJ was exported [2]. These domestically extracted fuels are primarily coal and natural gas and are extracted from several sites across Australia. Also, the mining sector alone was responsible for 19 Mt CO_2-e of GHG emission in 2020 [3], with an additional 50 Mt CO_2-e (10% of the total country emissions [4]) of fugitive GHG emissions associated with fossil fuel extraction. The net-zero transition will entail the repurposing/retrofit of some existing extraction sites, the early phase out of others, in addition to a rapid transition from fossil fuels to alternative energy sources in several different industries. Besides the rapid shift from fossil fuel use in the power generation sector in favour of renewable projects, the unabated use of fossil fuels will cease also across heavy industries like iron and aluminium production, glass and cement.

1.2 Scope of this document

This document describes the background, methodology and outcomes of downscaling the NZAu Project's modelling of fossil fuel industries. More specifically, the following are characterised and discussed:

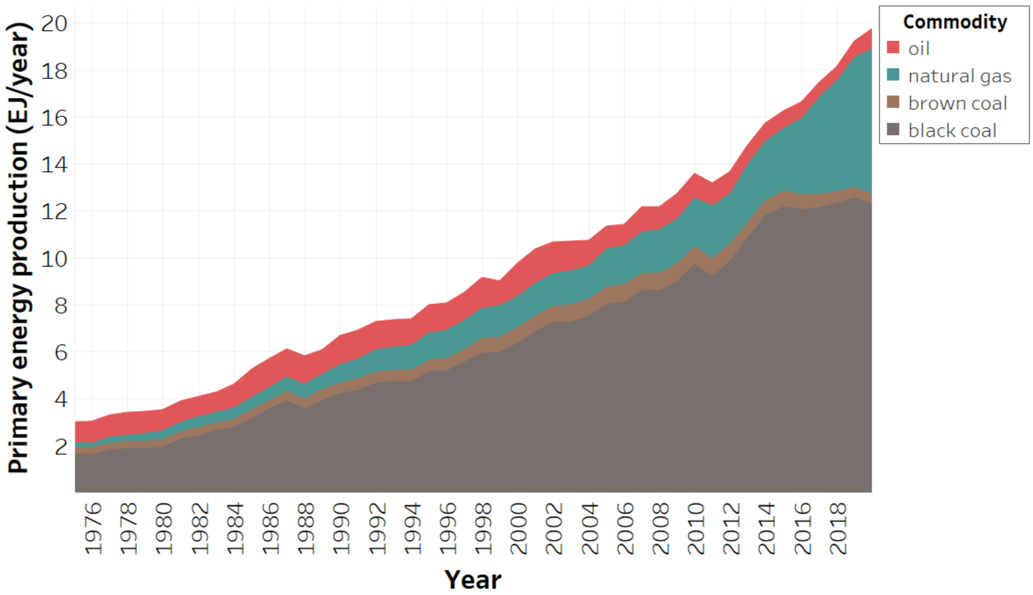
- the evolution over time of fossil fuel demand and associated resources at the extraction basins currently operating across Australia;
- the scheduling of new-build infrastructure and retirements of fossil fuel extraction facilities, particularly brown and black coal mines; and
- the analysis of import and export flows of oil and other oil derivatives between 2020 and 2060, with a focus on Australia's two remaining oil refineries in Geelong and Lytton.

Fossil fuel commodities considered in this document have been grouped into *coal* (black and brown, with the former including thermal coal and metallurgical coal), *natural gas* (conventional gas or coal seam gas) as well as *oil* and *refined fossil fuels* (which include diesel, petrol and aviation fuels). The discussion is limited to the *upstream and midstream* fossil fuel supply chain (i.e. prior to the final use in power plants and other downstream processes) and encompasses the extraction of fossil fuels for both domestic and export use, their refining and domestic distribution. Detailed discussion of the downstream utilisation processes of fossil fuels can be found in the companion downscaling reports *Downscaling - Firm generation & pumped hydro energy storage*, and *Downscaling - Buildings, rooftop photovoltaics and batteries*, while in-depth study of liquefied natural gas (LNG) flows and facilities is tackled in the companion *Downscaling - Energy export systems* report.

2 Background: fossil fuel industries in Australia

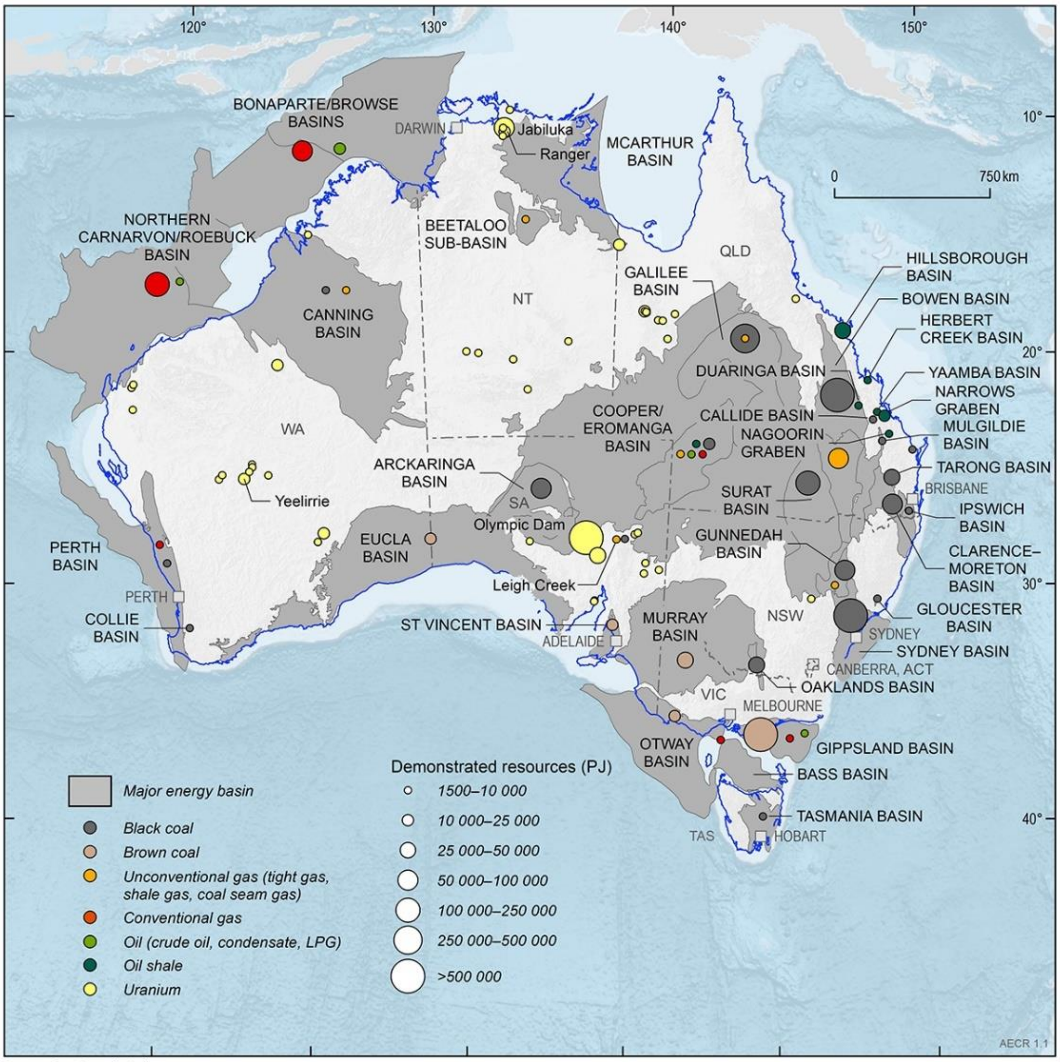
Figure 1 shows the historical production of fossil fuels in Australia, which has experienced significant growth over the last decade, particularly in the production of natural gas.

Figure 1 | Historical trend of primary energy production from the major fossil fuel commodities in Australia; data from [5].



Fossil fuel reservoirs are commonly characterised as *reserves* and *resources*. Adopting the definitions of Geoscience Australia [6], reserves identify quantities that are known to exist and are commercially viable; resources are sometimes further subdivided into as 'contingent' or 'sub-economic' and refer to quantities that have been identified but whose extraction is currently not viable or economic. Total demonstrated resources (TDR) is sum of reserves and resources. Figure 2 maps the main fossil fuel basins in Australia, showing vast and widely spread resources across the country.

Figure 2 | Fossil fuel basins across Australia; data from Geoscience Australia [6].



Source: Geoscience Australia.
Note: LPG = liquefied petroleum gas. PJ = Petajoules.

The TDR for individual commodities as of 2020 is reported in Table 1. The evolution of this TDR will be influenced by the prevailing pathways for domestic and international decarbonisation and the extent to which fossil fuels play a role in that pathway.

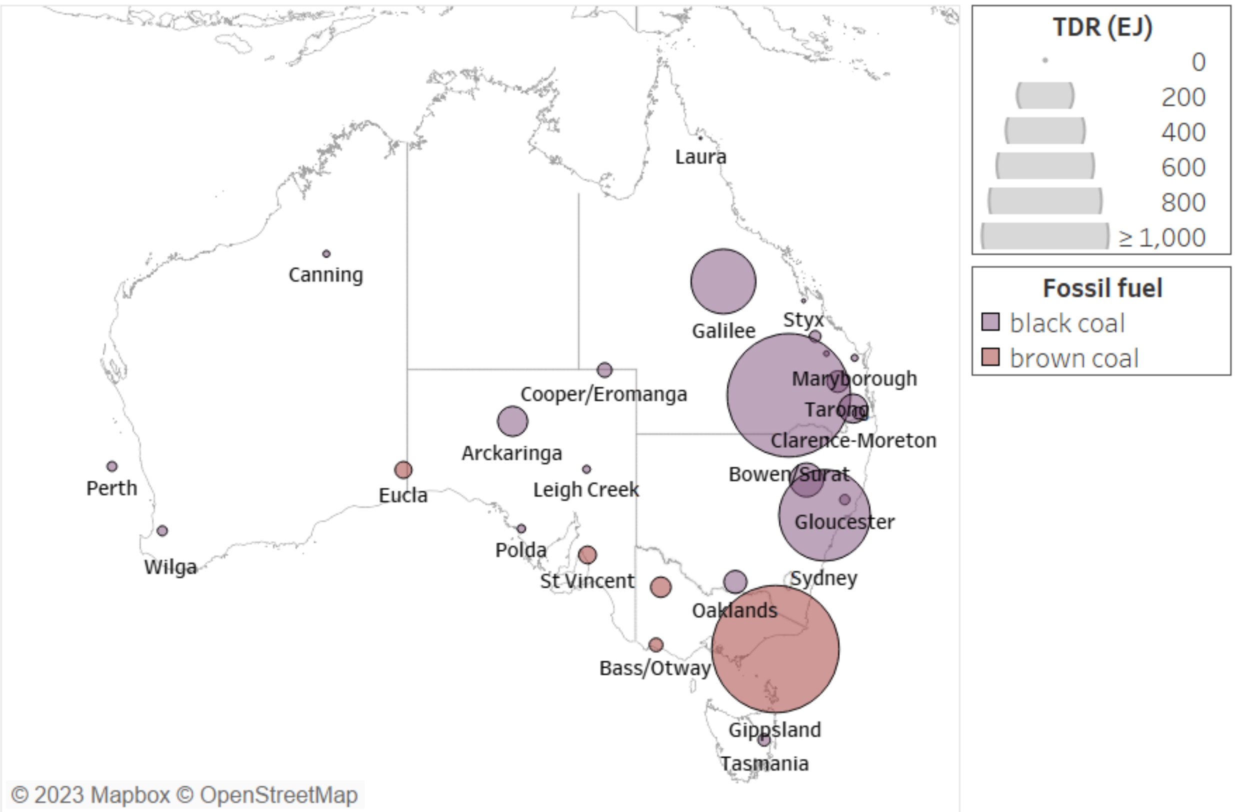
Table 1 | Fossil fuel energy commodity reserves and resources in Australian basins as of 2020.

Commodity	Reserves [EJ]	Contingent resources [EJ]	TDR [EJ]
Conventional natural gas	72.1	120.2	192.3
Coal seam gas	29.0	26.2	55.2
Crude oil	1.8	3.4	5.2
Condensate	6.8	8.7	15.5
LPG	0.8	0.5	1.3
Black coal	1924.2	97.3	2021.5
Brown coal	730.7	2517.2	3247.9

2.1 Black and brown coal

In 2019, Australia accounted for 6% of the black and the brown coal production worldwide, being the fifth largest producer of black and the seventh of brown coal. Australia's coal resources are illustrated in Figure 3; the main coal reservoirs being the Gippsland basin (in Victoria) for brown coal and the Bowen basin (in Queensland) and the Sydney basin (in New South Wales) for black coal. Approximately 90% of coal produced in Queensland and 73% in New South Wales is exported [5]. While black coal is currently both used domestically and exported, brown coal is exclusively used domestically for coal-fired power generation in Victoria.

Figure 3 | Australian coal basins location and associated total demonstrated resources as of 2020.



2020 registered a contraction in the consumption for both black (-2.2%) and brown (-4.4%) coal relative to the previous year, which is an ongoing trend over the last years [6]. With 2020 black and brown coal consumption, the present TDR would ensure 164 years of future black coal availability and more than 7000 years of brown coal. The reserves and resources of each coal basin in Australia are reported in Table 2 and Table 3.

Table 2 | Black coal Australian resources as of 2020; data from Geoscience Australia [6].

Basin name	NZAu region	Reserves [EJ]	Resources [EJ]	TDR [EJ]
Arckaringa	SA	10.6	44.7	55.3
Ashford	NSW-north	0.0	0.2	0.2
Bowen/Surat	QLD-south	750.5	3.5	754.0
Callide	QLD-south	8.0	0.0	8.0
Canning	WA-north	2.7	0.0	2.7
Clarence-Moreton	QLD-south	51.3	0.4	51.7
Collie	WA-south	5.8	0.0	5.8
Cooper/Eromanga	SA	12.5	0.0	12.5
Galilee	QLD-north	253.7	3.9	257.6
Gloucester	NSW-north	6.1	0.0	6.1
Gunnedah	NSW-north	50.5	19.3	69.8
Ipswich	QLD-south	0.0	8.5	8.5
Laura	QLD-north	0.5	0.0	0.5
Leigh Creek	SA	1.7	2.0	3.7
Maryborough	QLD-south	2.1	0.7	2.8
Mulgildie	QLD-south	1.8	0.0	1.8
Oaklands	NSW-south	32.1	0.0	32.1
Perth	WA-south	2.3	3.2	5.5
Polda	SA	0.0	4.2	4.2
Styx	QLD-north	0.9	0.0	0.9
Bowen/Surat	QLD-south	185.1	0.0	185.1
Sydney	NSW-central	508.9	6.7	515.6
Tarong	QLD-south	28.2	0.0	28.2
Tasmania	TAS	9.1	0.1	9.2
Wilga	WA-south	0.0	0.0	0.0

Table 3 | Brown coal Australian resources as of 2020; data from Geoscience Australia [6].

Basin name	NZAu region	Reserves [EJ]	Resources [EJ]	TDR [EJ]
Eucla	WA-south	10.1	7.2	17.3
Gippsland	VIC-east	717.7	2457.6	3175.3
Murray	VIC-west	0.0	25.3	25.3
Bass/Otway	VIC-west	2.8	8.3	11.1
St Vincent	SA	0.0	18.9	18.9

2.2 Natural gas

Australia is among the largest natural gas producers and LNG exporters in the world. Australia's substantial conventional gas reserves (72 EJ, plus 120 EJ contingent resources) are mainly located in the Northern Carnarvon, Browse and Bonaparte basins, all of which are in the North-West of the country. Conventional gas reserves are also found in the Gippsland and the Otway basins (in Victoria), the Cooper/Eromanga (in South Australia) and the Perth basins (in Western Australia). Coal seam gas (CSG) is also extracted from shallow coal seems mainly from the Bowen/Surat basin in Queensland, with an additional 55 EJ of TDR (29 EJ, plus 26 EJ contingent resources). Australian gas basins are depicted in Figure 4.

Figure 4 | Australian natural gas basins location and associated total demonstrated resources as of 2020.

Natural gas extraction serves both domestic natural gas demand and export demand, mainly via LNG shipping, with both experiencing a positive average annual growth in the last decade. At current rates of extraction, 42 and 35 years of residual TDR availability have been estimated, respectively, for conventional natural gas and CSG [6].

Fossil fuel extraction reserves were not included among the modelling constraints of the Regional Investment and Operations (RIO) optimisation platform but are here evaluated by the NZAu Project within this downscaling task. The reserves and resources of Australia's natural gas basins, divided between conventional gas and CSG, are reported in Table 4 and Table 5.

Table 4 | Conventional natural gas Australian resources as of 2020; data from Geoscience Australia [6].

Basin name	NZAu region	Reserves [EJ]	Resources [EJ]	TDR [EJ]
Adavale	QLD-north	0.0	0.0	0.0
Amadeus	NT	0.2	0.3	0.5
Bass/Otway	VIC-west	1.0	0.7	1.7
Bonaparte/Browse	NT	16.2	56.7	72.8
Bowen/Surat	QLD-south	0.3	0.1	0.4
Canning	WA-north	0.0	0.0	0.0
Northern Carnarvon/Roebuck	WA-north	49.5	57.0	106.5
Cooper/Eromanga	SA	1.1	1.6	2.7
Galilee	QLD-north	0.0	0.2	0.2
Gippsland	VIC-east	2.4	3.0	5.4
Gunnedah	NSW-north	0.0	0.0	0.0
McArthur	NT	0.0	0.0	0.0
Perth	WA-south	1.5	0.6	2.1

Table 5 | Coal seam gas Australian resources as of 2020; data from Geoscience Australia [6].

Basin name	NZAu region	Reserves [EJ]	Resources [EJ]	TDR [EJ]
Bowen/Surat	QLD-south	28.9	21.2	50.1
Clarence-Moreton	QLD-south	0.0	0.7	0.7
Galilee	QLD-north	0.0	2.6	2.6
Gunnedah	NSW-north	0.0	1.7	1.7
Sydney	NSW-central	0.0	0.0	0.0

2.3 Oil and refined fossil fuels

Alongside coal and natural gas, Australia has some minor oil reserves, as displayed in Figure 5. These are mainly located in Western Australia and the Northern Territory, in the Northern Carnarvon and Browse basins.

Figure 5 | Australian oil basins location and associated total demonstrated resources as of 2020.

Along with oil, other refined products and refinery feedstocks such as liquefied petroleum gas (LPG) account for almost the entirety of Australia's energy imports. These imports are then domestically refined into petrol, diesel, jet fuel and other petroleum products at Lytton and Geelong oil refineries (after the recent closure of Kwinana and Altona), with a combined throughput of 14 billion litres of fuel products per annum [7].

Alongside imports, crude oil and condensate extraction for domestic use grew by 18% in 2020, to 798 PJ. This amounts to 28 years of remaining commodity extraction, based on the small Australian oil reserves by world standards (9.3 EJ, and 12.5 EJ of contingent resources). Oil reserves and resources of Australia are reported in Table 6.

Table 6 | Oil and oil derivatives Australian resources as of 2020; data from Geoscience Australia [6].

Basin name	Commodity	NZAu region	Reserves [PJ]	Resources [PJ]	TDR [PJ]
Amadeus	Crude oil	NT	10	1	12
Bass/Otway	Crude oil	VIC-west	0	40	40
Bonaparte/Browse	Crude oil	NT	189	549	737
Bowen/Surat	Crude oil	QLD-south	11	46	58
Canning	Crude oil	WA-north	21	0	21
Northern Carnarvon/Roebuck	Crude oil	WA-north	1105	1907	3012
Cooper/Eromanga	Crude oil	SA	363	354	717
Gippsland	Crude oil	VIC-east	53	512	566
Perth	Crude oil	WA-south	8	35	44
Amadeus	Condensate	NT	0	0	0
Bass/Otway	Condensate	VIC-west	59	36	94
Bonaparte/Browse	Condensate	NT	3319	5973	9292
Bowen/Surat	Condensate	QLD-south	9	0	9
Canning	Condensate	WA-north	0	0	0
Northern Carnarvon/Roebuck	Condensate	WA-north	3010	2296	5306
Cooper/Eromanga	Condensate	SA	94	123	218
Gippsland	Condensate	VIC-east	298	231	529
Perth	Condensate	WA-south	0	0	0
Amadeus	LPG	NT	0	0	0
Bass/Otway	LPG	VIC-west	75	19	94
Bonaparte/Browse	LPG	NT	168	137	306
Bowen/Surat	LPG	QLD-south	15	0	15
Canning	LPG	WA-north	0	0	0
Northern Carnarvon/Roebuck	LPG	WA-north	0	0	0
Cooper/Eromanga	LPG	SA	92	104	196
Gippsland	LPG	VIC-east	401	196	597
Perth	LPG	WA-south	0	0	0

3 Outputs of RIO to be downscaled

In the NZAu Project, any future fossil fuel production is modelled to be proportional to the current distribution across the country of fossil fuel extraction in order not to exceed the capacity of existing mines and extraction sites [8]. Each fossil fuel was assigned an emissions factor for the CO_2e emissions embodied in a unit of primary energy of that fuel, which accounts for the GHG emissions arising from combustion. In addition, a fugitive emissions factor is used to account for the GHG emissions arising from extraction and conversion activities in the upstream energy supply chain. For natural gas primary commodities, these fugitive emissions factors are modelled to reduce over time assuming a concerted industry effort to mitigate fugitive methane emissions. The values of these parameters are reported in Table 7.

Table 7 | Emission factors [kg-CO_2-e/GJ] for the major fossil fuels in the NZAu modelling [8].

Fossil fuel	Emission factor	Fugitive emissions, 2020	Fugitive emissions, 2030	Fugitive emissions, 2040
Black coal	90.2	2.18		
Brown coal	93.8	0.03		
Coal seam gas	51.6	1.83	0.91	0
Conventional natural gas	51.6	6.06	5.34	4.62
Oil	69.9	-	-	-
Refined fossil fuels	69.9	-	-	-

The projected domestic primary energy supply by source is presented in Figure 6 for the NZAu core scenarios. Both the absolute primary energy and its proportion of the total domestic primary energy supply are shown. In 2020, fossil fuels account for 94% of the domestic primary energy supply. This share diminishes across all scenarios, settling between 0 and 37% by 2060 depending on the scenario. The E− Scenario retains 1.3 EJ of refined fossil fuel supply in 2050, while in the E+RE− Scenario this value is 0.76 EJ. This is the major difference in fossil fuel usage across scenarios and largely due to the slower fuel switching and electrification of the final demand in the transport sector in the E− Scenario [8].

Figure 6 | Australian domestic primary energy, by type.

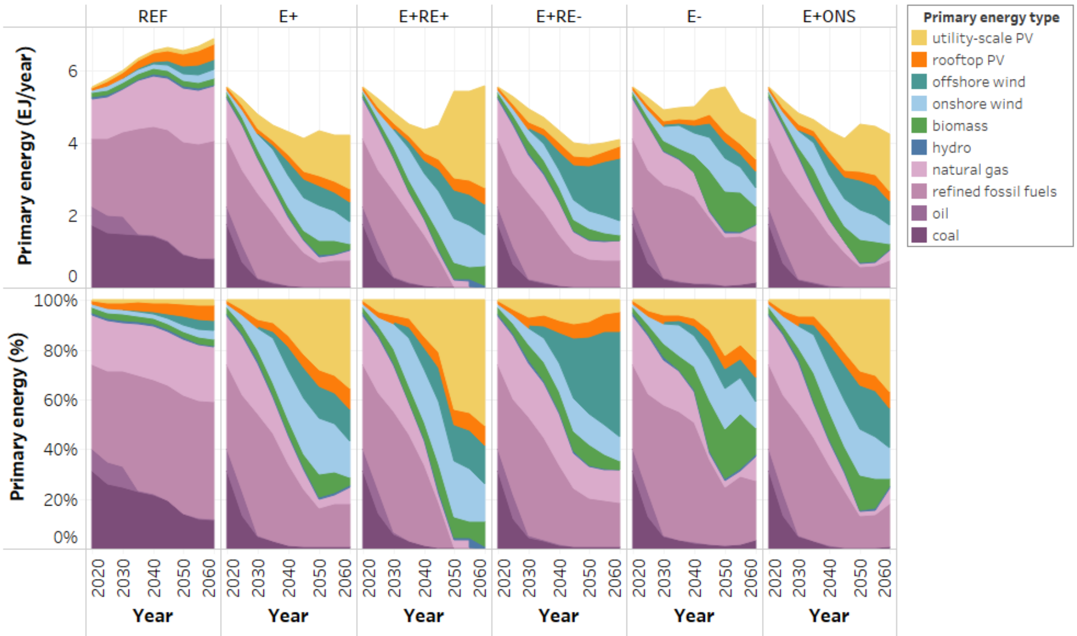
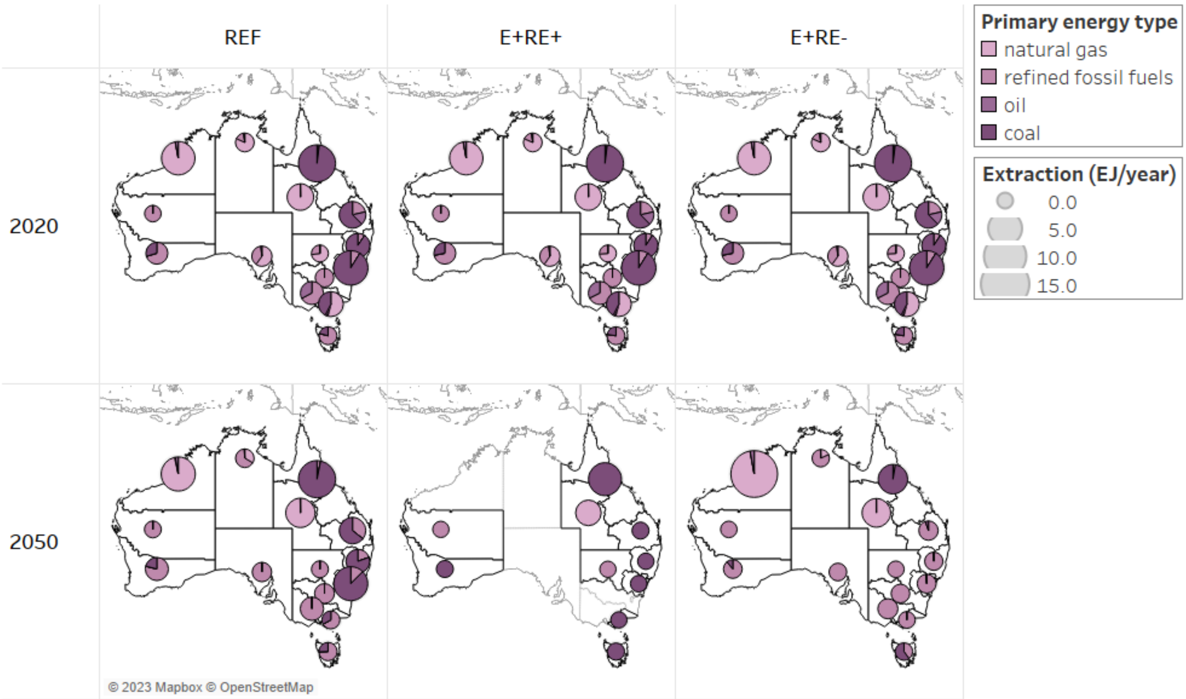


Figure 7 presents the domestic primary fossil fuel supply by the end-use sector supplied. The starkest shifts in fossil fuel supply are evident for coal and oil across all net-zero scenarios. Some natural gas is still supplied in 2050 to serve mainly the industry sector. This is the case even for the E+RE+ Scenario where direct air capture (DAC) and biomass with CCS are used to offset small levels of residual natural gas emissions. The use of refined fossil fuels (mostly aviation fuel, diesel and gasoline) also diminishes in all net-zero scenarios, alleviating to a significant extent Australia's reliance on oil imports.

Figure 7 | Fossil primary energy sources and their supply to domestic end-use sectors in different scenarios.

Figure 8 shows modelled fossil fuel production over time, by NZAu region and for selected Scenarios. Regardless of the scenario, coal currently extracted from the Gippsland, Sydney and Surat basins is modelled to drastically decrease. Despite the overall reduction of fossil fuel use, natural gas production increases in the E+RE− Scenario, with the Northern Carnarvon/Roebuck and Bonaparte basins mostly providing the resource required in this scenario.

Figure 8 | Fossil fuel primary energy extraction/import by region and its evolution over time, by type.



4 Downscaling task

In the NZAu Project, existing Australian fossil fuel extraction facilities and their annual production capacity is regionally allocated to the 15 domestic regions modelled, together with costs for extraction of black coal, brown coal and oil and their evolution over time sourced from the AEMO ISP inputs and WA whole of system plan [8]. The downscaling of fossil fuel industries across NZAu's core scenarios follows these steps:

1. the modelled fossil fuel production over the modelling horizon to 2060 is evaluated and compared with historical trends;
2. the imported and exported fossil fuel flows are evaluated, to characterise the change in the reliance of Australia on certain fossil fuel imports;
3. the progressive depletion of existing fossil fuel basins and their residual TDR is assessed; and
4. early fossil fuel extraction infrastructure retirements, as well as any new build requirements are analysed and scheduled in the period 2020-2060.

4.1 Fossil fuel production by type

Results from RIO from 2020 onwards were compared with the documented historical data from the Australian Energy Statistics up to year 2020. The analysis was aggregated nationally for all the fossil fuel production and without differentiating between downstream domestic or export use. Average decadal variations in extraction volumes by commodity were computed and the analysis was carried out for all the scenarios.

4.2 Imported and exported oil and refined fossil fuels

Trends in imports and exports of oil and refined fossil fuels, were examined and compared with historical data. The current proportions of domestic production and imports for liquid fossil fuels are evaluated, along with their evolution over time, as the net-zero transition unfolds. The share of products from oil refineries was also characterised to track the supply chain and the use of oil derivatives across scenarios. Exports of coal are the modelled transition to hydrogen-derivative exports are detailed elsewhere in the companion downscaling report *Downscaling - Energy export systems*.

4.3 Depletion of basins and the residual TDR

The modelled production of fossil fuels was downscaled to individual fossil fuels basins by first associating each fossil fuel basin with one of the 15 NZAu domestic regions, based on their location, and with its reported TDR from Geoscience Australia [6]. An optimisation was developed to allocate the modelled consumption of fossil fuels in each NZAu domestic region to individual fossil fuel basins, using a proximity-based criterion. This optimisation ensured the closest basins to the region of modelled fossil fuel consumption were exploited first. Then, should there be no resource availability, commodities could be extracted from progressively farther regions, until the modelled consumption is fully allocated. Based on the downscaled production flows from each basin, TDR evolution over time and by scenario was then evaluated starting from 2020 TDR values, including reserves and resources, and assuming no future resource exploration. This optimisation problem formulation is presented in the Appendix. Results from such analysis are only reported for natural gas and oil, since resource availability for both black and brown coal are much larger than their modelled consumption in all scenarios, as presented in Section 2.1. The E+RE+ and E+RE−

scenarios were considered as a focus, aggregating in both cases primary energy production to serve both domestic and export energy demand.

4.4 Analysis of infrastructure retirements

The modelled retirement and any new installation of fossil fuel production and conversion assets was downscaled to individual sites and basins. In RIO, a single capital cost was used for extraction facilities of various types, with no difference between existing and new assets. Similarly, technical parameters of fossil fuel production efficiency (parasitic energy consumption of a fossil fuel production/conversion facility) were the same for same type of fossil fuel extraction and conversion assets (see Table A.1 in the Appendix). To work out a retirement schedule for extraction assets, priority was given to closing smaller assets first, as the smallest extraction capacity is likely to coincide with the highest running costs.

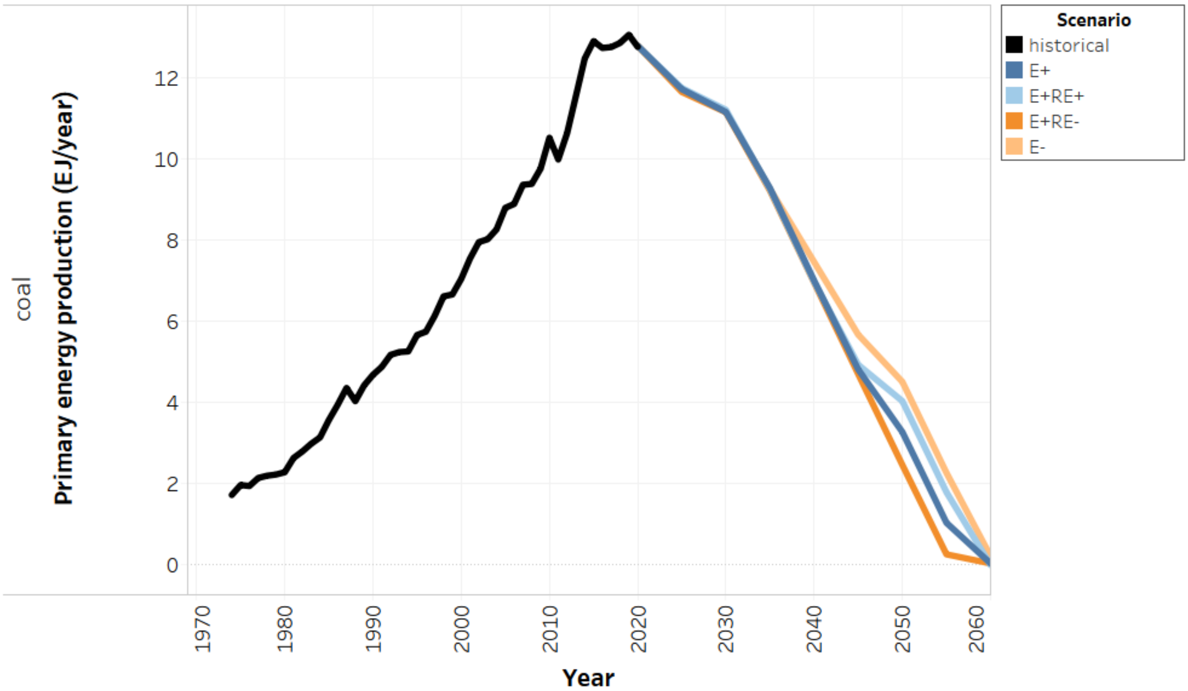
The retirement of black and brown coal extraction assets was then assigned to individual existing sites. The analysis was carried out by NZAu region for natural gas extraction facilities using the aggregated capacity therein, since information on the capacity of the individual extraction facilities was not available. The retirement of oil refineries was analysed for the plants at Geelong and Lytton.

5 Results

5.1 Black and brown coal extraction

Figure 11 compares the historical and modelled future trends of primary production of coal. This data aggregates production of black and brown coal for both domestic and export sectors. We find that the reduction in coal production is on average 163 PJ/year in the first 10 years of the transition, further escalating to average reductions of 426 PJ/year in the second decade. This greater rate of reduction after 2030 corresponds to the application of the project's export emissions constraint. No significant difference is registered across scenarios since coal use has the highest emissions intensity.

Figure 9 | Historical and modelled future trends in the primary energy production of black and brown coal.

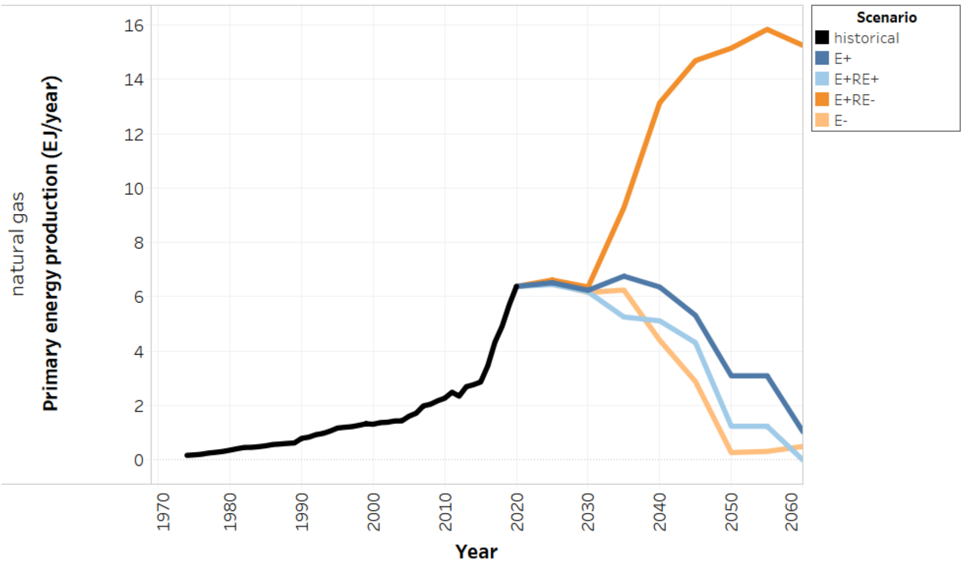


5.2 Natural gas extraction

Figure 10 compares the historical and the modelled future trends in the primary production of natural gas. In the last decade, historical gas extraction for domestic use and exports has increased, on average, by 410 PJ per annum, mainly as a result of the rapid expansion of the liquefied natural gas export industry. However, all modelled net-zero scenarios project a significant change to this trend, with no further expansion of natural gas production between 2020 and 2030. Past 2030, natural gas production is reduced for most net-zero scenarios, with the exception being the constrained renewables E+RE− scenario with its dramatic growth in the use of CCS for blue hydrogen production for export.

Natural gas production consistently diminishes after 2035 for the E+, E− and E+RE+ Scenarios. However, some residual natural gas demand is still observed in 2050 and 2060, which is compensated under the net-zero emissions constraints with atmospheric CO_2 removals via DAC, BECCS or other carbon offset mechanisms. The E+RE− Scenario shows a distinct increase in the production of natural gas, which by 2050 reaches more than 15 EJ/year, a value that is comparable with current levels of coal production. This stark expansion of natural gas production in the E+RE− Scenario results in a faster depletion of domestic gas reserves and the need for increased extraction capacity, as further discussed in Section 5.5 and Section 5.6 of this document.

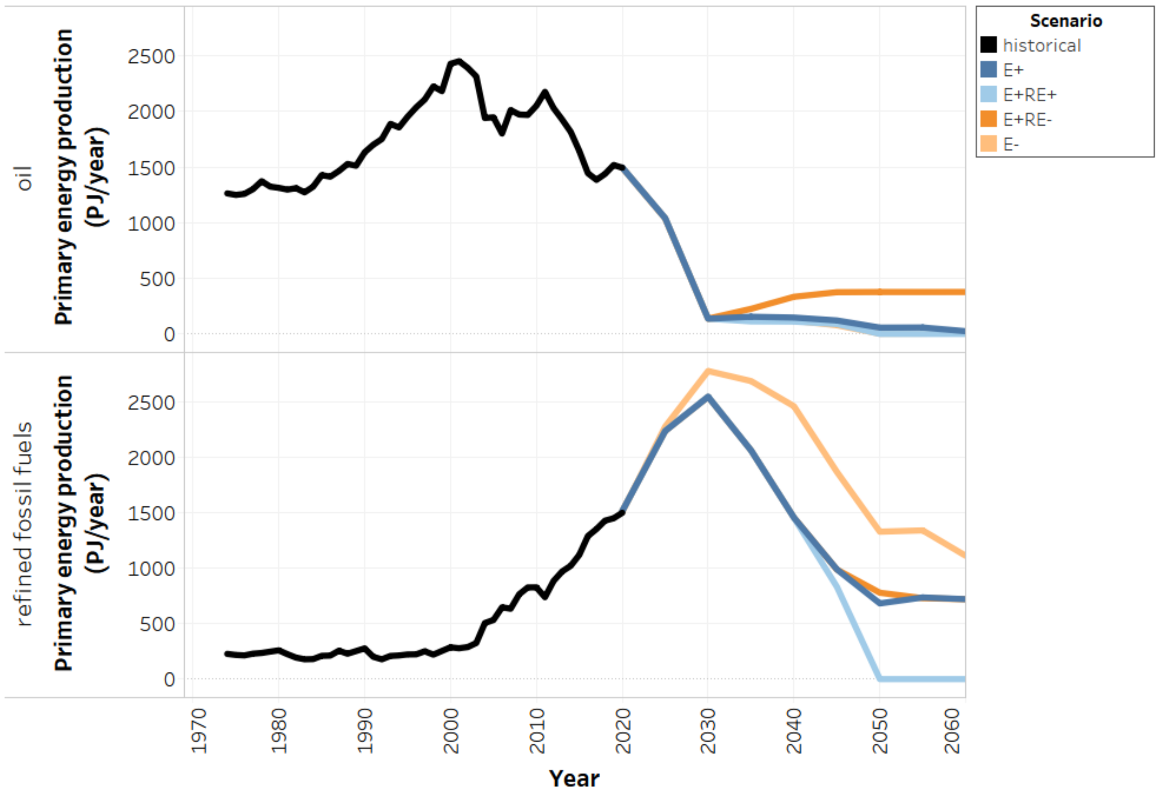
Figure 10 | Historical and modelled future trends in the primary energy production of natural gas.



5.3 Oil extraction and refined fossil fuels

Figure 11 compares the historical and modelled future trends in the primary energy production and import of oil and refined fossil fuels. Driven by fuel switching in industry and the transport sectors, as well as the adoption of a progressively more fossil-free vehicle fleet, the domestic demand for oil decreases significantly across all scenarios. The trend follows a reduction of ~90 PJ/year in the first decade – more than twice the historical average decrease of 39 PJ/year from 2000 to 2020. On the other hand, the demand for refined fossil fuels initially increases, by ~100 PJ/year, in the first modelled decade, which is about two times the observed upward trend from 2000 to 2020 of 62 PJ/year. Most of this crude oil and the refined fossil fuels are imported at present (Section 2.3), and the NZAu modelling shows this is not expected to change in the near future: Australia keeps relying on oil and refined fossil fuel imports for the initial part of the net-zero transition. However, crude oil imports drop from 2030 onwards following the closure of Geelong and Lytton refineries, as later discussed in Section 5.4. The demand for refined fossil fuels also diminishes. It eventually becomes null in 2050 in the E+RE+ Scenario, where Fischer-Tropsch process served by renewable electricity, green Hydrogen and captured CO_2 as feedstock is supplying the residual consumption of refined liquid fuels. In the other scenarios, between 720 PJ to 1100 PJ of refined fossil fuels are still required in 2060.

Figure 11 | Historical and modelled future trends in the primary energy production and import of oil and refined fossil fuels.



Concerning energy exports, both refined fossil fuels and oil exports progressively decrease to zero across all scenarios, with the exception of the E+RE− Scenario, where a residual 374 PJ per annum of condensates are domestically produced and exported as a by-product of the conventional natural gas extraction in the basins of Western Australia.

5.4 Exported and imported liquid fossil fuels

A closer look at the imported and domestically produced fossil fuel flows is shown in Figure 12, which each serve domestic Australian demand. Energy imports to Australia consist of crude oil and refined fossil fuels; all other liquid fossil fuels (including a small amount of crude oil) are domestically extracted. Figure 12 shows that the E+RE+ Scenario removes Australia's dependence on imports by 2050. Australia then becomes purely an exporter: from 2050, onwards, the refined fuels still used by the transport and the industrial sectors are substituted by domestically produced biomass and synthetic alternatives. In all other scenarios, a dependence on imported fossil fuels is retained, particularly for aviation fuel and some industrial applications. This residual use of imported refined fossil liquid fuels requires that associated GHG emissions be offset with atmospheric removals in other modelled sectors.

Figure 12 | Fossil fuel primary energy production: imported vs extracted share supplying the Australian domestic energy demand.

Although absolute imports are in the range 0.7-1.1 EJ per annum in 2060, imports contribute to supplying 55%-83% of the domestic fossil fuel demand in 2060. Transport is the main sector responsible for continued refined fossil fuel demand, with aviation in particular consuming between 80 and 100% of these imports.

Contrary to continued refined liquid fossil fuel imports, Figure 12 shows oil imports cease in all modelled net-zero scenarios by 2030, as the two main industrial facilities responsible for the oil import demand – Lytton and Geelong refineries – are modelled terminate their operation. In 2020, these two refineries produced an aggregate of only 0.4 EJ output mainly comprised of diesel, aviation fuel and gasoline. Since the energy input to the refining process is comparable with that of the imported oil entering refineries as a feedstock, it is economically cheaper to import the refined fuel directly. Therefore, the RIO optimisation models the closure of Lytton and Geelong sites in 2030, which is in alignment with the currently announced closure of Lytton in 2027.

5.5 Resource depletion

Figure 13 and Figure 14 show, respectively, the progressive depletion of conventional natural gas and coal seam gas basins for the E+RE− Scenario. This downscaling of modelled RIO results reveals that, for the E+RE− Scenario, current TDR of Australian conventional natural gas resources could be depleted by 2050, and those of coal seam gas resources exhausted by 2055. The E+RE− Scenario applies constraints to the annual build rates of renewable projects [8], which has the main effect of increasing the need to produce natural gas for conversion to hydrogen to serve energy export demand. As observed in Figure 10, more than twice the current natural gas production would be needed to supply both exports and domestic needs in this scenario.

In contrast, the modelled net-zero scenarios with unconstrained renewable deployment rates result in natural gas production of 0.5-1.24 EJ in 2060. Downscaling of the results for the E+RE+ Scenario show no depletion of the available gas resources in Australia. These findings highlight how shifting towards renewable energy generation may also avoid large investments in further FF basin exploration and identification of new reserves: an often overlooked yet unavoidable aspect of a reliance on fossil fuels along the net-zero transition pathway, as NZAu Project's results underscore.

Figure 13 | Evolution of total demonstrated conventional natural gas resource (TDR) for the E+RE− Scenario. The maps present both the remaining TDR for each basin in each year, and the proportion of initial (2020) TDR remaining in each year.

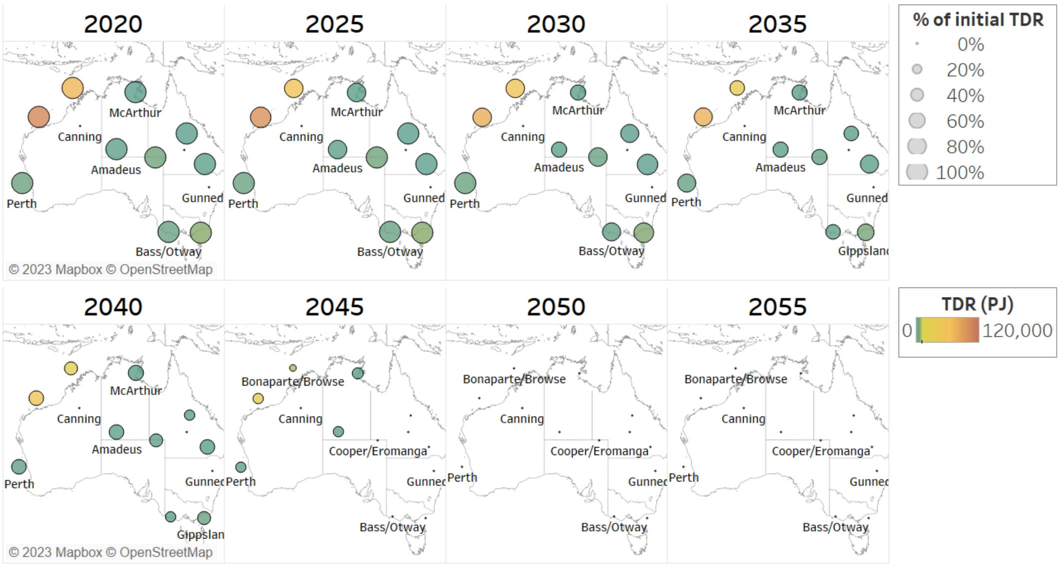
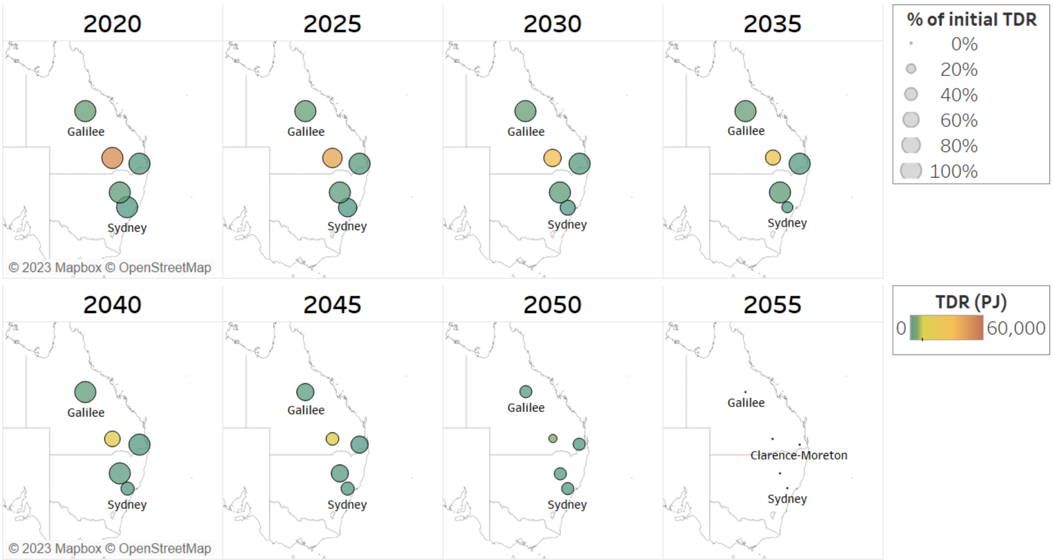


Figure 14 | Evolution of total demonstrated coal seam gas resource (TDR) for the E+RE− Scenario.



Between 2020 and 2030, most of the conventional natural gas is extracted from the Bonaparte basin in the Northern Territory, primarily to supply the neighbouring export needs from WA-north. From 2025, the Northern Carnarvon basin contributes significantly with over 4 EJ/year to the Australian exports from Western Australia. Other basins mostly provide the local FF demand However, from 2040 onwards these minor basins also support some of the exports demand from WA, as the closest Bonaparte and Northern Carnarvon are approaching depletion of their current TDR. The evolution of conventional gas flows over time and residual TDR is further shown in Figure A.2 in the Appendix.

Coal seam gas resources in Queensland and New South Wales are used locally and for LNG exports. The Bowen/Surat basin is used to provide over 1 EJ/year throughout the transition, with contribution from the Galilee and Gunnedah basins, from 2035 onwards. As noted, our downscaling projects depletion of current TDR of coal seam gas resources by 2055 in the E+RE− Scenario. Detailed account of the natural gas flows between basins and NZAu regions, with their evolution over time is shown in Figure 15.

Figure 15 | Conventional and coal seam gas flows between basin and NZAu region and their evolution over time for the E+RE− Scenario. Note differences in the y-axis scales and the 'Import' entry has been added to make up for modelled NG production that is above current TDR .

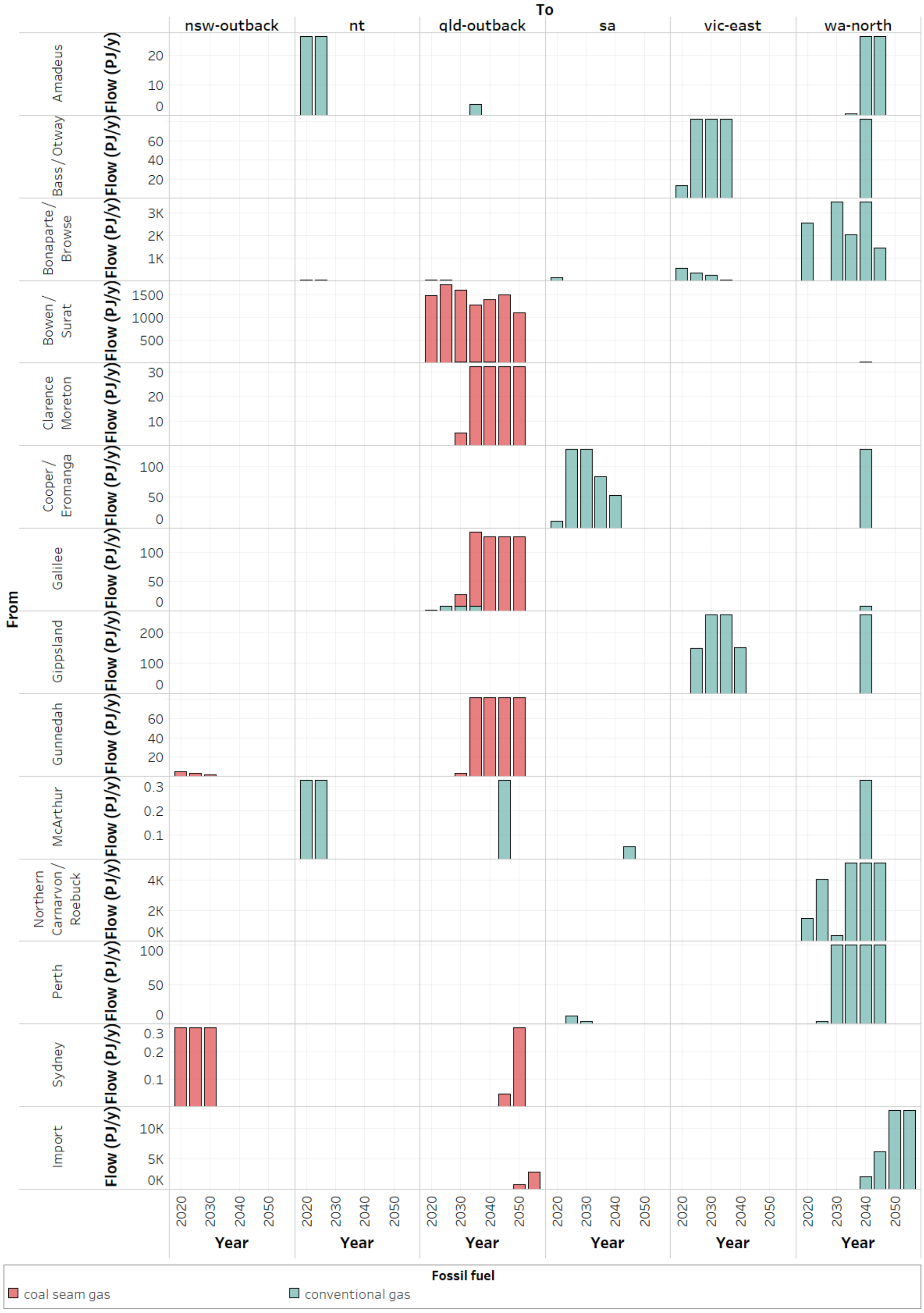


Figure 16 shows oil basins TDR depletion for the E+RE− Scenario. Australian crude oil imports are modelled to terminate by 2030, with the closure of Lytton and Geelong refineries. Domestic crude oil resources are mostly extracted and used locally. The Bonaparte and Northern Carnarvon basins provide over 15 PJ/year each in the first transition years, supported by the Cooper/Eromanga, from 2025, onwards. These basins are all located close to the WA-north region, where oil demand is linked to the extraction activity of the large conventional gas quantities for export purposes. Modest production from other minor basins such as the Gippsland, Perth and Canning contribute to the overall fulfilment of domestic demand for crude oil.

However, as observed for natural gas, Australian TDR, such as the E+RE− Scenario. As soon as the primary crude oil used in domestic refining is excluded, crude oil production is largely a by-product of conventional natural gas extraction. Once again, the large deployment of renewables in the E+RE+ Scenario does not exhaust the Australian crude oil resources and with 1500 PJ left and still available by 2060. Detailed representation of the flows between basins and NZAu regions is shown in Figure 17.

Figure 16 | Evolution of total demonstrated oil basin resources for the E+RE− Scenario.

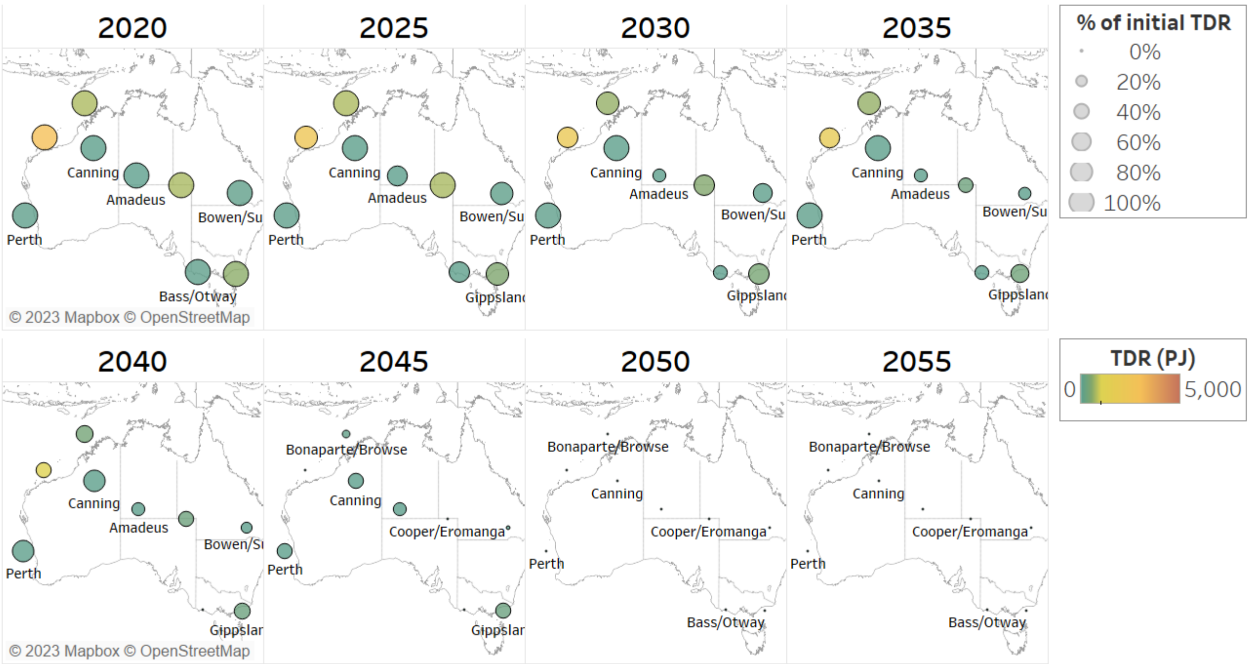
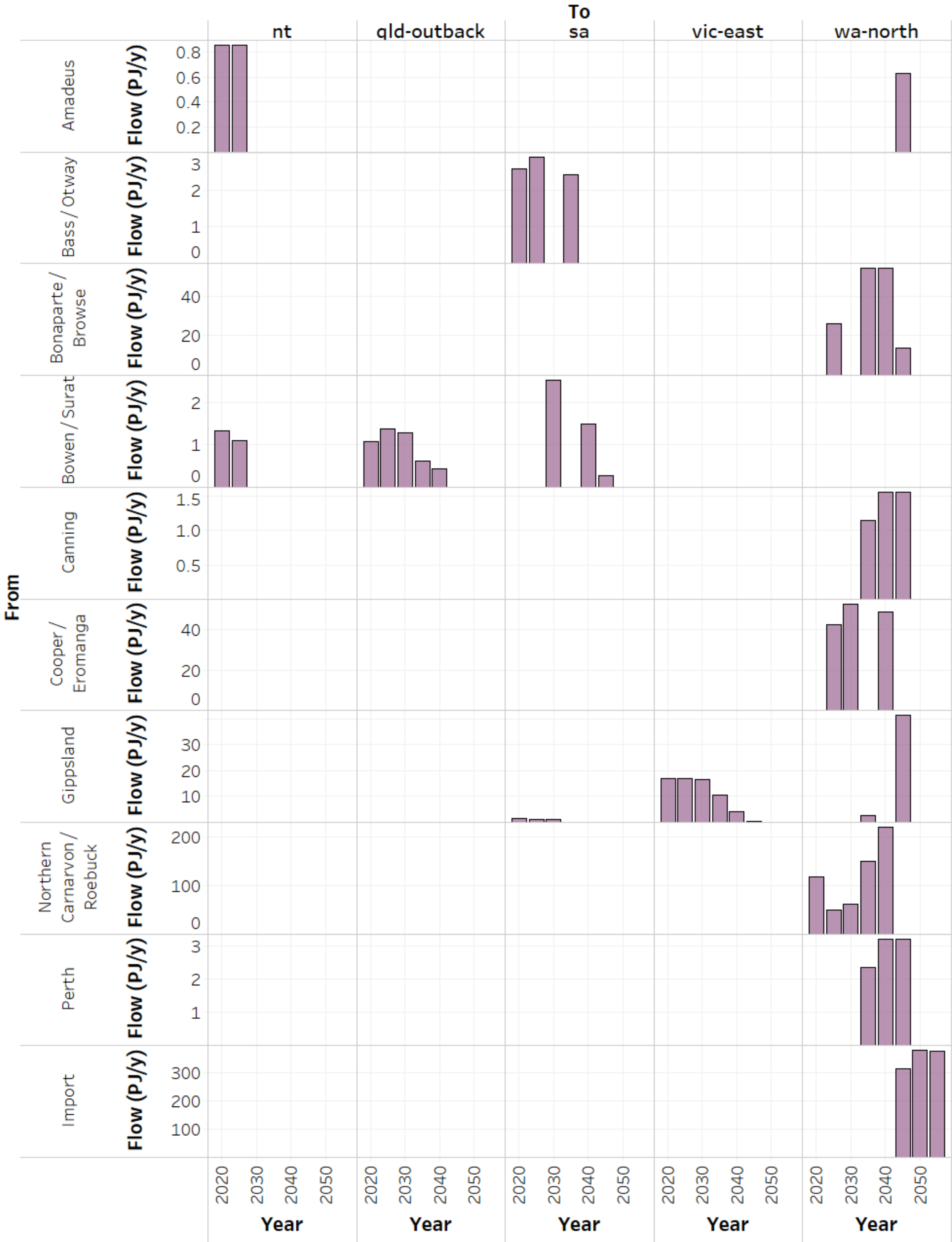


Figure 17 | Crude oil flows between basin and NZAu region and their evolution over time for the E+RE– Scenario. Note differences in the y-axis scales.



5.6 Scheduling of fossil fuel extraction assets

Retirements and new builds of black and brown coal extraction mines for the Ref, E+RE+ and E+RE− Scenarios are shown in Figure 18. We find extensive early retirements of these facilities, and so the modelled retirement scheduling of coal extraction facilities is further downscaled geographically and presented in Figure 19. Table 8 then also presents the modelled retirement schedule for coal mines in NSW-central, where most of these extraction facilities are located. As expected, the E+RE+ Scenario shows the most rapid phase out of coal. For black coal, early shut-down of extraction facilities prior to their commercial end of life was found for all the net-zero scenarios. Every five years, existing mines are retired, with a substantial decrease in the aggregated extraction capacity that is between 0.5 and 2.3 EJ/year. Brown coal extraction is completely phased out in Victoria between 2025 and 2030.

Figure 18 | The capacity of retirements (negative) and new builds (positive) for black and brown coal mines by NZAu region and scenario. Note differences in the y-axis scales.

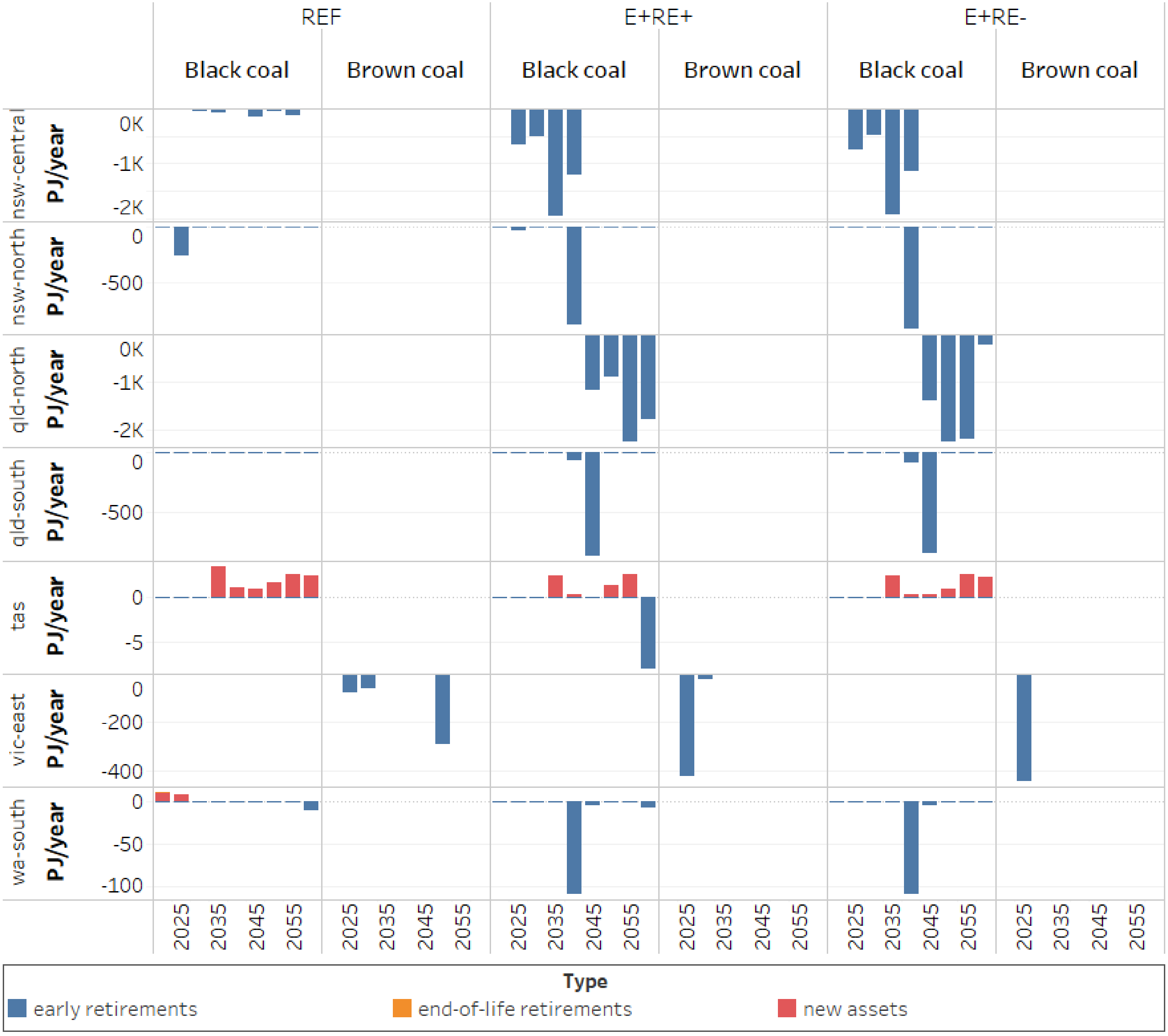


Figure 19 | Phase out schedule for existing black coal mines in the E+RE+ Scenario.

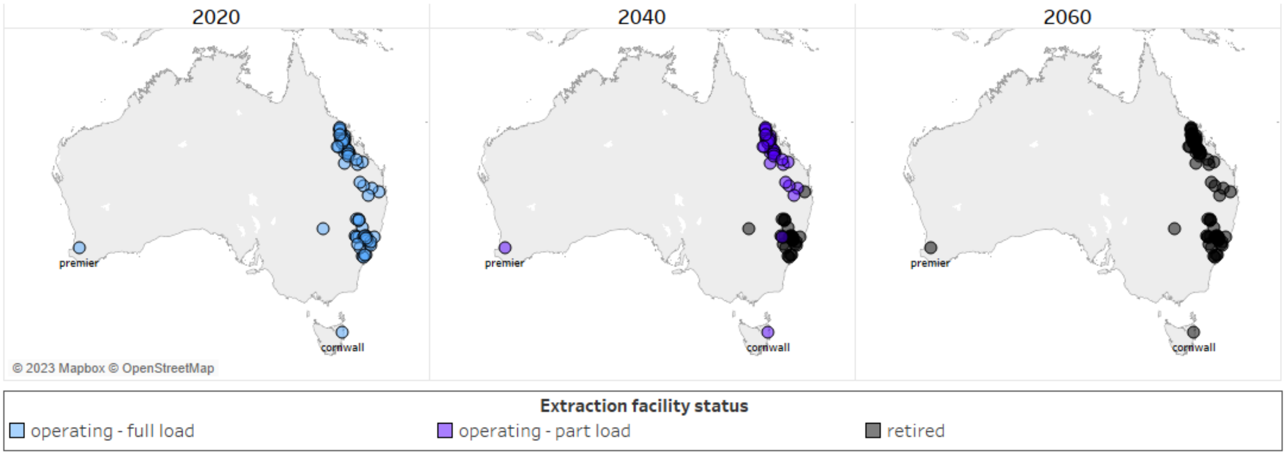
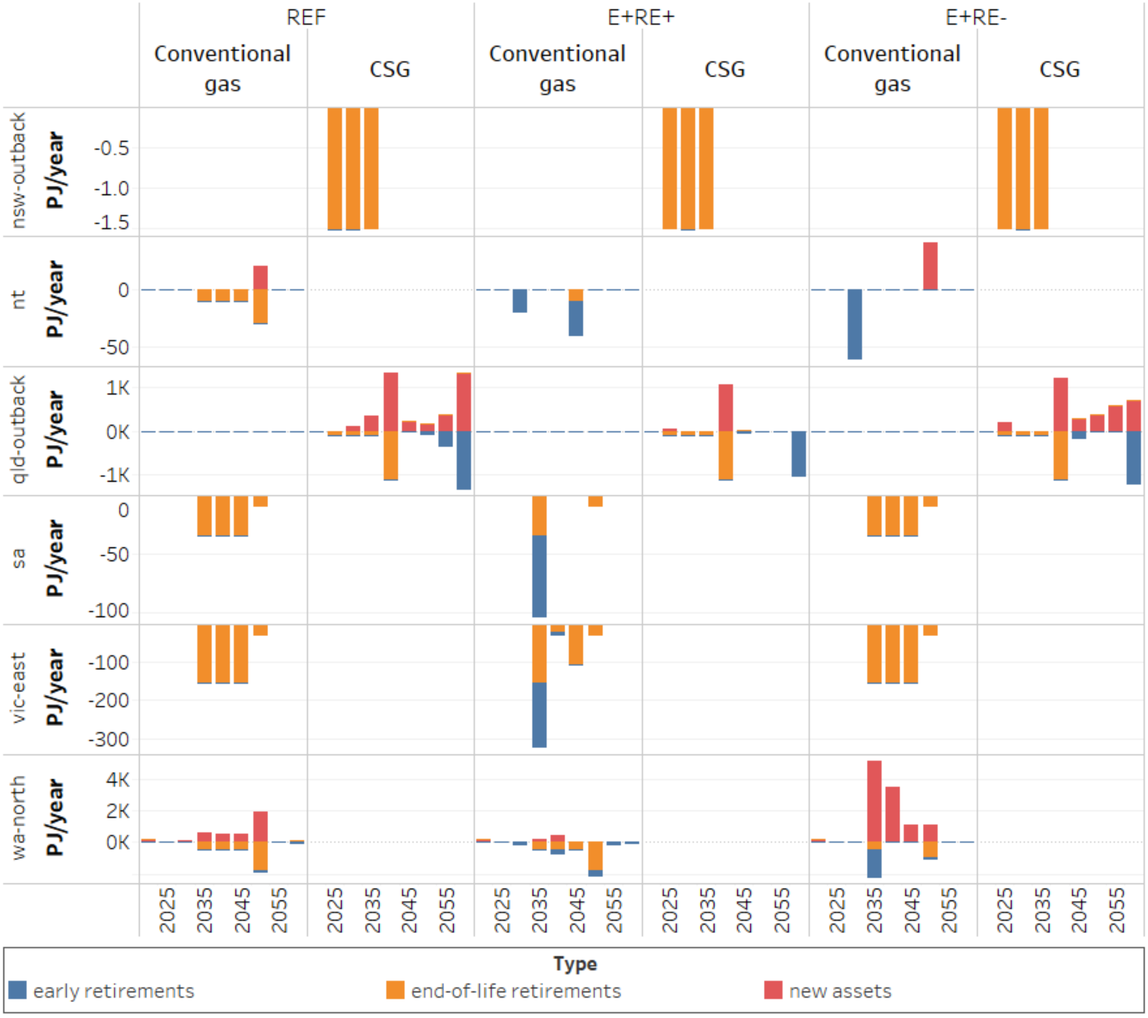


Table 8 | Retirement schedule of black coal extraction facilities in the NZAu NSW-central region for the E+RE+ Scenario.

Year	Retirements	Part-load operation
2025	Rixs Creek, Metropolitan, Bloomfield, Integra, Airly, Wambo, Muswellbrook, Clarence, Tahmoor, Chain Valley, Austar, Liddell, Mandalong, Dendrobium	Mandalong (49%)
2030	Ashton, Mount Pleasant, Bulga	Mount Owen (98%)
2035	Mount Owen, Hunter Valley Operations, Mangoola, Appin, Ulan, Wilpinjong, Ravensworth	Bengalla (65%)
2040	Bengalla, Mount Thorley	Moolarben (2%)
2045	Moolarben	
2050		
2055		
2060		

Retirements and new builds of gas extraction facilities for the Ref, E+RE+ and E+RE− Scenario are shown in Figure 20. New gas extraction facilities are built in the outback of Queensland and in the northern regions of Western Australia, making up for the closure of existing facilities according to their closure schedule and with minimal early retirement. New extraction facilities tap into the coal seam gas resources of the Bowen-Surat basin in Queensland and the conventional gas in the Northern Carnarvon basin in Western Australia. In particular, the Northern-Carnarvon basin is favoured in the E+RE− Scenario, given its proximity to the major industrial clusters for the production of export fuels and the ports of Western Australia and The Northern Territory.

Figure 20 | The capacity of retirements (negative) and new builds (positive) for natural gas extraction facilities by NZAu region and scenario. Note differences in the y-axis scales.



Appendices

Basin allocation optimisation model

Let the following sets be defined:

- $\mathcal{B}$, from 1 to B, denoting the basins
- $\mathcal{R}$, from 1 to R, denoting the 15 domestic NZAu regions
- $\mathcal{Y}$, from 1 to Y, denoting the years

Given a weighting coefficient for the pathway connecting basin *b* to region *r*, $W_{b,r}$, and the unknown matrix, $\boldsymbol{x}_{b,r,y}$, where each entry denotes the portion of the extraction capacity of basin *b* which is delivered to region *r*, the linear resource allocation optimisation problem can be formulated for each fossil fuel as

$$\min_{x_{b,r,y}} \left(\sum_{b,r,y} \boldsymbol{x}_{b,r,y} W_{b,r} + \sum_{b,y} \boldsymbol{y}_{r,y} EC \right) \Delta t \tag{1}$$

subject to:

$$\sum_{b} \boldsymbol{x}_{b,r,y} C_{b,y} + \boldsymbol{y}_{r,y} = D_{r,y} \quad \forall\, y \in \mathcal{Y} \tag{2}$$

$$TDR_{b,y} = TDR_{b,y-1} - \left(\sum_{r} \boldsymbol{x}_{b,r,y} C_{b,y} \right) \Delta t \quad \forall\, b \in \mathcal{B}, y \in \mathcal{Y} \setminus \{0\} \tag{3}$$

$$TDR_{b,y} = TDR_{b,0} \quad for\ y = 0 \tag{4}$$

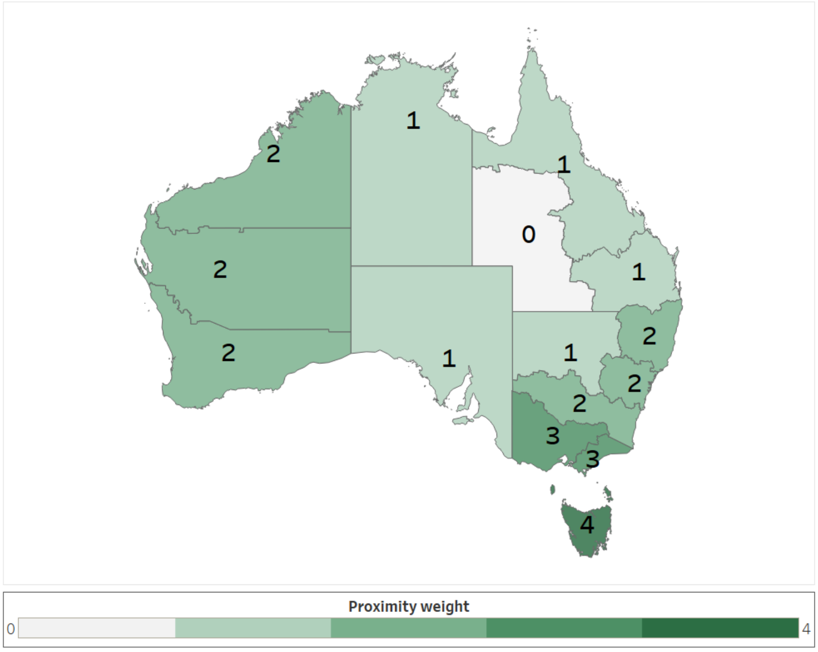
$$0 \leq \boldsymbol{x}_{b,r,y} \leq 1 \quad \forall\, b \in \mathcal{B}, y \in \mathcal{Y}, r \in \mathcal{R} \tag{5}$$

$$TDR_{b,y} \geq 0 \ \forall\, b \in \mathcal{B}, y \in \mathcal{Y} \tag{6}$$

Equation 2 ensures that the demand of each region is satisfied. Equation 5 requires that the capacity of each extraction site is not exceeded. In addition, Equation 3 tracks the evolution of TDR from the initial condition specified by Equation 4 over time. To ensure that the model is feasible, an additional international import stream $\boldsymbol{y}_{b,y}$ was considered, with high associated extra cost coefficient, EC. This addition ensures the fossil fuel demand over time as predicted by the NZAu modelling can always be satisfied. Only in the case of the complete depletion of the existing basins, external imports are considered, given the high associated cost EC.

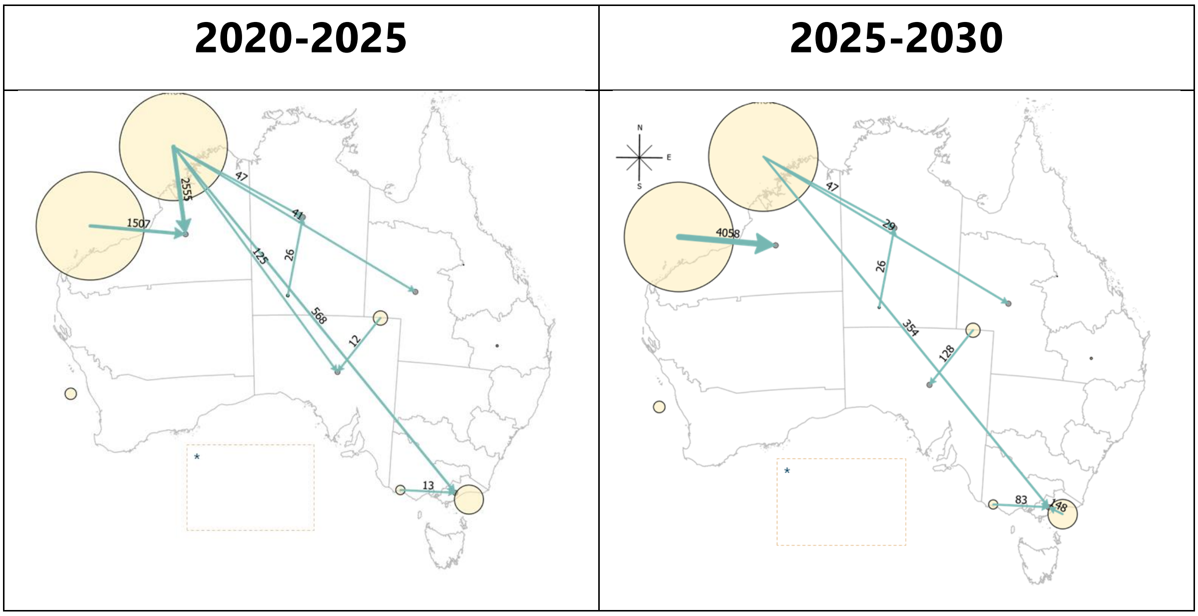
All the input parameters to the basin resources allocation optimisation were available from the RIO model inputs and the weight matrix was computed assigning a rank to each region where the lowest rank, 1, denotes neighbouring regions and the rank increases for regions that are progressively farther apart. An example for basins located relative to the Qld-outback region is shown in Figure A.1.

Figure A.1 | Exemplary proximity weights assigned to basins located in the region Qld-outback.

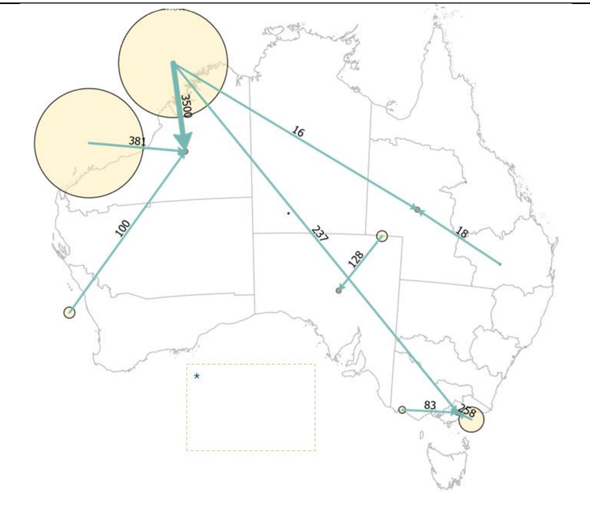


Results of the basin allocation optimisation for the use of conventional national gas for the E+RE− Scenario is represented in Figure A.2.

Figure A.2: Time evolution of annual fossil fuel flow between basins and consumption sites (PJ/year) and resource depletion as predicted by the resource allocation optimisation model for the E+RE− Scenario.

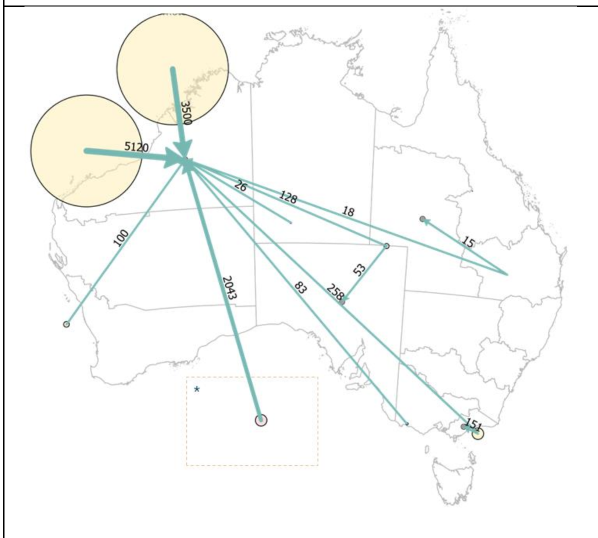


2030-2035

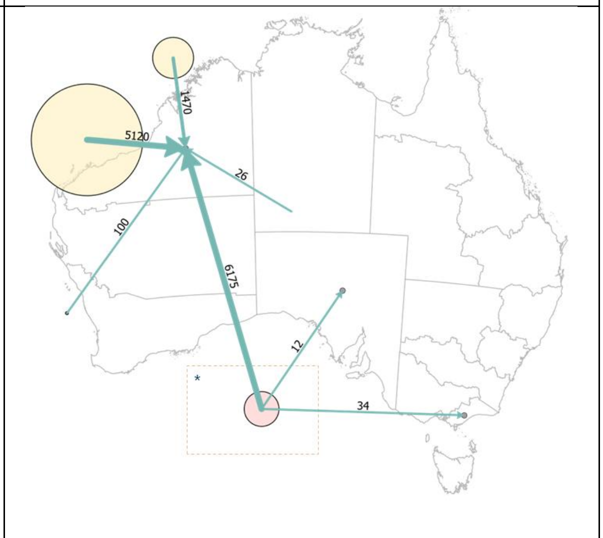


2035-2040

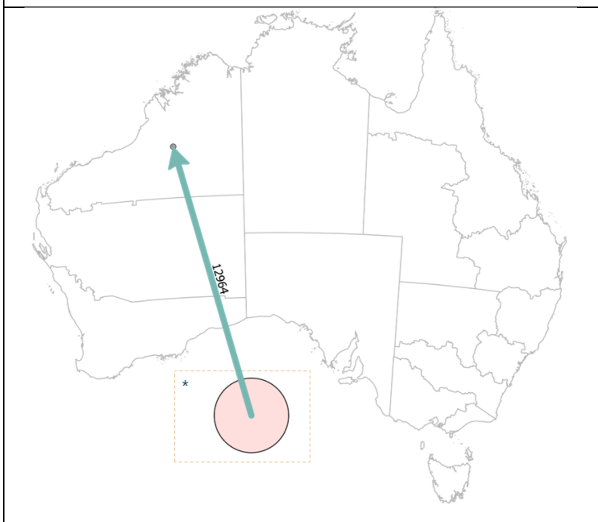
2040-2045



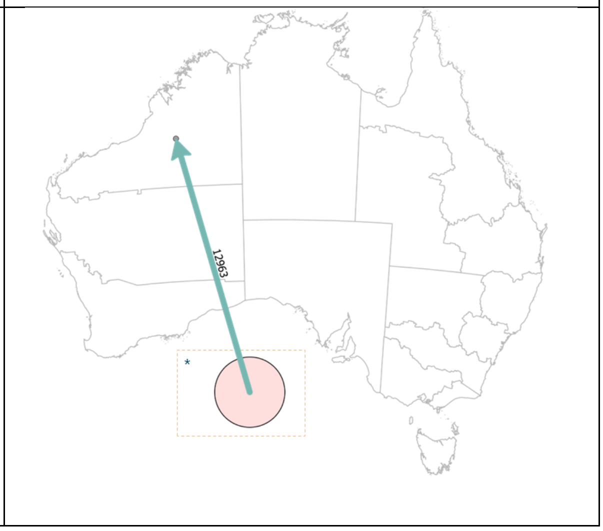
2045-2050



2050-2055



2055-2060



Techno-economic inputs to the RIO optimisation platform

Table A.1: Capital and operational expenditure parameters for the main fossil fuel extraction infrastructure.

Facility	Existing CAPEX [AUD/kW]	New CAPEX [AUD/kW]	Fixed O&M [AUD/kW]	Variable O&M [AUD/GJ]
Oil refinery	1000	N.A.	100	0
Black coal mine	50	50	5	0
Brown coal mine	50	50	5	0
CSG extraction	1218	1218	10	0.0629
Gas extraction	614.3	614.3 to 982.9	10	0.0629
Gas extraction w/cc	N.A.	614.3 to 982.9	10	0.0721

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