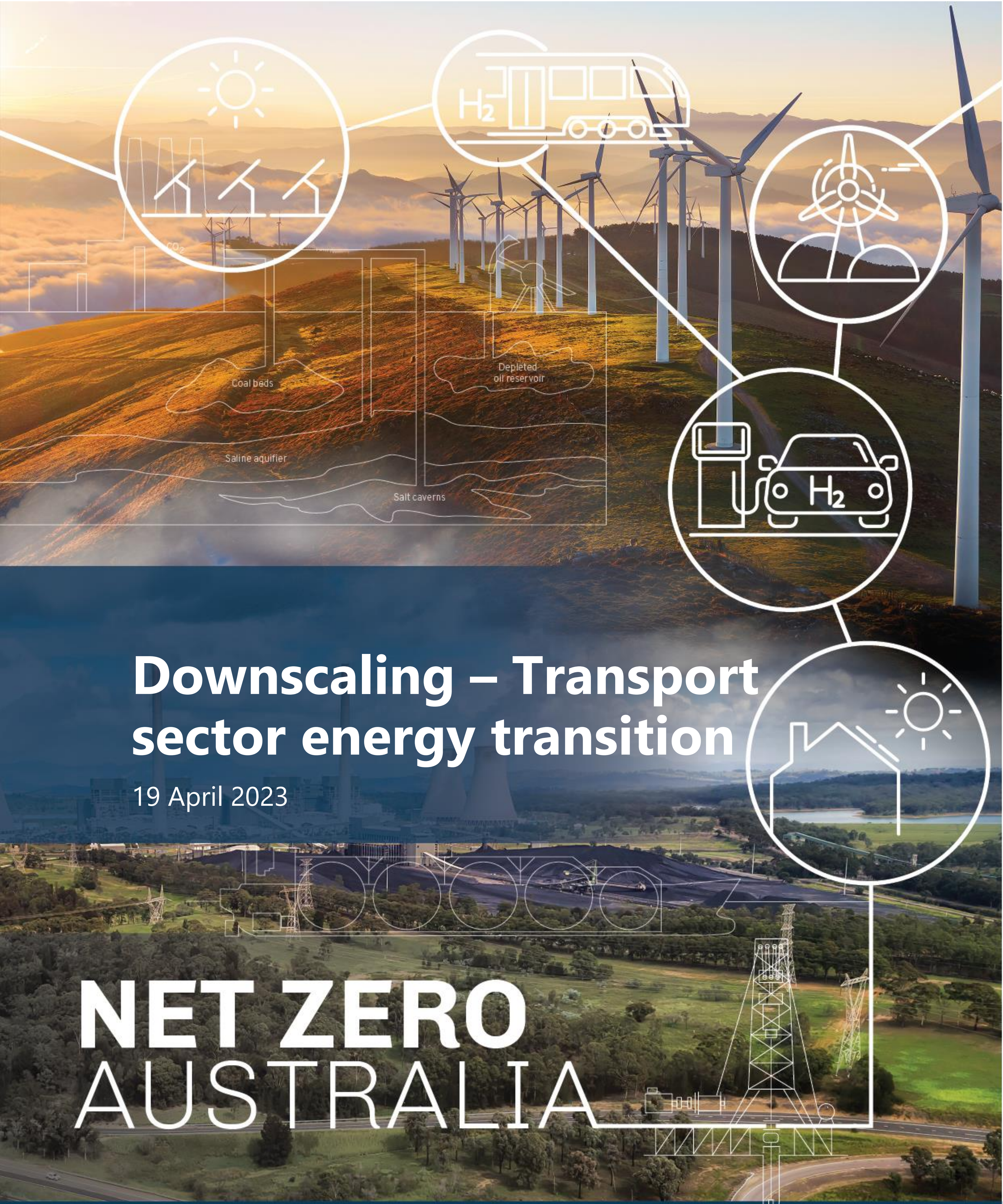

Downscaling – Transport sector energy transition

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 – Transport sector energy transition

19 April 2023

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[1] The University of Melbourne

Contents

1 Introduction

Australia's transport sector accounted for 101 Mt-CO_2e in the 2019 greenhouse gas (GHG) inventory (DISER, 2021b). This is approximately 19% of Australia's total GHG emissions, which has remained relatively consistent over recent years. Indeed, absolute transport sector emissions have steadily risen over recent decades. The majority of transport sector emissions can be attributed to on-road motor vehicles (84.2%), which highlights Australia's significant reliance on motor vehicles for personal mobility and freight. Aviation (8.4%), rail (4.1%) and water transport (2.3%) contribute less to transport sector GHG emissions, but each sub-sector has its own challenges in mitigating GHG emissions.

The *Net Zero Australia* (NZAu) project has modelled pathways to the decarbonisation of the transport sector, through a transition of on-road vehicles to battery electric (BEV) and hydrogen fuel cell vehicles (HFCV), and for aviation, rail and water transport through pursuing energy efficiency gains, fuel switching to electricity, hydrogen and ammonia, and in some cases through the supply of synthetic liquid fuels. In this report, we explore the net-zero transition across these four transport sub-sectors (on-road, aviation, rail and water transport), providing detail on transport sector decarbonisation, as well as associated costs and geospatial implications.

2 Transport system modelling

The modelled transport system spans on-road, air, rail and water transport sub-sectors, with the representation of energy-service and final energy demands across the range of sub-sector components listed in Table 1. For each of the sub-sectors, current and projected future final energy demands, by final energy type, are determined with a bottom-up stock-rollover model named EnergyPATHWAYS (EP) (Williams et al., 2021). The methodology for projecting final energy demands by region and time has been presented in the NZAu Methods, Assumptions, Scenarios and Sensitivities (MASS) document (Net Zero Australia Project, 2022), and is therefore only briefly outlined here.

The final energy demand for the on-road transport sub-sector by the vehicle classes shown in Table 1 is calculated from:

- the current vehicle stock, i.e. the number of registered vehicles of various classes and fuel types;
- current vehicle fuel economies; i.e. the fuel consumption per distance travelled;
- the current vehicle energy-service demands in vehicle-kilometres travelled;
- projections of population and associated freight task; and
- exogenously specified vehicle sales shares of different vehicle types.

The modelling accounts for the lifetimes of all existing and new vehicles and determines the annual vehicle replacements of a type consistent with the specified new vehicle sales shares.

In contrast, the final energy demands for the air, rail and water transport sub-sectors are more simply characterised by their current final energy consumption and projections of future demand tied to population, income and gross state product, as well as energy efficiency and specified fuel switching measures. The prescribed technology type sales shares for on-road sub-sectors with stock representation and the prescribed fuel switching and energy efficiency measures for the air, rail and water transport sub-sectors are detailed in the NZAu MASS document (Net Zero Australia Project, 2022) and are explored later in this report.

Table 1 | Composition of the transport sector modelled in the Net Zero Australia project and summary of the emissions abatement strategies modelled.

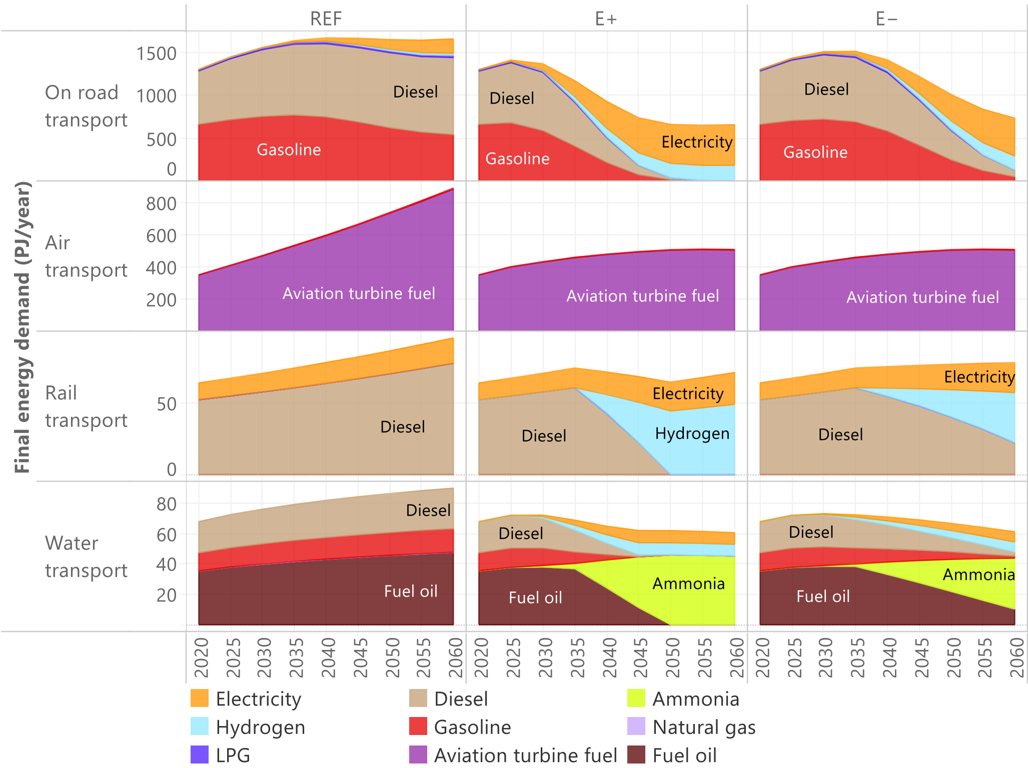
Transport sub-sector	Modelled components of the sub-sector	Summary of emissions abatement strategies
On-road transport	Passenger vehicles Light commercial vehicles Rigid and other trucks Articulated trucks Buses Motorcycles	Specified battery electric and hydrogen fuel cell vehicle shares of all new vehicle sales.
Air transport	Domestic air transport International air transport	Energy efficiency improvement, drop-in fuels.
Rail transport	Rail transport	Fuel switching to electricity and hydrogen.
Water transport	Domestic water transport International water transport	Energy efficiency improvement, fuel switching to electricity, hydrogen and ammonia.

Figure 1 presents the modelled final energy demands for each of the four transport sub-sectors considered and for the Reference (REF), E+ and E− Scenarios. The modelled switching of final energy to electricity and hydrogen – particularly in the largest on-road transport sub-sector – results in a significant reduction in absolute final energy demand, such that by 2050 transport sector final demand is 75% in E+ and 96% in E− of 2020 levels, despite the growing need for transport services.

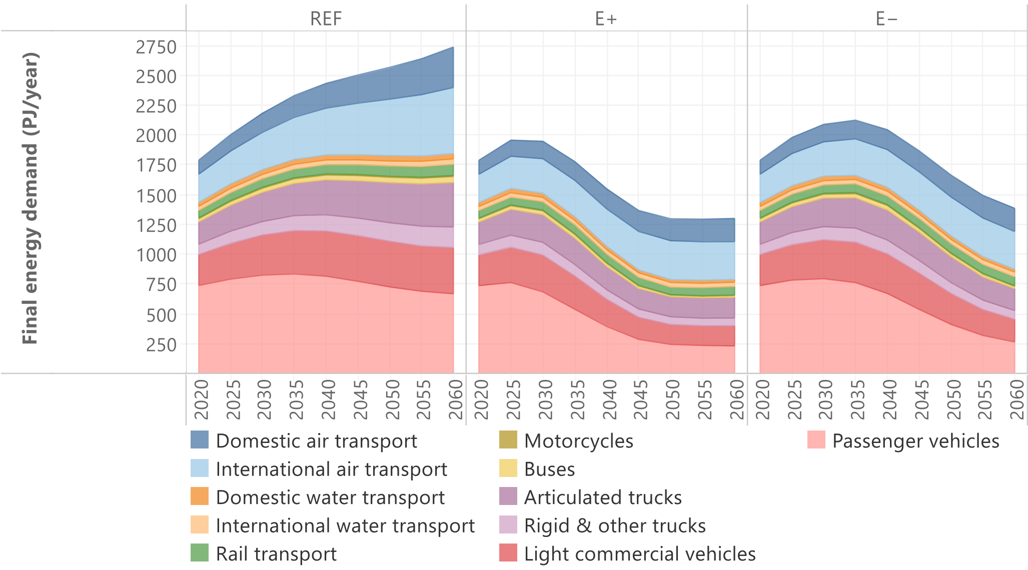
We note that energy-service demands are the same across the three scenarios shown in Figure 1, so that the different scenarios explore the effects of the different uptakes of electrification and other emissions abatement strategies. The rapid electrification E+ Scenario sees transport final energy demand peak earlier than the slower electrification E− Scenario and reaches a lower absolute final energy demand by 2050. This highlights the greater tank-to-wheel efficiencies of battery electric (and to a lesser extent hydrogen fuel cell) vehicles than those of internal combustion engines.

Figure 1 | Transportation sector final energy demand, organised by (a) different sub-sectors of the transport system and their final energies; and by (b) mode of transport. We show only the demand-side Scenarios, REF, E+ and E−, here. The other Core Scenarios, E+RE+, E+RE− and E+ONS, have the same final energy demands as E+. Note independent vertical axis scales.

(a) Final energy demand, by sub-sector and final energy type



(b) Final energy demand, by mode of transport



To determine how final transportation energy demand is served over the years 2020 to 2060 and the GHG emissions associated with its supply, we use a supply-side model, the Regional Investment and Operations (RIO) modelling tool, to determine the least-cost technology mix and operations to serve the demand shown in Figure 1. The supply of this final demand is optimised alongside the supply of all other sectors' modelled final demand, and subject to the project's overall emissions constraint. That is, no one individual sector but all sectors combined must reach net-zero emissions.

Note, however, that the RIO optimisations do not represent true 'least cost' solutions to a total, national transport task since the uptake of different vehicles and their propulsive energy (i.e. their fuel or electricity) is imposed over the transition. This is consistent with how all end-use appliances in all sectors are modelled with the EP tool. If true, least cost solutions are sought, then vehicle and propulsive energy choice would be part of the optimisation. This, however, requires a much more demanding optimisation to be solved, and this is beyond the scope of the present study.

Figure 2 presents the annual GHG emissions associated with supplying transportation sector final energy demand. GHG emissions reductions are driven by declines in the use of gasoline, diesel, and fuel oil across all the Core Scenarios. The modelled uptake of BEVs and HFCVs displaces diesel and gasoline internal combustion engines across the on-road, rail and transport sub-sectors. It is also noteworthy that the supply of final electricity to on-road transport has minimal associated GHG emissions during the intermediate transition years, while rail transport electricity supply is decarbonised by 2030. Interestingly, air transport sub-sector emissions grow during the transition to 29-35 Mt-CO_2e/year by 2050 in most Scenarios, which is lower than is projected to be the case without energy efficiency improvement (REF), but nevertheless is retained as residual emissions that need to be offset elsewhere. Only the 100% renewable Scenario E+RE+ exhibits abatement in the air transport sub-sector, through the modelled supply of synthetic aviation drop-in fuel. This suggests aviation is the most costly transport sub-sector to decarbonise.

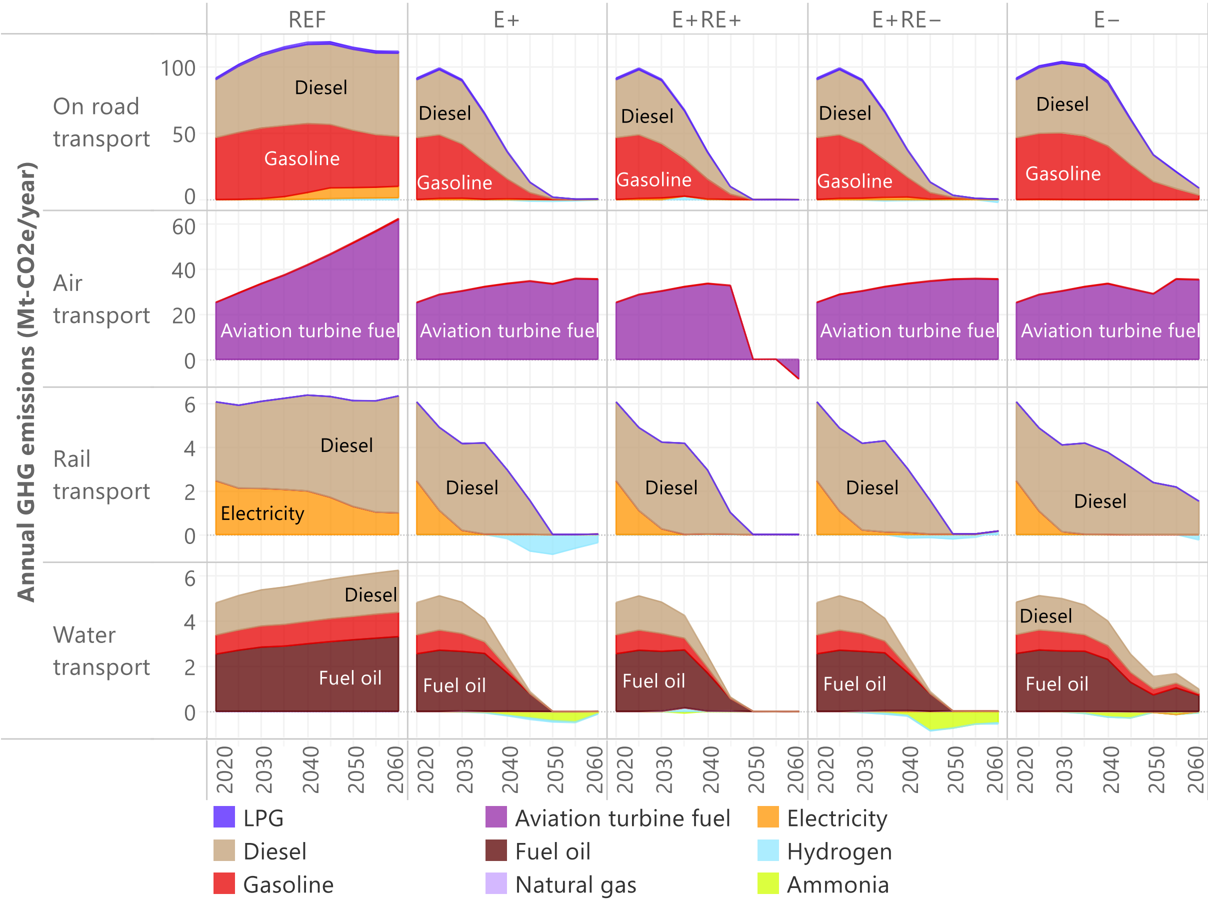
Figure 3 presents the levelised annual transport system cost over the net-zero transition for the Core Scenarios and disaggregated by transport sub-sector. This shows that the transport system cost increases from a total of $95 billion in 2020 to $154–184 billion by 2050 for the net-zero Scenarios, which is 19–42% greater in 2050 than the Scenario without emissions abatement (REF). This increased cost of decarbonisation is attributed partly to increased capital costs of decarbonised transport options (the demand side in Figure 3), which are 10-13% greater in 2050 for net-zero Scenarios than for REF. Also, the cost of supplying low-emissions fuels to the transport sector in the net-zero Scenarios is 35-118% greater than fuel supply in REF.

Across the net-zero Scenarios, it can be seen that E+RE+ has the highest energy costs in the air transport sub-sector, due to the need replace all fossil-based jet fuel in this scenario with a synthetic drop-in fuel. On the other hand, the energy costs of the on-road, rail and water transport sub-sectors are highest in the E+RE− Scenario, which reflects the Scenario's greater constraints on renewable electricity siting, which is the precursor to the final electricity, hydrogen and ammonia consumed in these sub-sectors in 2050.

These transport sectoral trends are explored further in the sections below.

Figure 2 | Annual GHG emissions associated with transport, by (a) different sub-sectors of the transport system and their final energies; and by (b) mode of transport. We show all supply-side Core Scenarios, except for E+ONS, which has similar trend to E+. Note independent vertical axis scales.

(a) Annual GHG emissions, by sub-sector and final energy type



(b) Annual GHG emissions, by mode of transport

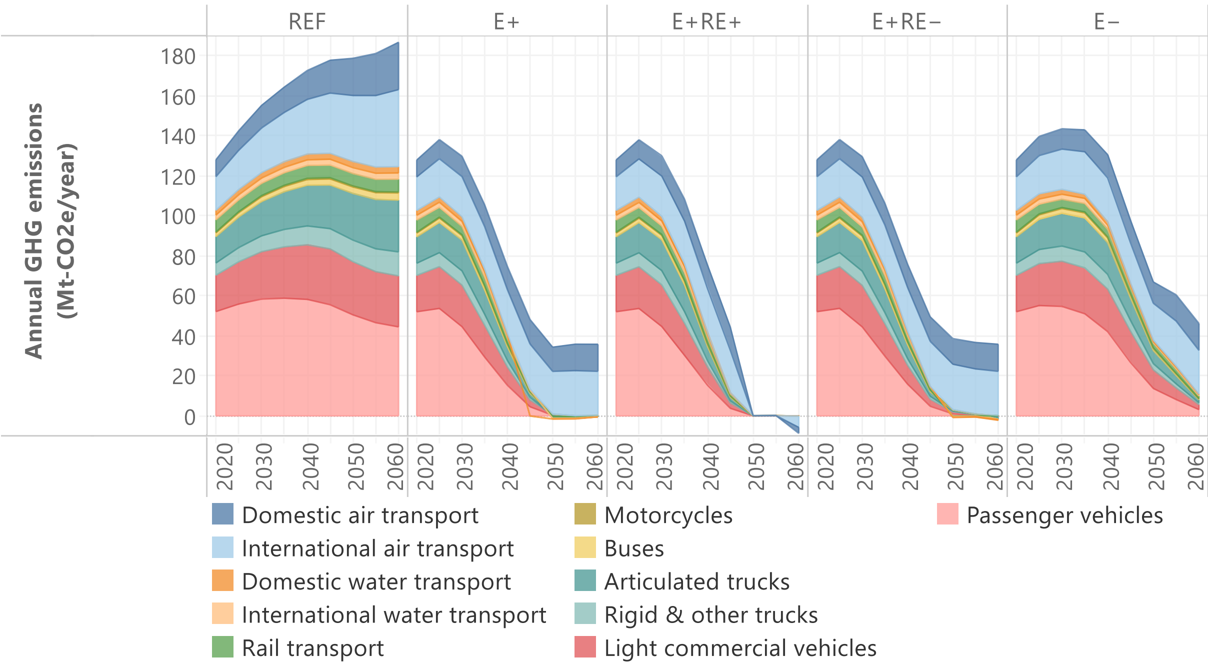
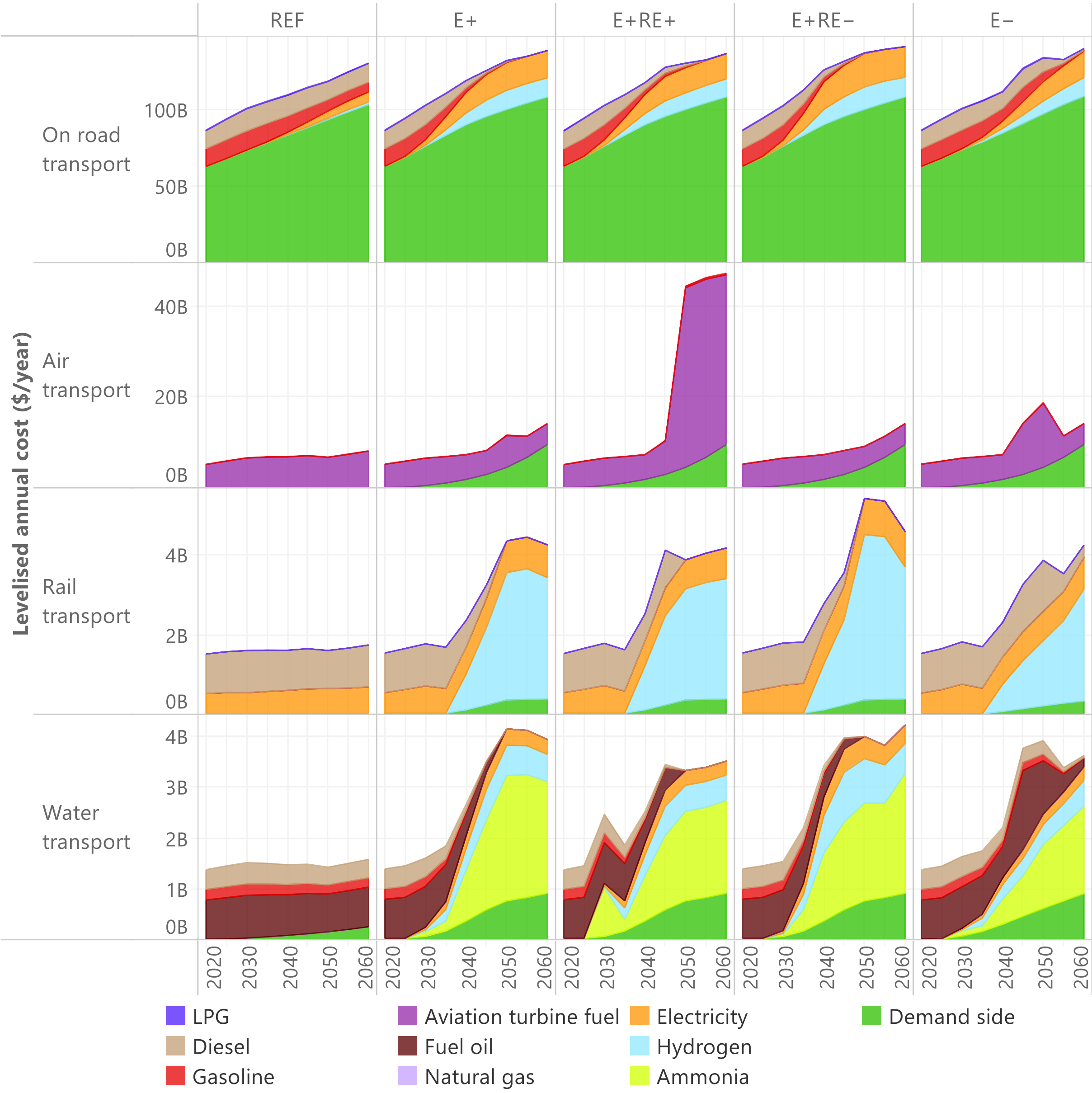


Figure 3 | Levelised annual transport system cost. Costs are disaggregated by the levelised cost of supplying sub-sectoral final energies and levelised demand-side costs. 'Demand side' here refers to levelised vehicle and charger capital costs and levelised costs incurred in air, rail and water transport sub-sectors by fuel switching and improving energy efficiency. We show all supply-side Scenarios, except for E+ONS, which has similar trend to E+.



3 On-road transport

The on-road transport sub-sector modelled in this work includes the following classes of vehicles:

- Passenger vehicles,
- Light commercial vehicles,
- Rigid & other trucks,
- Articulated trucks,
- Buses, and
- Motorcycles.

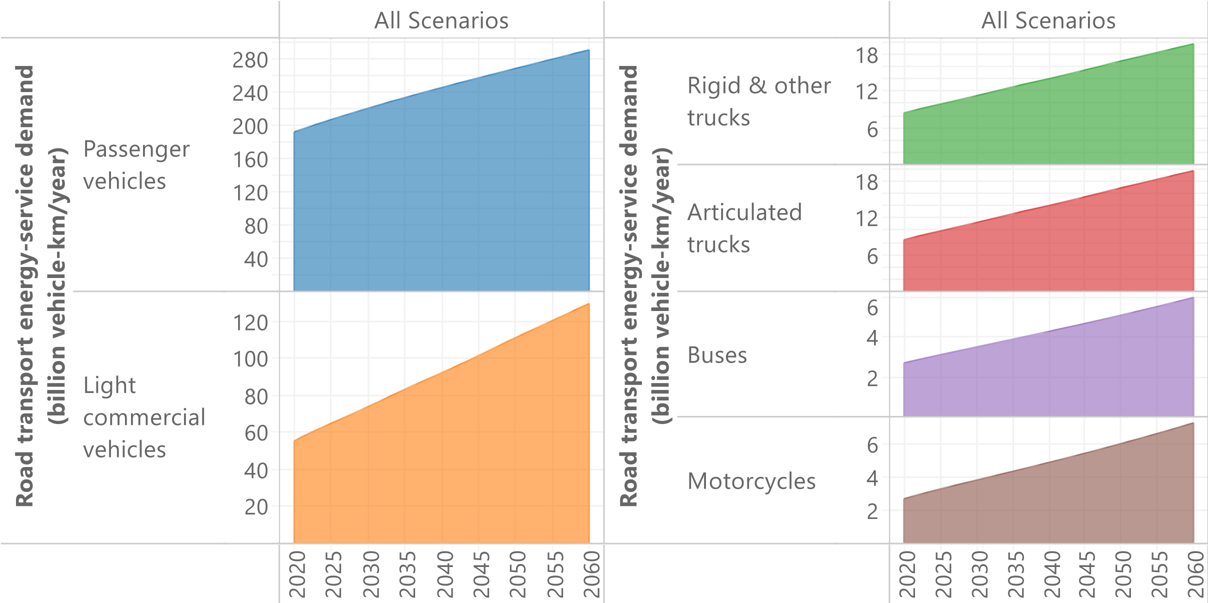
The modelled transition of these vehicle classes is presented below.

3.1 Energy-service demand, vehicle stock and final energy use

We project demand for energy-services across the NZAu modelled regions and over the 40-year modelling horizon using the EP modelling tool. For the on-road transport sub-sector, these energy-services are expressed in annual vehicle-kilometres, with 2020 levels based on data from the Australian Infrastructure Statistics (Bureau of Infrastructure and Transport Research Economics, 2020). The projections of on-road vehicle energy-service demand out to 2060 are shown in Figure 4 and exhibit growth across all vehicle classes, driven largely by population projections and corresponding projections of increased freight demand.

We have not accounted for a large-scale modal shift in mobility services, such as an increasing uptake of public transport, micromobility and ridesharing, or shifting of road freight to other transportation means. Each of these may serve to decrease future demand for transport services, relative to the projections shown in Figure 4. However, with Australia's population projected to reach 37 million by 2050, and because of Australia's large land area and low population density, on-road transport is likely to remain the largest sub-sector within the transport system.

Figure 4 | On-road transport projected energy-service demand by vehicle class.

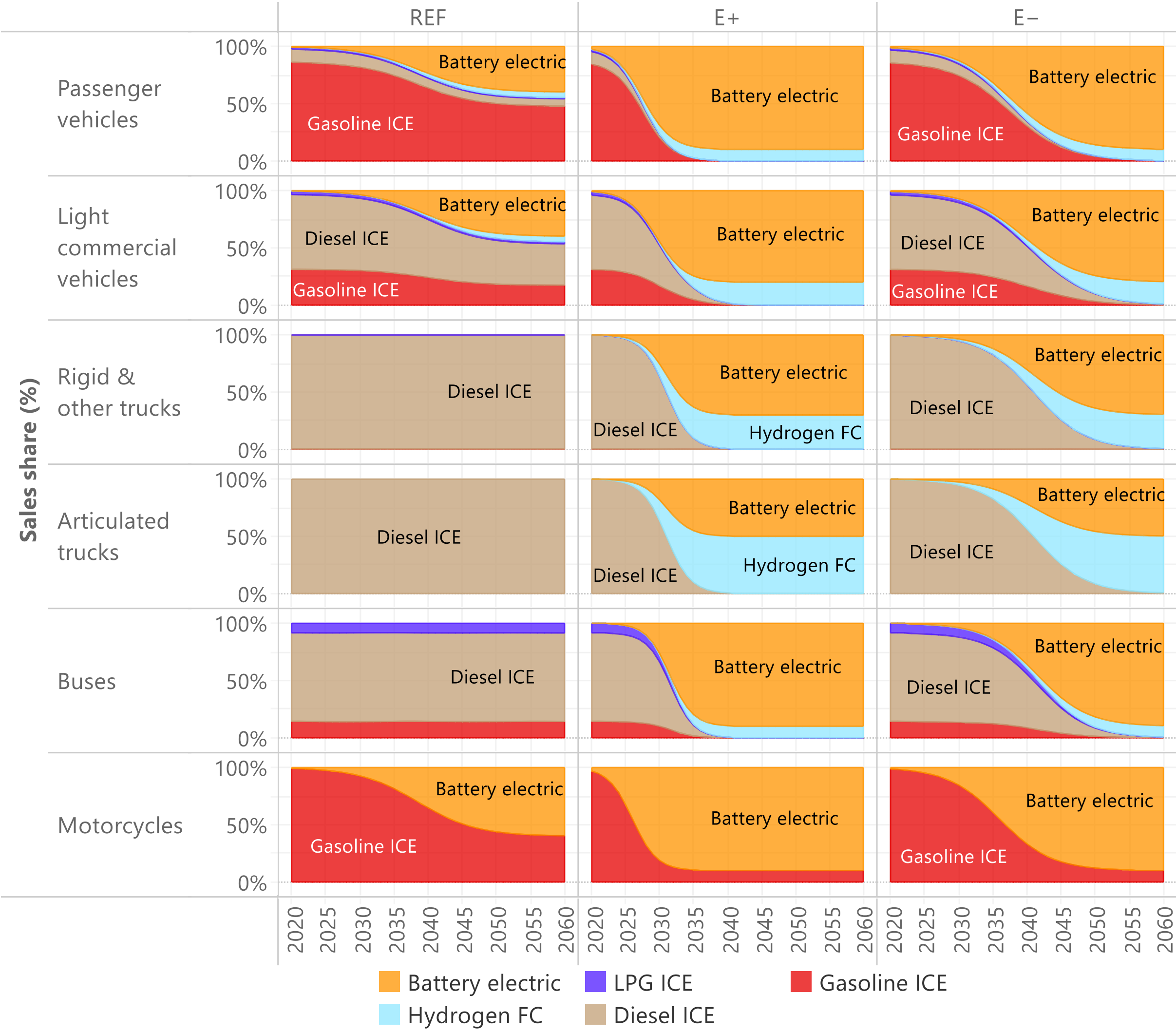


In addition to projecting demand for transport energy-services, we also specify the share of new vehicle sales of different vehicle technologies across the six vehicle classes out to 2060. These sales shares are presented in Figure 5, showing a transition from internal combustion engine vehicles (ICEVs) to electric-drive vehicles – battery electric (BEVs) and hydrogen fuel cell vehicles (HFCVs) – with proportional uptake of BEVs and HFCVs dependent on the vehicle class, and with the speed of the transition dependent on Scenario. That is, emissions reduction in the on-road transport sub-sector is driven by the sales of vehicles with zero tailpipe GHG emissions.

The rollout of BEVs and HFCVs is fastest in the rapid electrification E+ Scenario, where the imposed sales of electric-drive vehicles are projected to reach 69% of all vehicle sales by 2030, 94% by 2035 and >99% by 2040. To explore the implications of a demand-side uptake of low-emissions technology that lags the E+ Scenario, the slower electrification E– Scenario projects uptake of electric-drive vehicles reaching only 12% of new vehicles sales in 2030 and 61% in 2040. HFCVs are projected to play a minor role in serving light-duty transport needs, with a 10% share of zero-emissions passenger vehicles sales and 20% of light commercial vehicle sales.

For heavy-duty transport, up-time, volume and mass constraints of freight-carrying vehicles mean that in many cases hydrogen-fuelled vehicles will be preferred over battery-electric vehicles. This is reflected in the imposed greater share of HFCVs for the heavier duty vehicle classes in Figure 5, with 30% and 50% shares of zero-emissions rigid & other trucks and articulated trucks vehicle sales, respectively.

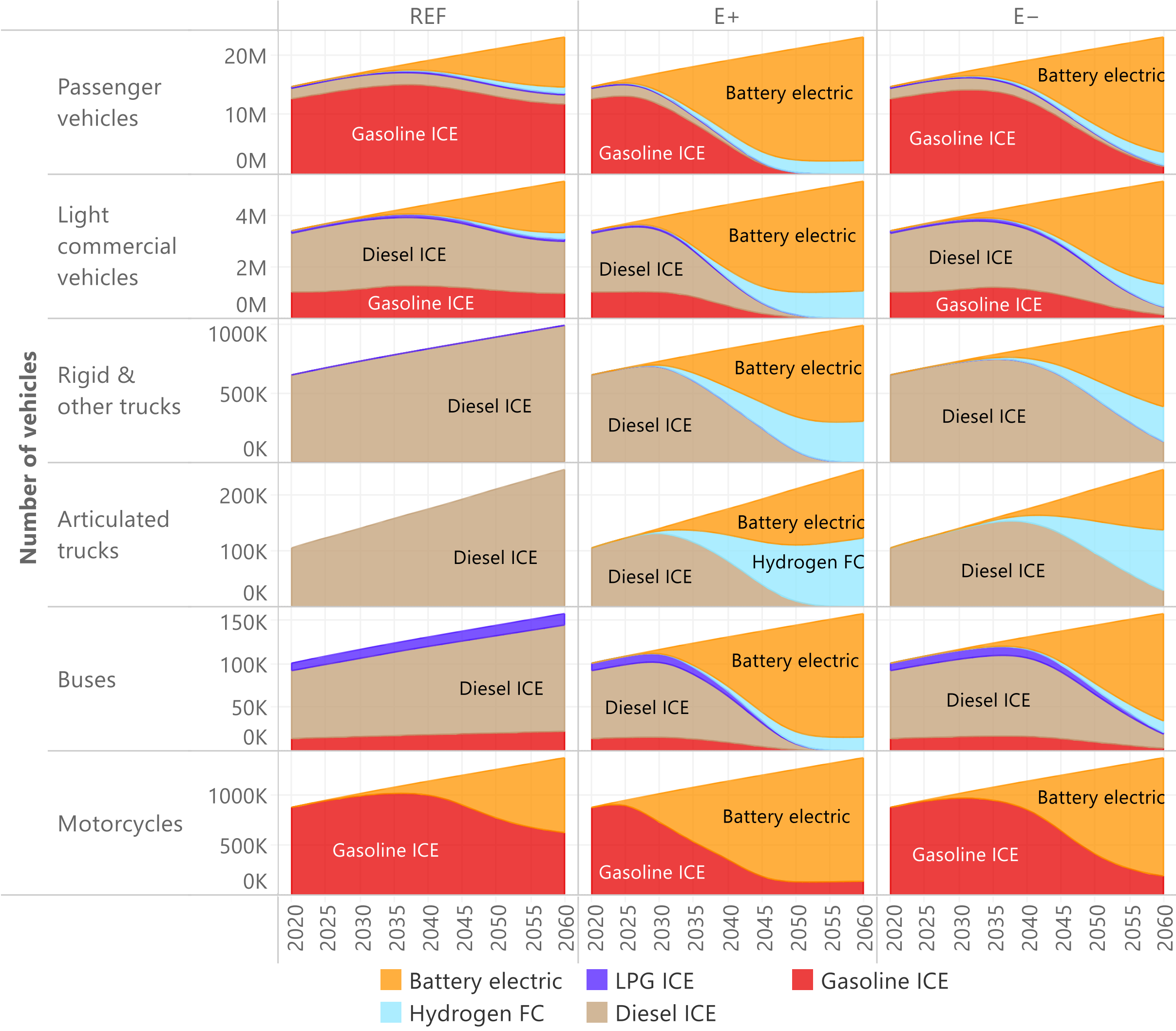
Figure 5 | Specified new sales shares of different vehicle propulsive energy types across the six vehicle classes modelled for the on-road transport sub-sector, and the demand-side scenarios. The other Core Scenarios, E+RE+, E+RE− and E+ONS, have the same sales shares as E+.



While the modelled transition of new vehicle sales shown in Figure 5 is relatively rapid for E+, the timeframe for decarbonisation of the on-road transport sub-sector is constrained by the existing transport system. That is, the existing fleet of ICEVs comprises vehicles with a wide distribution of ages, many of which will not be retired until reaching the end of their useful lives. EP accounts for this by tracking not only the composition of the on-road vehicle stock by vehicle fuel, class and geography, but also retains a representation of vehicle age distribution from current vehicle age distribution data for 2020 and throughout the modelled period. This enables determination of the rate of vehicle stock rollover, where vehicles are retained within the operating stock until they reach the end of their assumed useful life, at which point they are replaced with a new, more efficient vehicle, of a propulsive energy type consistent with the sales shares in Figure 5, also incurring a vehicle capital cost.

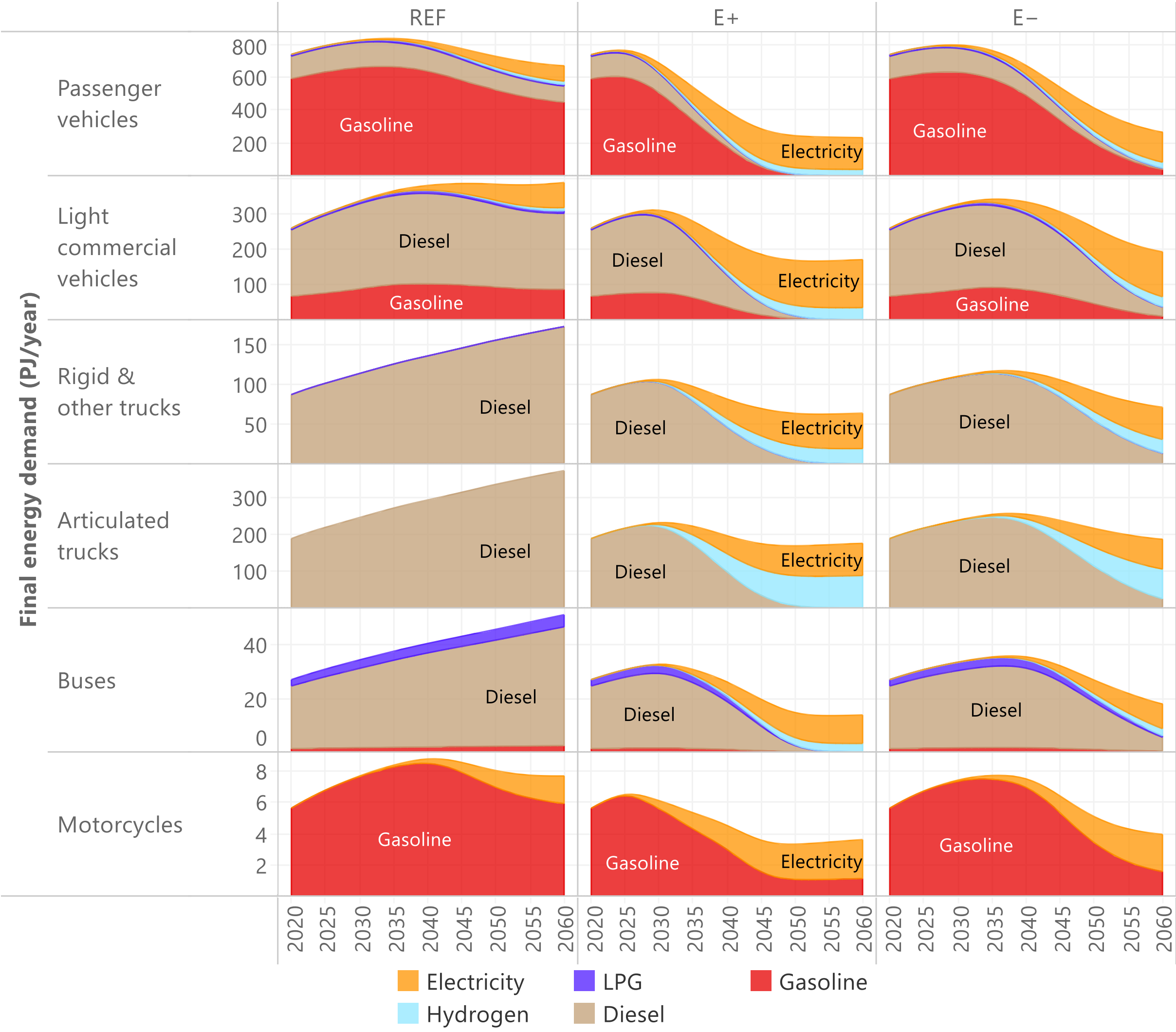
Figure 6 then presents the projected number of vehicles of different types across the six vehicle classes modelled, resulting from the stock rollover model and the prescribed sales shares in Figure 5. This shows that, in the E+ Scenario, ICEVs are progressively replaced by electric-drive vehicles from 2025, such that by 2050 the on-road vehicle fleet is almost entirely comprised of BEVs and HFCVs. By 2050, out of 26 million passenger and light commercial vehicles more than 22 million are BEVs. In the E− Scenario, ICEV replacement occurs at a slower rate, with a third of all vehicles in 2050 still fuelled by hydrocarbon fuels. This slower transition highlights the potential value of low-emissions liquid fuels supply in the E− Scenario.

Figure 6 | Projected number of vehicles of different vehicle types across the six vehicle classes modelled using the stock rollover model for the on-road transport sub-sector, and the demand-side scenarios. The other Core Scenarios, E+RE+, E+RE− and E+ONS, have the same vehicle numbers as E+. Note the different vertical axis scales.



Also, we assume a 1% per year efficiency improvement in new vehicles. By tracking the age distribution of vehicles in service, the average vehicle fleet efficiency and final energy demand can then be determined across the different vehicle classes. Figure 7 presents the projected final energy demand for various transport energies across the six vehicle classes modelled for the on-road sub-sector. This shows the significant energy productivity benefit of switching from ICEVs with energy efficiencies of ~30% to BEVs with efficiencies of ~80%. As each of the vehicle classes transitions to higher penetrations of BEVs, the absolute final energy demand then reduces significantly. The efficiency benefits of HFCV vehicles are not as pronounced as for BEVs, and therefore the reduction in absolute final energy demand for rigid & other trucks and articulated trucks shown in Figure 7 is less significant than the lighter vehicle classes.

Figure 7 | Projected final energy demand by various final energies across the six vehicle classes modelled for the on-road transport sub-sector, and the demand-side scenarios. The other Core Scenarios, E+RE+, E+RE− and E+ONS, have the same final energy demands as E+. Note independent vertical axis scales.



3.2 Emissions standards of the light-duty fleet

The modelled transition for the light-duty fleet, which includes passenger vehicles and light commercial vehicles, entails a rapid switch of new vehicle sales from ICEVs to electric-drive vehicles that do not produce tailpipe GHG emissions. As mentioned previously, this transition to vehicle fleets dominated by BEVs also results in significant energy-service efficiency gains. Tailpipe emissions and energy-service efficiency improvements will be first apparent in the average new vehicle, as is shown in Figure 8. The average light-duty fleet efficiency and tailpipe emissions will then lag the average new vehicle, due to the remaining lifetime of the current vehicle stock.

We note that the current average new light vehicle efficiency and tailpipe emissions shown in Figure 8 is based on data for historical fuel consumption and consumption rate from the ABS' Survey of Motor Vehicle Use (Australian Bureau of Statistics, 2020b). These data are presented in Figure 9 for light-duty vehicles and show that petrol (gasoline) consumption has remained relatively constant over recent years, while diesel consumption has grown. Significantly, fuel consumption rates across both passenger vehicles and light commercial vehicles, and across gasoline and diesel-fuelled vehicles has shown no decline in the last 10-15 years. This stands in contrast to global trends in passenger and light commercial vehicle fuel consumption rates, which have generally decreased over the last decades (Yang and Bandivadekar, 2017).

Figure 8 presents the average new vehicle tailpipe emissions which gives rise to the modelled light-duty vehicle transition. This can be considered analogous to a vehicle emissions standard, which has been proposed as a means of regulating emissions from light-duty transport in Australia and globally. Such regulation could require the average emissions of all light-duty vehicles sold by a particular vehicle manufacturer across the country in a given year to meet some specified standard, with that standard being lowered in subsequent years.

We find in our rapid electrification E+ Scenario that average new vehicle tailpipe emissions quickly reduce from high current levels (>250 g-CO_2e/km) to 73 g-CO_2e/km in 2030 and 14 g-CO_2e/km in 2035. These tailpipe emissions trends for the E+ Scenario are similar, but lag by a few years, the proposed light vehicle emissions standards recently published by the Grattan Institute (Terrill et al., 2021) and Climateworks Centre (Lynskey et al., 2022). They propose emissions standards to be implemented in 2024 with upper limits of 143 and 95 g-CO_2e/km, respectively. The Grattan Institute then proposes that limit be reduced to 100 g-CO_2e/km in 2027, 25 g-CO_2e/km in 2030 and both publications recommend 0 g-CO_2e/km by 2035.

It should however be noted that light-duty vehicle fuel-economy or GHG emissions standards are sensitive to the test procedure used to measure vehicle performance (e.g. CAFE's US combined cycle, or the EU's New European Driving Cycle), as well as the categorisation of vehicles into (and potential differentiation between) passenger vehicles and light commercial vehicles (Yang and Bandivadekar, 2017). Furthermore, it has also been shown that real-world LDV fuel-efficiencies and emissions diverge from those specified by various implemented vehicle standards, in some cases by more than 30% (Tietge et al., 2017). These are potential reasons for the current average fuel consumption rate (Figure 9) and modelled current tailpipe emissions (Figure 8) being significantly higher than recent global experience, but also highlights the need for any potential LDV emissions standard to seek vehicle testing procedures that accurately represent real-world LDV performance (Yang and Bandivadekar, 2017).

We note that our slower electrification E− Scenario exhibits a significantly slower trend with zero average new vehicle tailpipe emissions reached in around 2055, with significant residual tailpipe emissions in 2050 when the domestic net-zero constraint binds. This implies that slower rates of EV uptake will require either residual transport sector emissions to be offset or to be made carbon-neutral by the use of synthetic drop-in fuels made from renewable energy sources.

Figure 8 | Energy-service efficiency (fuel economy, L-gasoline-eq./100-vehicle-km); and tailpipe emissions (g-CO_2e/vehicle-km) of the light-vehicle fleet (passenger vehicles and light commercial vehicles). Here we assume tailpipe emissions only occur from ICEs with gasoline: 69.6 g-CO_2e/MJ_{LHV}, diesel: 70.4 g-CO_2e/MJ_{LHV}, LPG: 61.5 g-CO_2e/MJ_{LHV}; and noting that 1 L-gasoline-eq. = 32.0 MJ_{LHV}.

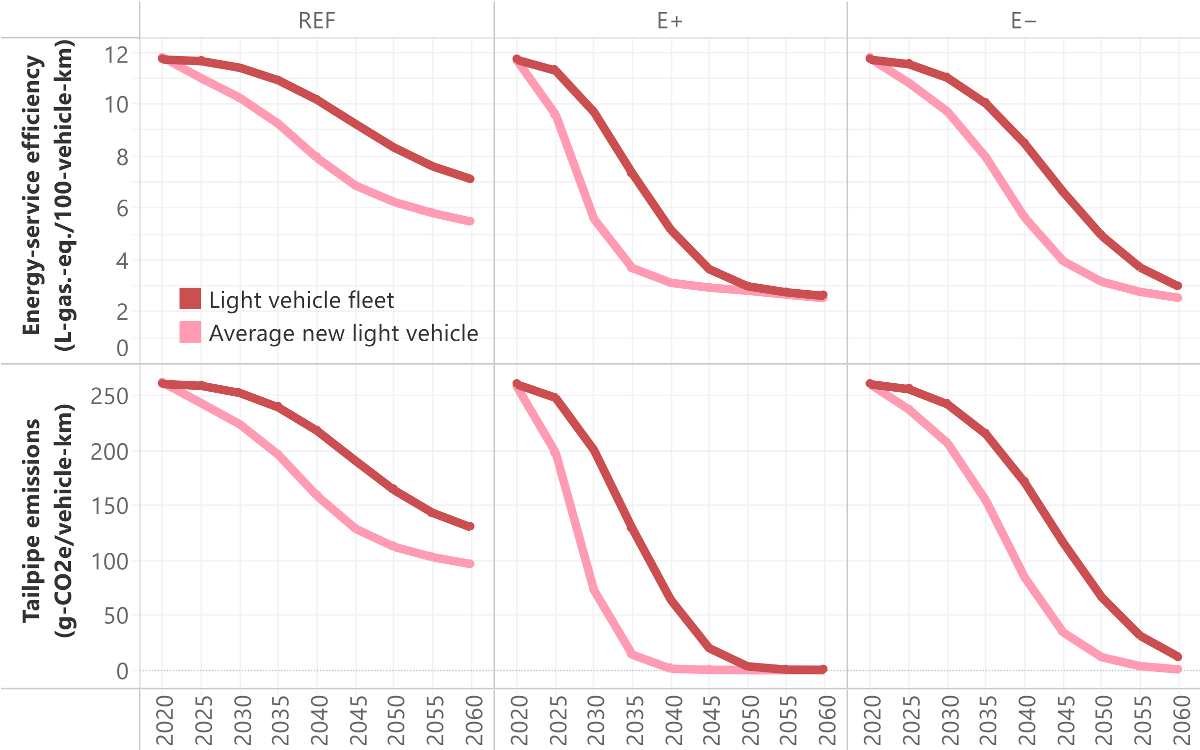
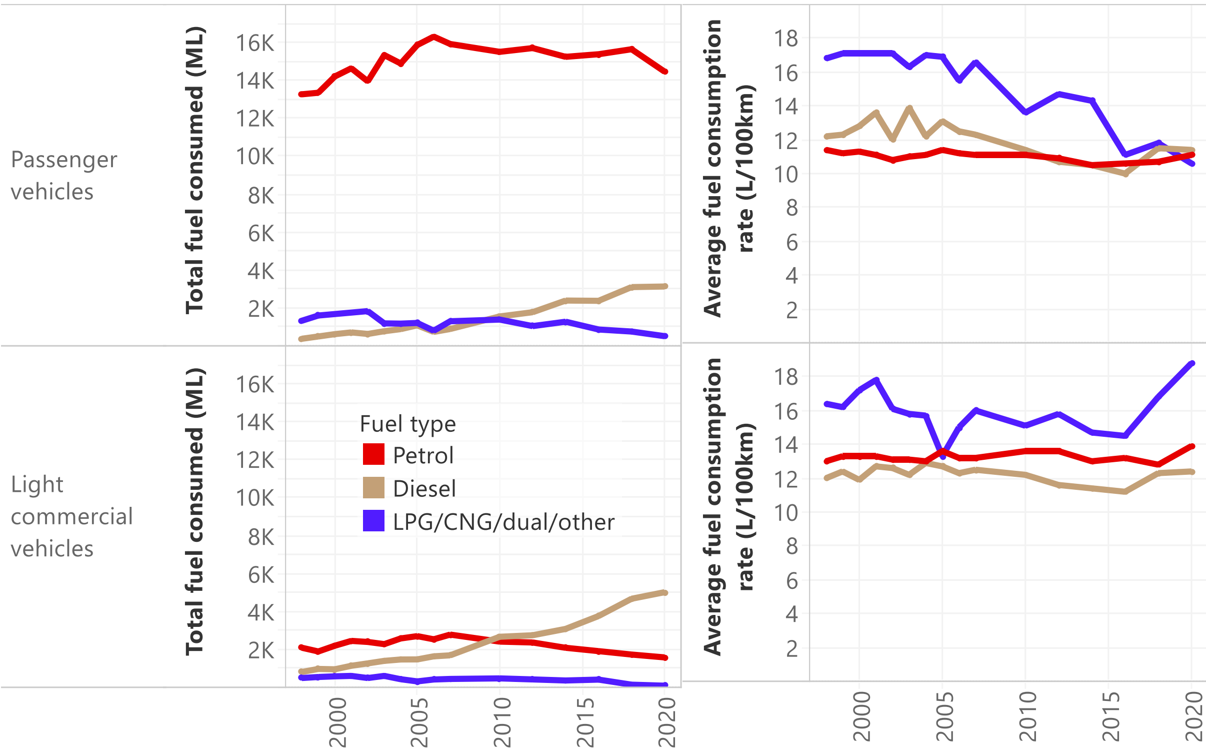


Figure 9 | Historical total fuel consumption and average fuel consumption rate for light-duty vehicles (passenger and light commercial) by vehicle fuel type (Australian Bureau of Statistics, 2020b).

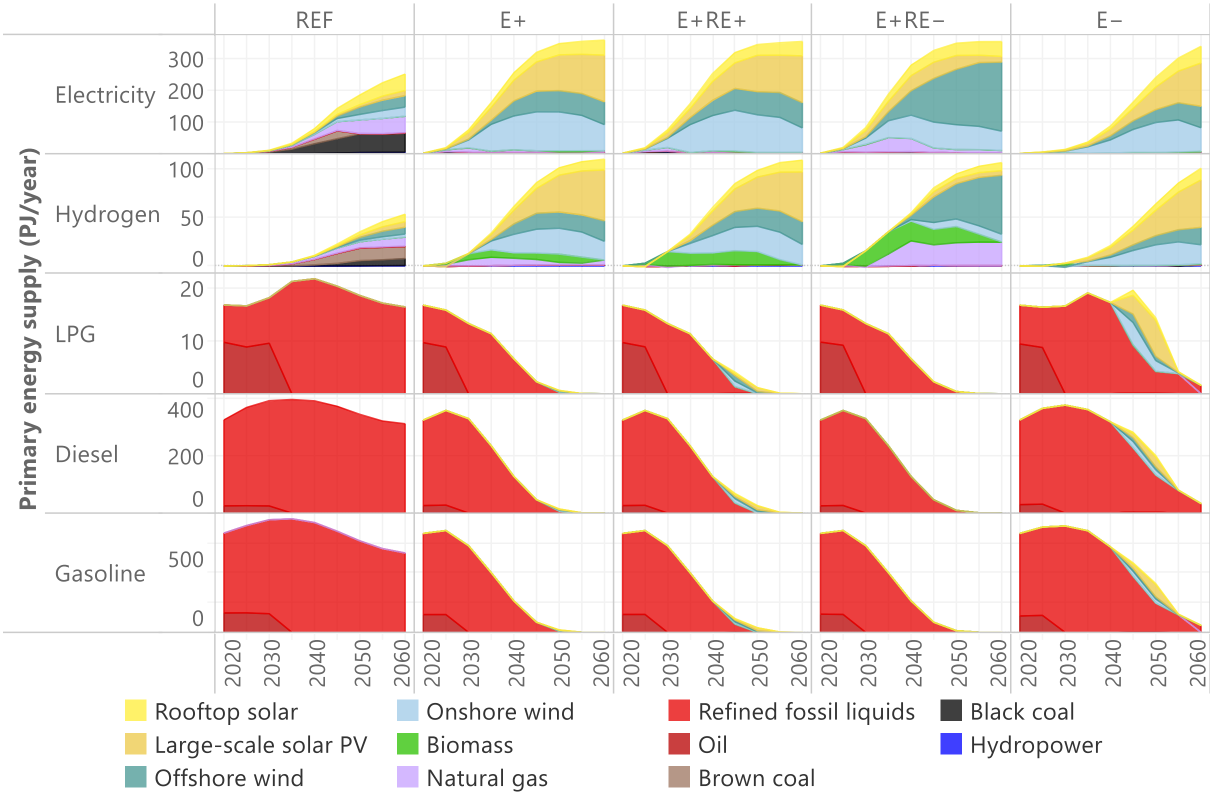


While the decarbonisation of road transport at the tailpipe is critical in the net-zero transition, it is also important to ensure decarbonisation of the supply of the road transport final energies. This aspect is optimised in Net Zero Australia's supply-side modelling across various scenarios and given the system-wide emissions constraint. Figure 10 presents the primary energy compositions that were found to supply the five different light-duty transport final energies: electricity, hydrogen, LPG, diesel and gasoline. This shows that electricity and hydrogen used in light-duty transport are largely supplied by renewable electricity generation in each net-zero Scenario, with some biomass and natural gas used to produce hydrogen in the E+ and E+RE− Scenarios. This results in the new light-duty BEVs and HFCVs of the energy transition being supplied with largely emissions-free energy, as is shown in the emissions panel of Figure 10.

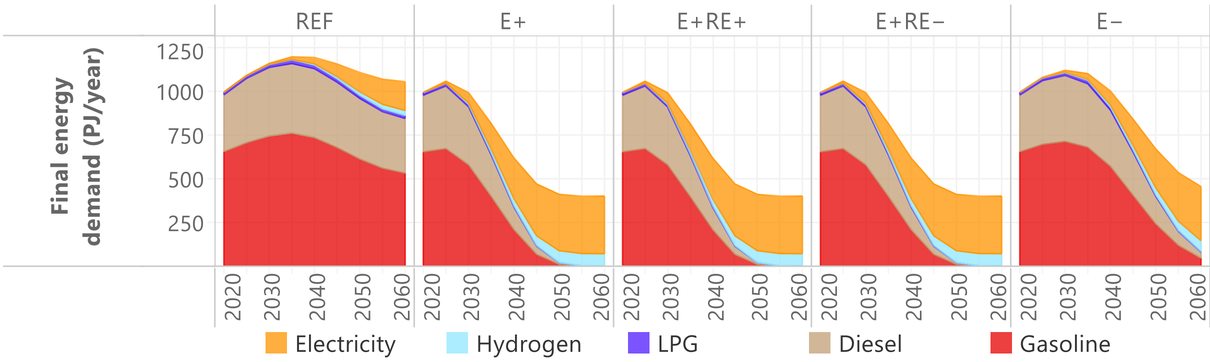
The primary energies supplying gasoline, diesel and LPG final light-duty transport energy demand are shown in Figure 10, and are largely imported in their refined form (denoted as refined fossil liquids) or as oil that is domestically refined. This primary energy supply reduces as transport energy switches to electricity and hydrogen. However, it should also be noted for the slower electrification E− Scenario with residual demand for gasoline, diesel and LPG in 2050 and beyond, that some of this demand is also supplied by renewable primary energy, which is then converted to synthetic liquid fuels via hydrogen electrolysis and Fischer-Tropsch processes. This has the effect of reducing the emissions from the liquid fuel final energy demand for E− with only low levels of residual emissions needing to be offset in other modelled sectors.

Figure 10 | Light-duty transport (a) primary energy supply for various final energy types, (b) total final energy demand, and (c) annual GHG emissions in final energy.

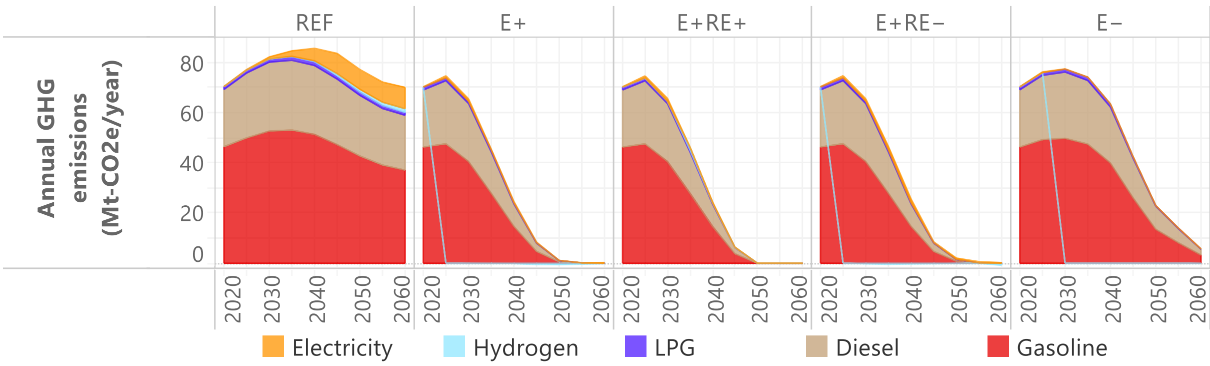
(a) Primary energy supply for various final energy types



(b) Final energy demand, by final energy type



(c) Annual GHG emissions, by final energy type



3.3 Spatial distribution of the light-duty fleet

Geographic distribution of the 2020 stock of modelled vehicles of all classes is based on the ABS' 2020 Motor Vehicle Census (Australian Bureau of Statistics, 2020a), which provides registered vehicle data by Australian postcode. During energy-system modelling, the initial stock postcode data was aggregated to the 15 modelled NZAu zones. Here we have now disaggregated the modelled vehicle stock over the modelling horizon from the 15 NZAu zones back to postcode level. This is done using the assumption that, for a given zone, the proportional distribution among constituent postcodes of vehicles of each vehicle class is constant over the modelled horizon. Because of the very granular nature of postcode level data, we present vehicle stock data below aggregated at higher geospatial levels.

Figure 11 presents the modelled light-duty vehicle stock by state of registration, showing that each state exhibits a similar transition to battery electric LDVs. It can also be seen that total LDV growth is highest in VIC and WA, whose populations are projected by the ABS to experience the highest growth rate. In contrast LDV growth is lowest in those states with lowest projected population growth, e.g. SA and TAS.

Figure 12 shows the total number of light-duty BEVs by ABS statistical area level 4 for the E+ Scenario and selected years. Maps are also included in Appendix A showing zoomed in selections of certain regions. These show that light-duty BEV growth is greatest in SA4 regions closest to capital cities, as is expected with Australia's population distribution. We note also that the projected spatial distribution of BEVs does not account for income by post-code and corresponding higher BEV uptakes in those with higher average income. However, this is not expected to have a significant influence on the macro-scale, spatially aggregated trends examined in this report.

Figure 11 | Light-duty vehicle stock by state of registration and vehicle propulsion type.

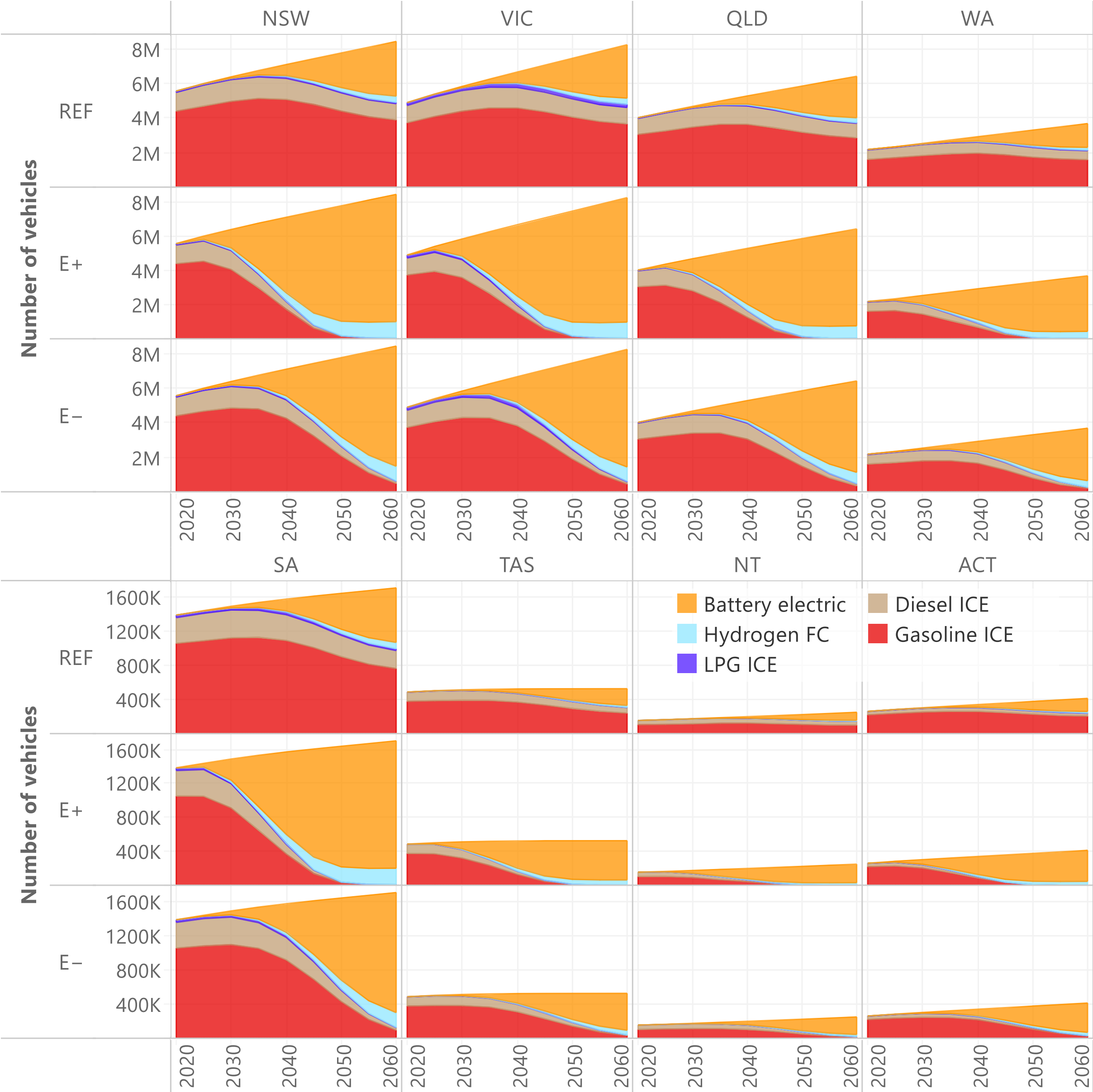
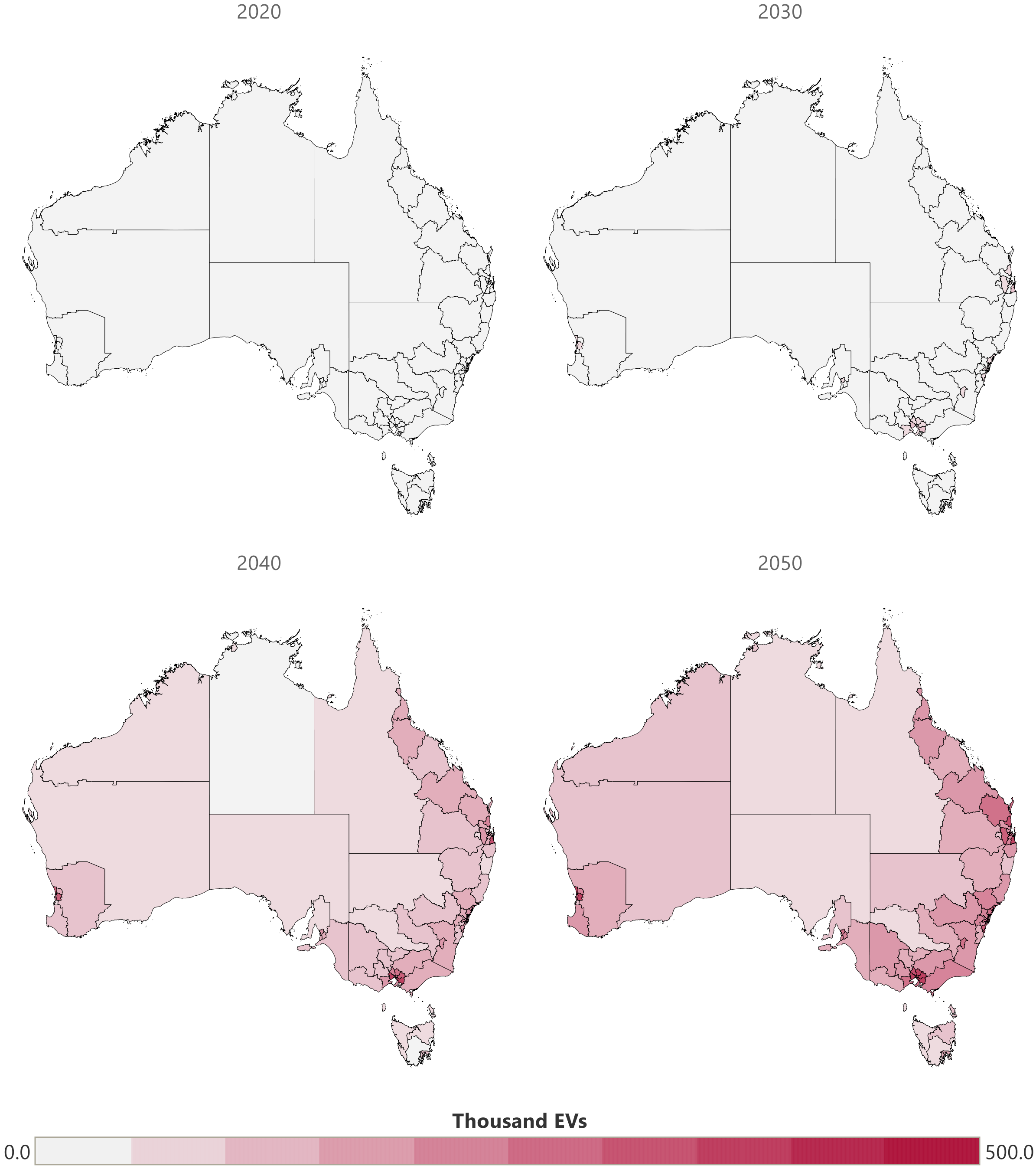


Figure 12 | Number of light-duty BEVs in the E+ Scenario, by selected year and SA4 region. Postcode level stock numbers are shown here aggregated to ABS statistical area level 4 (SA4). Zoomed in maps are also shown in Appendix A.



To explore the distribution of light-duty BEV growth further we use the ABS's *Remoteness Structure*, which designates 5 classes of remoteness based on measures of relative access to services (Australian Bureau of Statistics, 2021). Here we assign each postcode a remoteness, as shown in Figure 13, based on the majority land area overlap with the ABS' 5 classes of remoteness area. Figure 14 then shows the modelled number of light-duty BEVs registered in postcodes across the 5 classes of remoteness. Across the scenarios and years modelled 64% of light-duty BEVs are located within *Major Cities*, with a further 22% located in *Inner Regional Australia*. This suggests that the vast majority of BEV enabling infrastructure could be located in capital cities and their surrounds. We provide estimates below of the required *number* of public BEV chargers and enabling infrastructure, however we do not attempt to specify the *spatial distribution* of this infrastructure.

Figure 13 | The *remoteness* of Australian postcodes, based on the ABS' Remoteness Structure, which is an objective measure of relative access to services using the Accessibility and Remoteness Index of Australia (ARIA+), produced by the Hugo Centre for Population and Migration Studies at the University of Adelaide (Australian Bureau of Statistics, 2021).

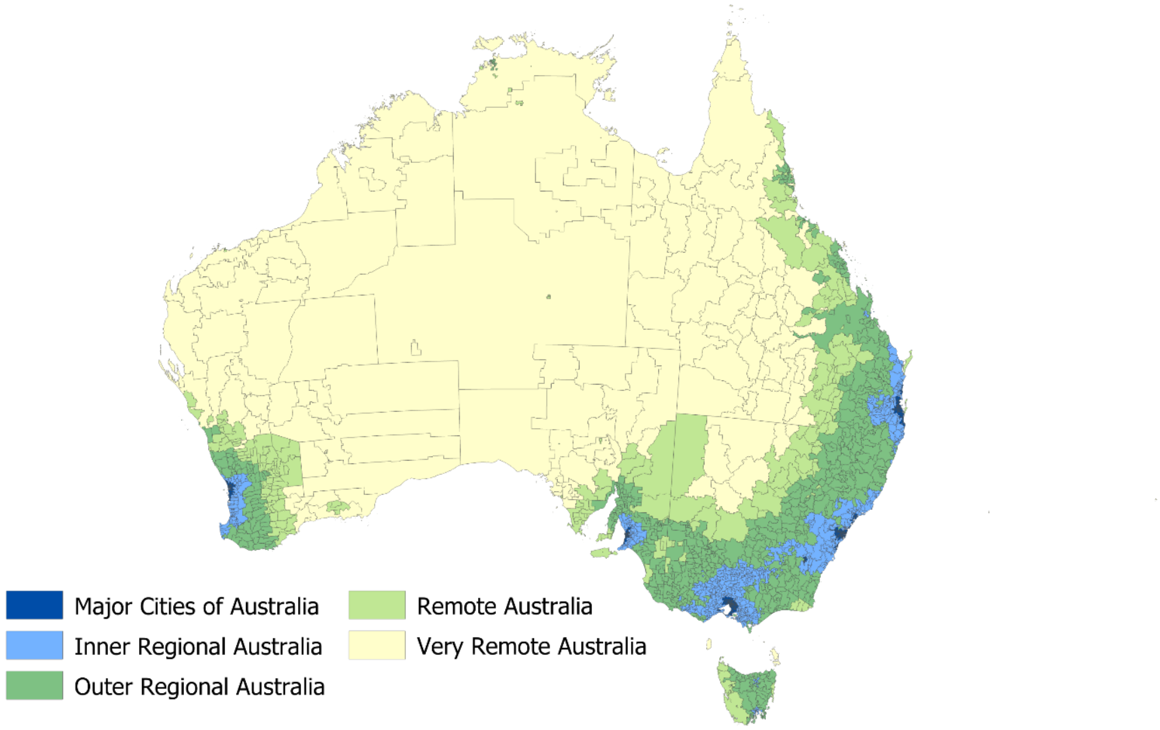
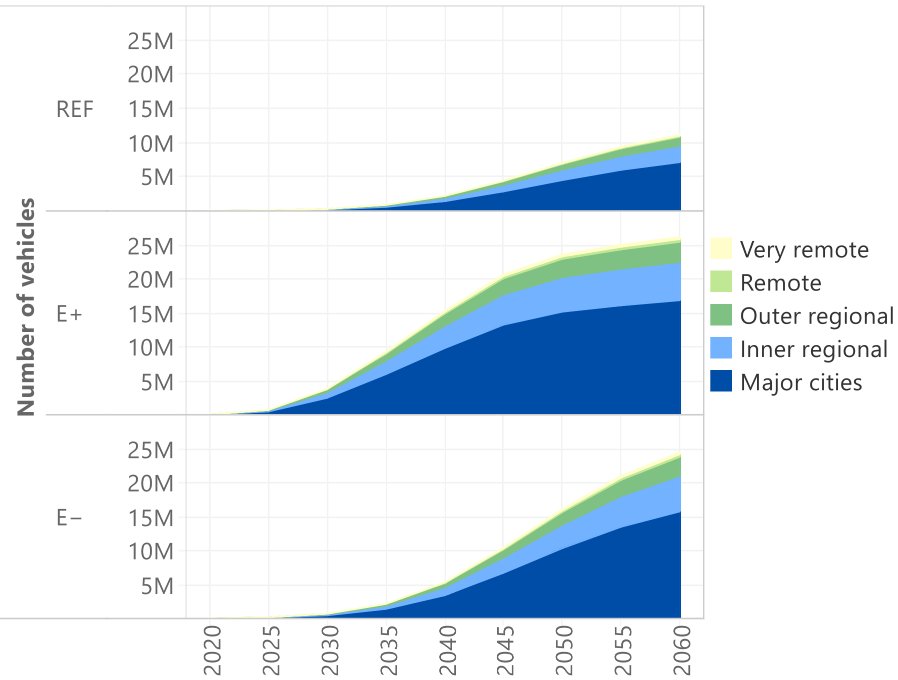


Figure 14 | Number of light-duty BEVs, by the remoteness of their postcode of registration, and by Scenario and year.

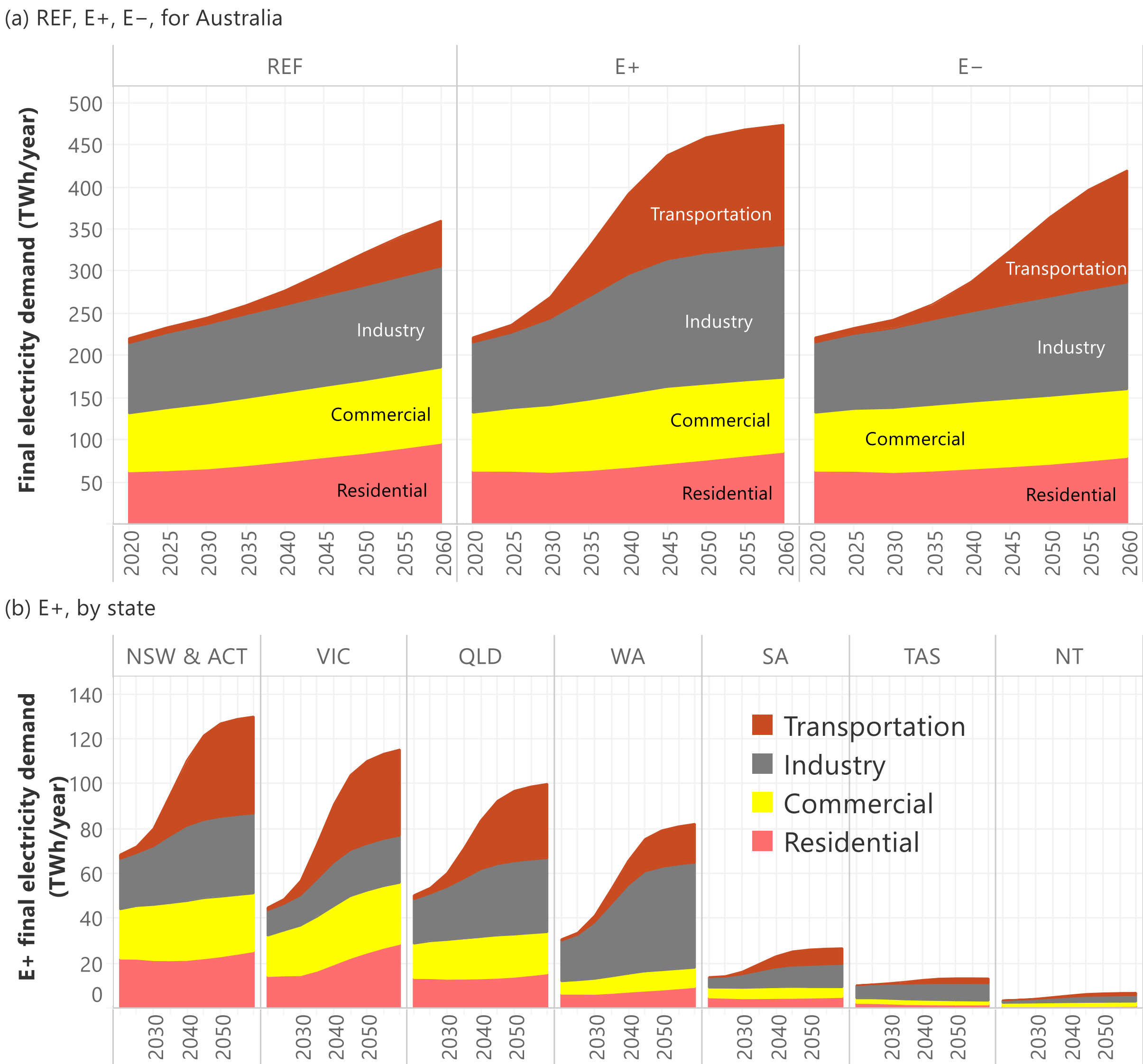


3.4 EV charging

3.4.1 Electrical energy demand

The uptake of BEVs implies significant growth in final demand for electricity, which is presented in Figure 15. Transportation is the end-use sector undergoing the greatest increase in final demand for electricity in all Scenarios, with the largest and most rapid growth occurring in E+. Across the country, the final electricity demand of the transport sector in the E+ Scenario increases from 6 TWh in 2020 to 137 TWh in 2050. Figure 15 also shows that this increased transport electricity demand growth occurs in all states and territories. Transport grows to account for a final electricity demand share between 17% (in TAS and NT) and 34% (in VIC) of total final electricity. Such a significant growth in electricity demand characteristics will require detailed consideration of many things, including electricity network augmentation (particularly distribution networks); the change in time-dependent demand profile and any potential flexibility afforded by BEVs; and other required enabling infrastructure like public BEV chargers.

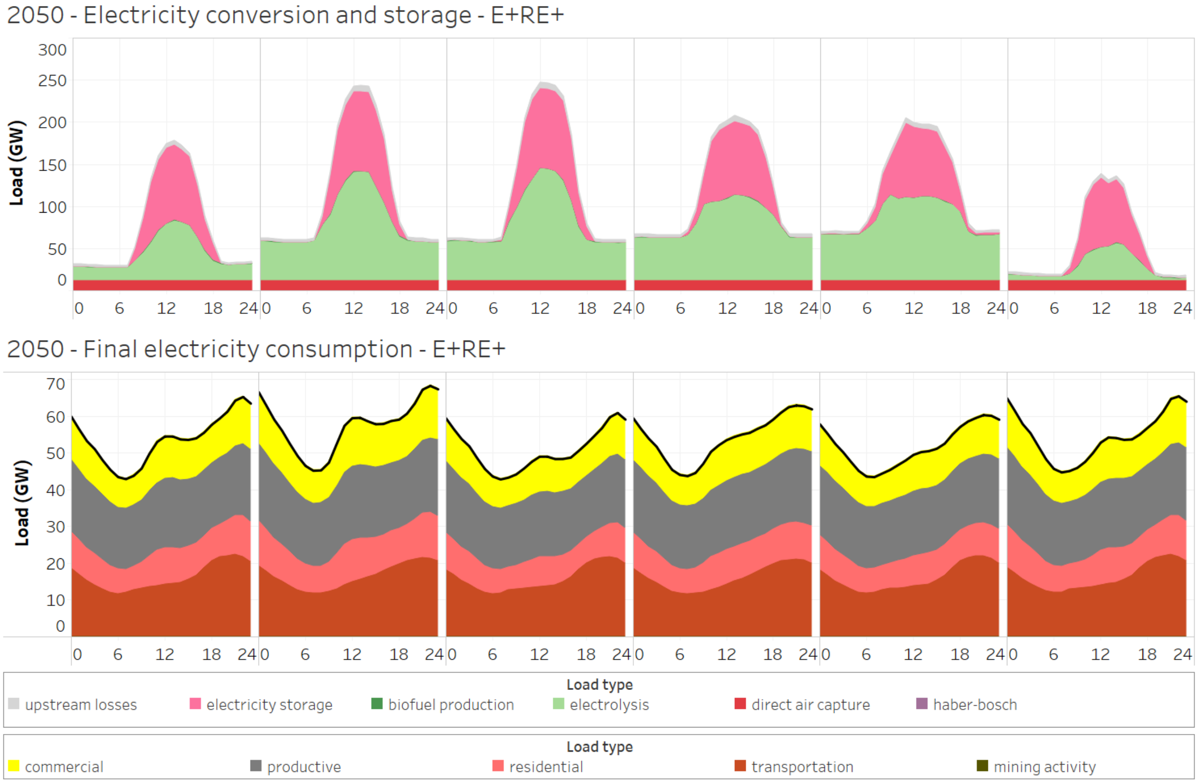
Figure 15 | (a) Final electricity demand by end-use sector modelled for the demand-side scenarios, REF, E+, and E−; and (b) final electricity demand for E+ only by end-use sector and state/territory.



NZAu's supply-side modelling considers hourly operations of the electricity system and the role of electricity storage in balancing electricity supply and demand. However, the role of flexible loads, such as flexible electric vehicle charging has not been considered in the present work, but could potentially have an important impact on hourly electricity system operations. Previous similar modelling in the Net Zero America project, allowed up to 70% of passenger and light commercial vehicle charging volume to be shifted by up to 8 hours, relative to typical consumption profiles at a small cost penalty, if the model finds that to be least-cost optimal. This potential shifting of BEV charging load can have the effect of avoiding demand for more costly electricity generation at certain times, and may avoid need for network (transmission and distribution) augmentation, while incurring a small opportunity cost associated with diverging from typical consumption patterns. More detailed modelling that is outside the scope of this project is required to test such assumptions further.

Figure 16 presents the hourly domestic electricity load profiles in 2050 for the E+RE+ Scenario across a subset of modelled days. This shows that transport final electricity demand has a significant influence on daily domestic final electricity load profiles, but that final electricity fluctuations are small relative to the load shape of electricity storage. Similar results are found for the other supply-side Scenarios modelled. Nevertheless, the transport final electricity load is shown in Figure 16 to peak in the evening, which is approximately coincident with, and therefore exacerbates, the peak final electricity demand. Here it is clear that the potential for flexible BEV load shifting could play a role in shifting load from these evening peaks to earlier in the day, when solar generation is significant. Shifting BEV charging away from evening demand peaks could serve to ease loads on distribution networks, as distribution network capacities and any required augmentation are driven in large part by peak demand. Shifting BEV charging to day-time hours could be enabled through roll out of workplace and destination public charging infrastructure.

Figure 16 | Hourly domestic (all regions) load profiles in 2050 across a subset of modelled days, by load type, modelled for the E+RE+ Scenario. Intermediate electricity consumption in conversion and storage technologies is shown on the top band, while the bottom band shows final electricity load across disaggregated end-use sectors.



3.4.2 Estimating the number of charging stations nationally

A large degree of optionality exists in the modes and locations of BEV charging during BEV rollout. Much of the future BEV charging task will be performed at home with Level 1 (~2 kW charging power from standard AC power point) and Level 2 (~7 kW dedicated AC unit) chargers. Terrill et al. (2021) showed that nearly 90% of Australian households live in detached or semi-detached houses (around a quarter of whom are renters), suggesting that a majority of Australian households can install home chargers. However, it has also been shown that investment in *non-residential* charging infrastructure is needed to support and even incentivise the transition to BEVs (Hall and Lutsey, 2017), particularly:

- if workplace and destination charging is able to relieve pressure on distribution networks (Szinai et al., 2020);
- for households without home charging availability, such as apartments, those without off-street parking and some rental properties (Hall and Lutsey, 2020; Terrill et al., 2021); and
- to assuage (at least initial) public concern about BEV range.

The required number of public chargers per BEV appears to be highly region specific, and dependent on a number of conditions and behaviours (Bauer et al., 2021; Hall and Lutsey, 2017; International Energy Agency, 2022), namely:

- access to private and workplace parking;
- housing and population density;

- commuting patterns; and
- the penetration of BEVs, among others.

Notwithstanding uncertainties in the importance of each of these factors and limited BEV and charging infrastructure experience in Australia, we here provide estimates of the number of non-residential BEV charging plugs that may require investment in unison with the modelled rollout of electric light-duty transport.

Public charging can include:

- urban fast charging and motorway charging stations with dedicated DC fast chargers of 50-150 kW charging power, or even up to 250 kW in ultra-fast chargers;
- destination charging, e.g. consumer and public interest locations with car parking, such as supermarkets, museums; and
- other curb-side chargers open to public use.

In addition, *workplace* charging may be included along with *public* charging in a broadly defined *non-residential charging* category, however these classifications of public and workplace charging categories are not entirely exclusive, due to some workplace charging also being available to public.

The Net Zero America Project estimated the numbers of non-residential EV chargers using charger deployment rates sourced from (Wood et al., 2017), which differentiate between requirements of cities, towns and rural areas. However, those rates were calculated for vehicle fleets that contained a substantial proportion of plug-in hybrid EVs. In another study – Charging Up America – Bauer et al. (2021) assessed charging needs in the USA through 2030. They found that by 2030 with 26 million EVs on USA roads 41 public EV chargers would be needed per 1000 EVs (17% of which are DC fast chargers), supplemented by an additional 51 workplace chargers, to total 92 non-residential EV chargers per 1000 EVs. They also showed that this need for public EV chargers decreases as EV penetration increases, due to network effects that mean demand and supply of EV charging can be more easily matched.

Here we use the same rate of charger deployment as was found for the USA average (Table 2), and consider that this rate is constant across all modelled regions, due to the relatively similar modelled speed of BEV uptake across the country, and with no variation across different remoteness regions. However, we acknowledge that while Australia has a similarly high-share of single family dwellings (with car parking) to the USA (International Energy Agency, 2022; Terrill et al., 2021), public and workplace EV charging requirements in Australia will be specific to Australian circumstances and differ from those of the US. Nevertheless, we expect these to provide a reasonable first approximation.

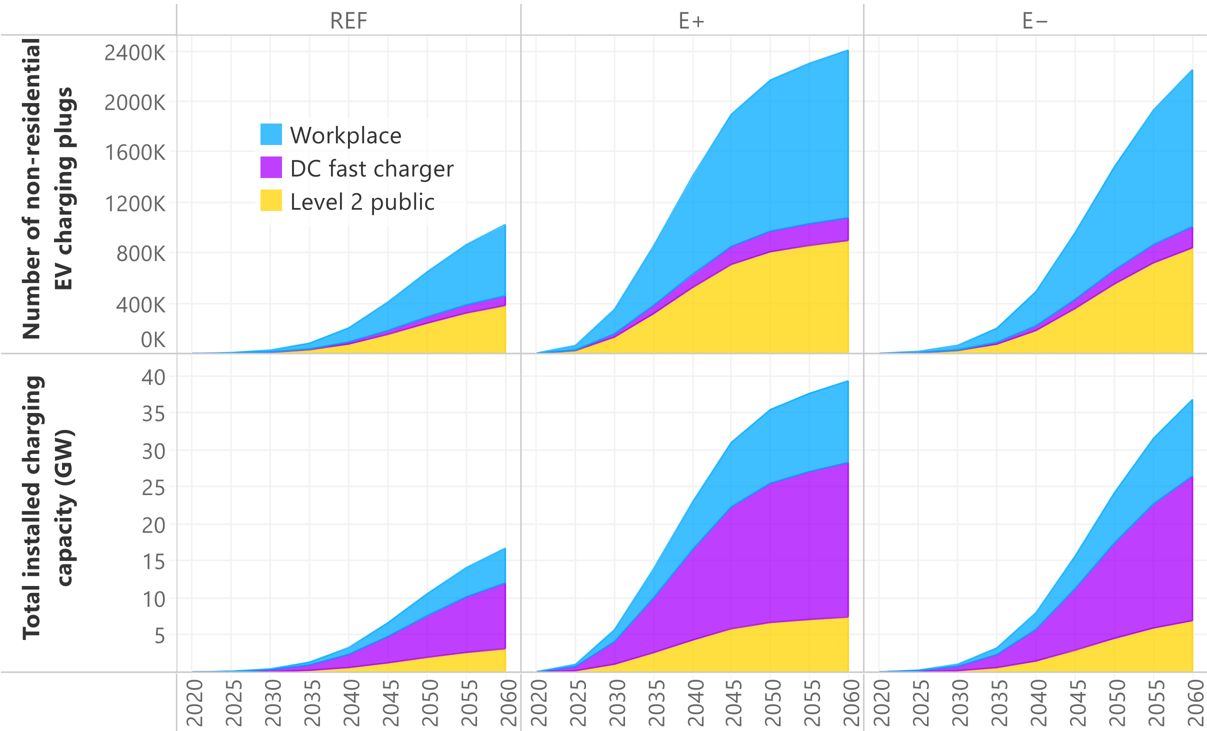
Table 2 | Estimated number of non-residential EV chargers required per 1000 BEVs, across different charging modes and power ratings. The values are adapted from those of Bauer et al. (2021).

Charger type	Chargers per 1000 BEVs
Public level 2	34
DC fast charger	7
Workplace level 2	51
Total non-residential	92

Figure 17 presents the estimated number and total installed charging capacity of non-residential EV charging plugs rolled out alongside the light duty vehicle transition. In E+, with 24 million BEVs on Australian roads by 2050, we estimate that 2.1 million non-residential EV charging plugs would be required, comprised of 1.2 million workplace charging plugs, 810 thousand public level 2 chargers and 160 thousand DC fast chargers. Figure 17b and Figure 18 show that the majority of these chargers would be located in the most populous regions of Australia, following the regional distribution of BEVs. We note that the cost of EV charging infrastructure has been incorporated in the energy system modelling, as is outlined in the project's MASS document (Net Zero Australia Project, 2022), and is presented as combined total residential and non-residential BEV charging costs as part of the demand-side costs in Figure 3.

Figure 17 | Estimates of national LDV non-residential charging infrastructure: (a) number of non-residential EV charging plugs and total EV charging capacity, by charger type; and (b) number of plugs for the E+ Scenario, by state/territory.

(a) National non-residential charging infrastructure



(b) LDV charging infrastructure for E+, by state/territory

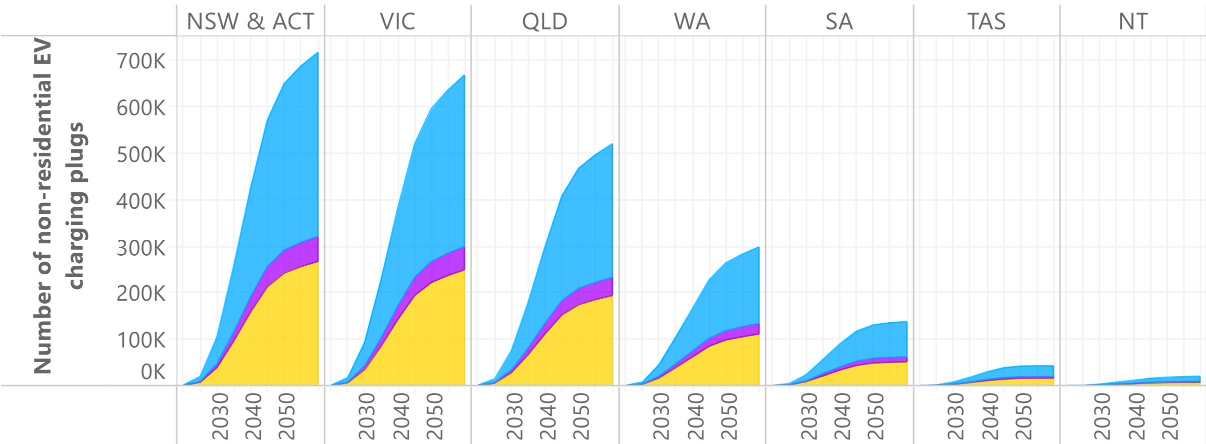
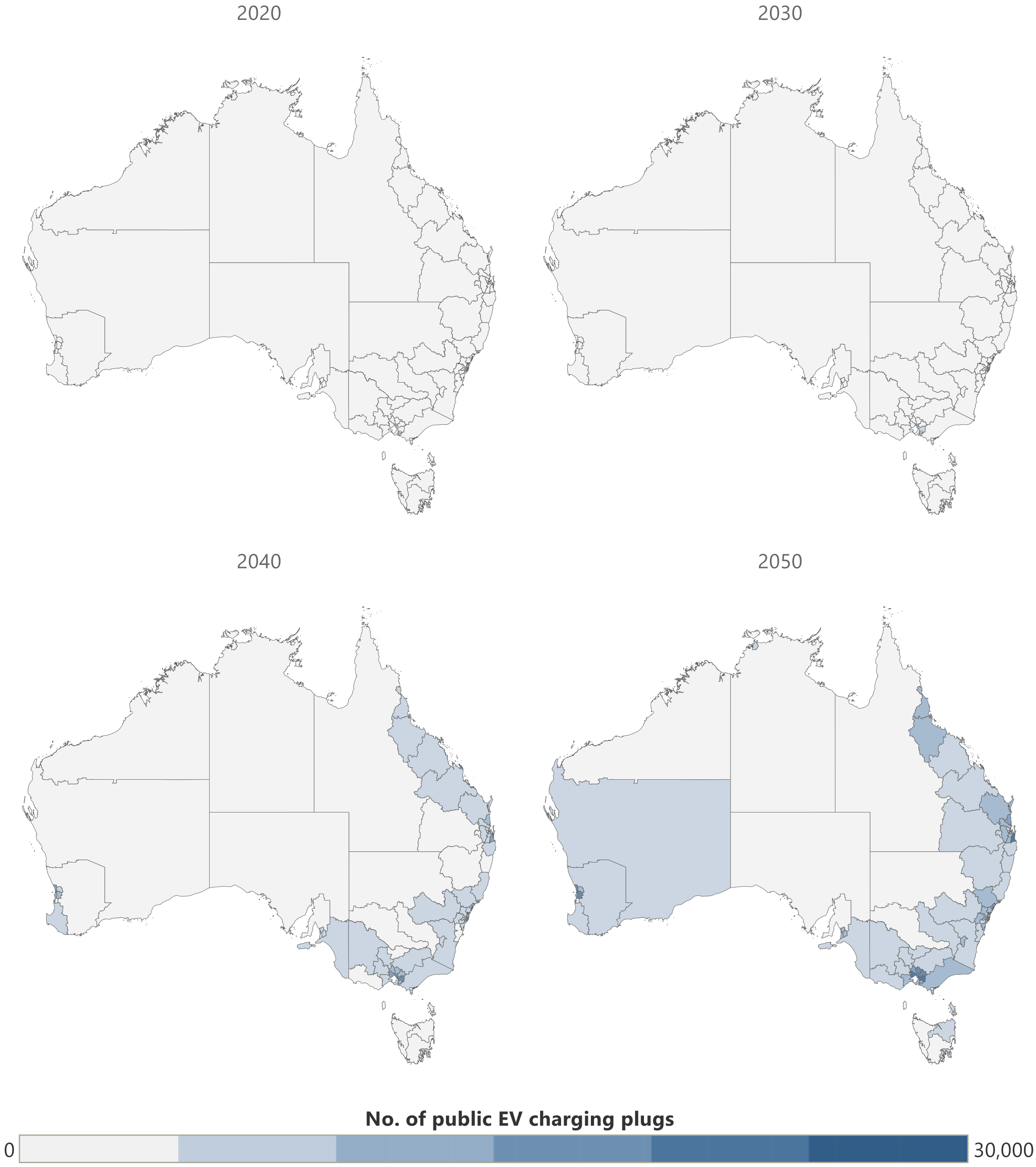


Figure 18 | Number of *public* EV charging plugs (Level 2 public and DC fast charger) in the E+ Scenario, by selected year and SA4 region. Postcode level charging plug numbers are shown here aggregated to ABS statistical area level 4 (SA4). Zoomed in maps are also shown in Appendix A.

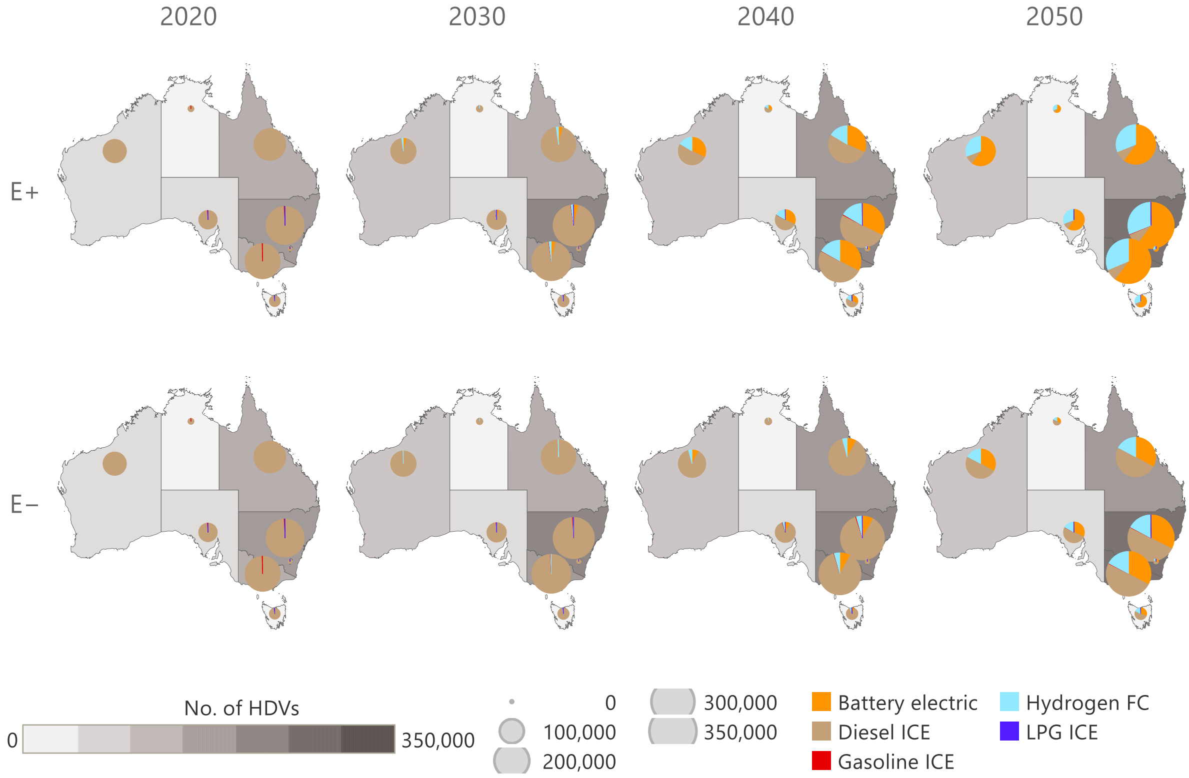


3.5 The heavy-duty fleet

Figure 6 above shows that heavy-duty vehicles (HDVs, which include the classes: rigid & other trucks; and articulated trucks) comprise 4% of the on-road transport vehicle fleet, but account for 21% of GHG emissions and a disproportionate amount of other pollutants (NSW EPA, 2019; Terrill et al., 2022). We have also shown previously (Figure 5) that the HDV fleet is decarbonised by phasing out the sales of diesel ICEs and replacing those with sales of battery electric and hydrogen fuel-cell vehicles. The E+ Scenario implements this phase out by 2040, which is in line with other international heavy-duty transport decarbonisation plans, such as the UK's recent pledge for the sales of all heavy goods vehicles weighing less than 26 tonnes to be zero-emissions vehicles by 2040 (Department for Transport, 2021).

Figure 19 then shows the evolution of the HDV fleet by state/territory for the E+ and E− Scenarios. The implemented decarbonisation strategy results in the majority of HDVs being battery electric or hydrogen fuel-cell vehicles by 2050 in the E+ Scenario, while the transition is significantly slower in the E− Scenario. Figure 19 also shows that the fleet of HDVs is relatively distributed across the country, with the largest populations in eastern Australia, but with SA and WA also having significant HDV stock.

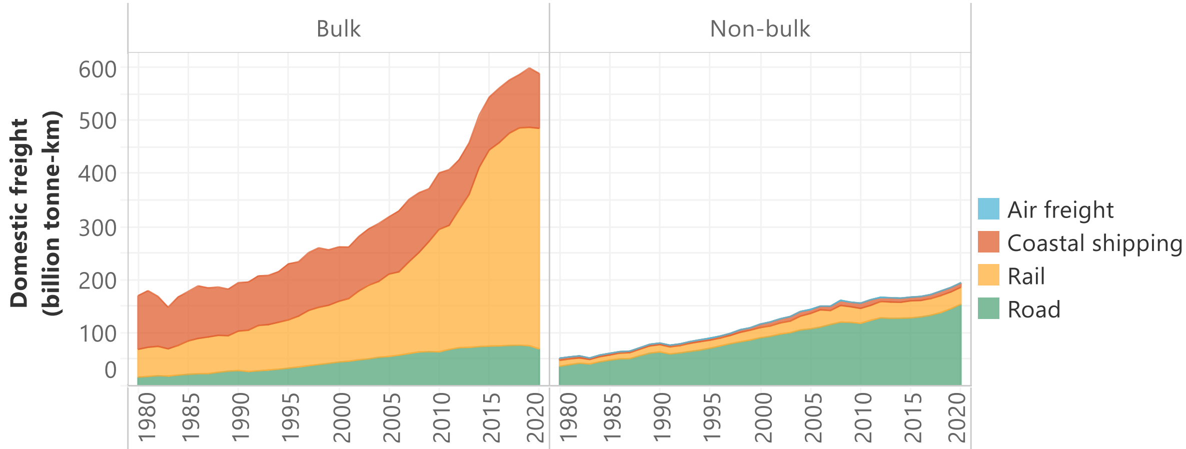
Figure 19 | Number of heavy-duty vehicles by state/territory of registration, and by Scenario, year and fuel type.



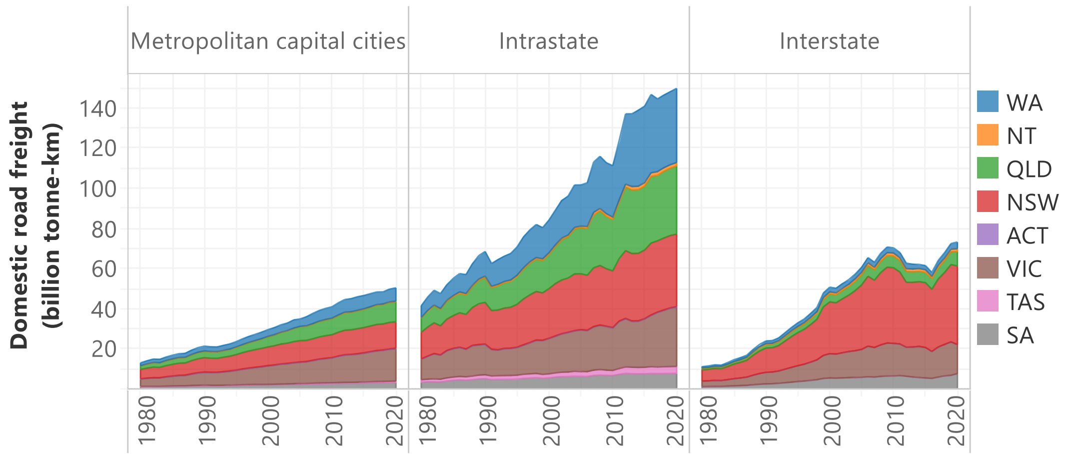
Australia's reliance on HDVs for road freight is demonstrated in Figure 20, which presents domestic freight trends over the last 40 years (Bureau of Infrastructure and Transport Research Economics, 2021a). Figure 20 presents trends in bulk and non-bulk domestic freight by mode of transport, where: bulk freight comprises large quantities of homogenous product, characterised by low unit value but high volume; while non-bulk freight comprises containerised or otherwise unitised heterogeneous goods, being moved between diffuse origins and destinations. Bulk domestic freight is dominated by the rail transport of iron ore and coal commodities from extraction points to ports because rail transport integrated into extractive industries offers economies of scale for transport of such bulk commodities over long distances. On the other hand, non-bulk freight is dominated by road transport with HDVs, much of which is intrastate – particularly within capital cities – transport of goods over shorter distance, as also shown in Figure 20.

Figure 20 | Domestic freight statistics of (a) bulk and non-bulk freight by mode of transport; and (b) road freight (of both bulk and non-bulk goods) by regional span and state/territory (Bureau of Infrastructure and Transport Research Economics, 2021a). Note that *Metropolitan capital city* road freight is a subset of *Intrastate* road freight.

(a) Historical domestic bulk and non-bulk freight, by mode of transport



(b) Historical domestic road freight, by regional span and state/territory

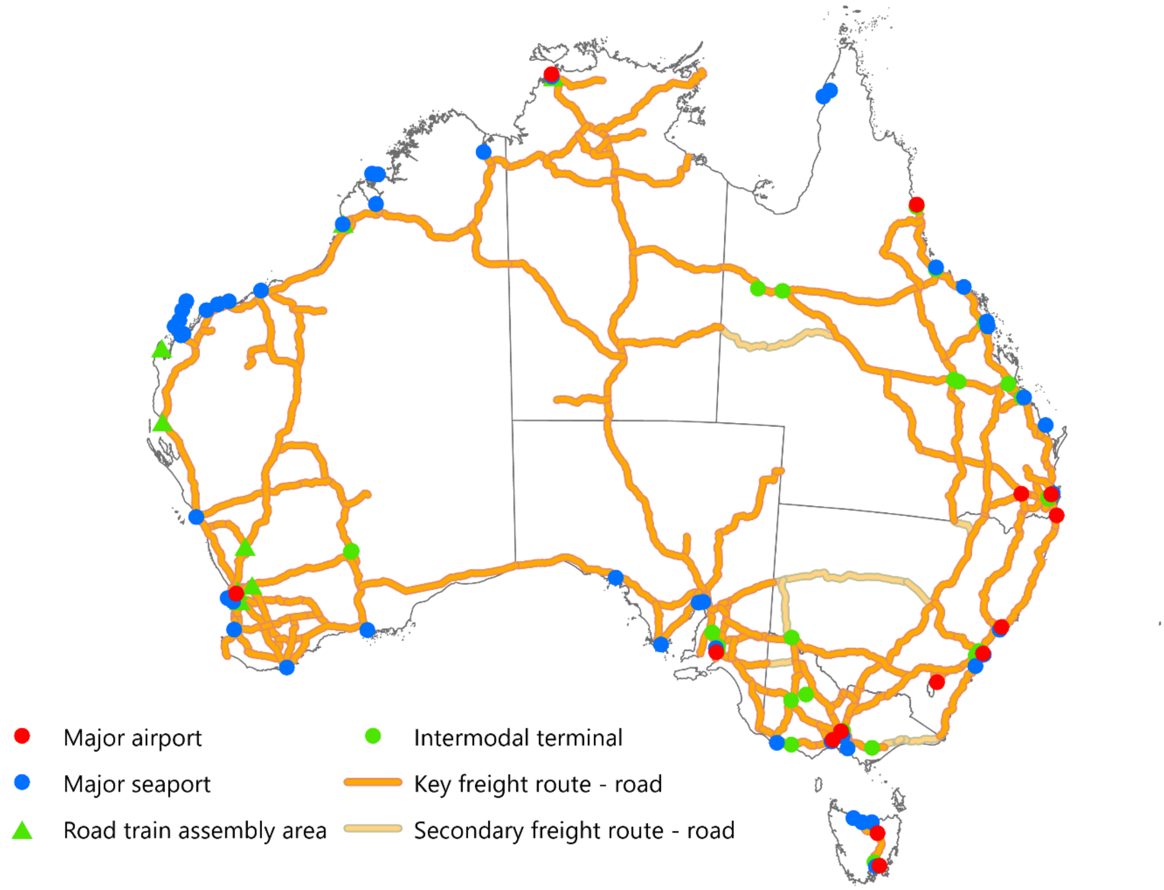


In 2020 the transport of goods within capital cities accounted for 23% of the total domestic road freight task and (34% of the intrastate road freight task), as shown in Figure 20. This shorter distance freight task could be preferentially performed by the battery-electric HDVs modelled in NZAu, due to the better suitability of BEVs to shorter distance transport. This would require a network of HDV charging infrastructure to be established within capital cities by 2040 for the E+ Scenario (Figure 19) that expands to serve the full fleet of city-based HDVs by 2050.

Figure 20 also shows that 45% of the domestic road freight task in 2020 consisted of *intrastate* transport across the regional span of the state (not entirely within capital cities), and 33% consisted of *interstate* road freight. It is likely that this longer distance task will be undertaken by a greater proportion of hydrogen fuel cell HDVs. However, a key practical barrier to this longer distance road freight transition is the availability of refuelling infrastructure (Terrill et al., 2022). Figure 21 shows Australia's key and secondary road freight routes with locations of air and seaports. This shows the road network that would require significant build out of zero-emissions HDV refuelling infrastructure for the modelled transition. Figure 20 then provides an indication of where this HDV refuelling infrastructure would be most required. The largest *intrastate* freight task that is not entirely in capital cities can be seen in WA and QLD, which have large land areas with significant interconnected road freight networks, while the largest *interstate* road freight task is associated with HDVs from NSW and VIC travelling interstate.

Both the continuing growth of Australia's road freight volumes and the need for the HDV fleet to transition to vehicles fuelled with electricity and hydrogen necessitates a coordinated strategy for deploying refuelling/recharging infrastructure. This is a large and separate undertaking that will need to be developed in advance of the HDV transition, which we have shown may occur at rapid pace in the 2030s in the E+ rapid electrification Scenario.

Figure 21 | Australia's key and secondary road freight routes and locations of air and seaports, and road freight infrastructure (Department of Infrastructure, 2022).



3.6 Road vehicle capital and operating costs

In this work we have used vehicle capital cost projections provided by CSIRO's *Electric vehicle projections 2021* report (Graham and Havas, 2021), as detailed in our MASS document (Net Zero Australia Project, 2022), and shown in Figure 22. The projections show that internal combustion engine vehicles (ICEs) currently have the lowest upfront costs across all vehicle classes, but that BEVs and Hydrogen FCVs are projected to experience significant technological learning and associated cost reductions, such that by 2030 light-duty vehicles reach near cost parity with ICEs. BEV and HFCV heavy-duty vehicles also undergo this same cost reduction, but do not reach cost parity with ICEs.

Figure 22 | Vehicle capital costs used as input into NZAu modelling, based on CSIRO projections (Graham and Havas, 2021).

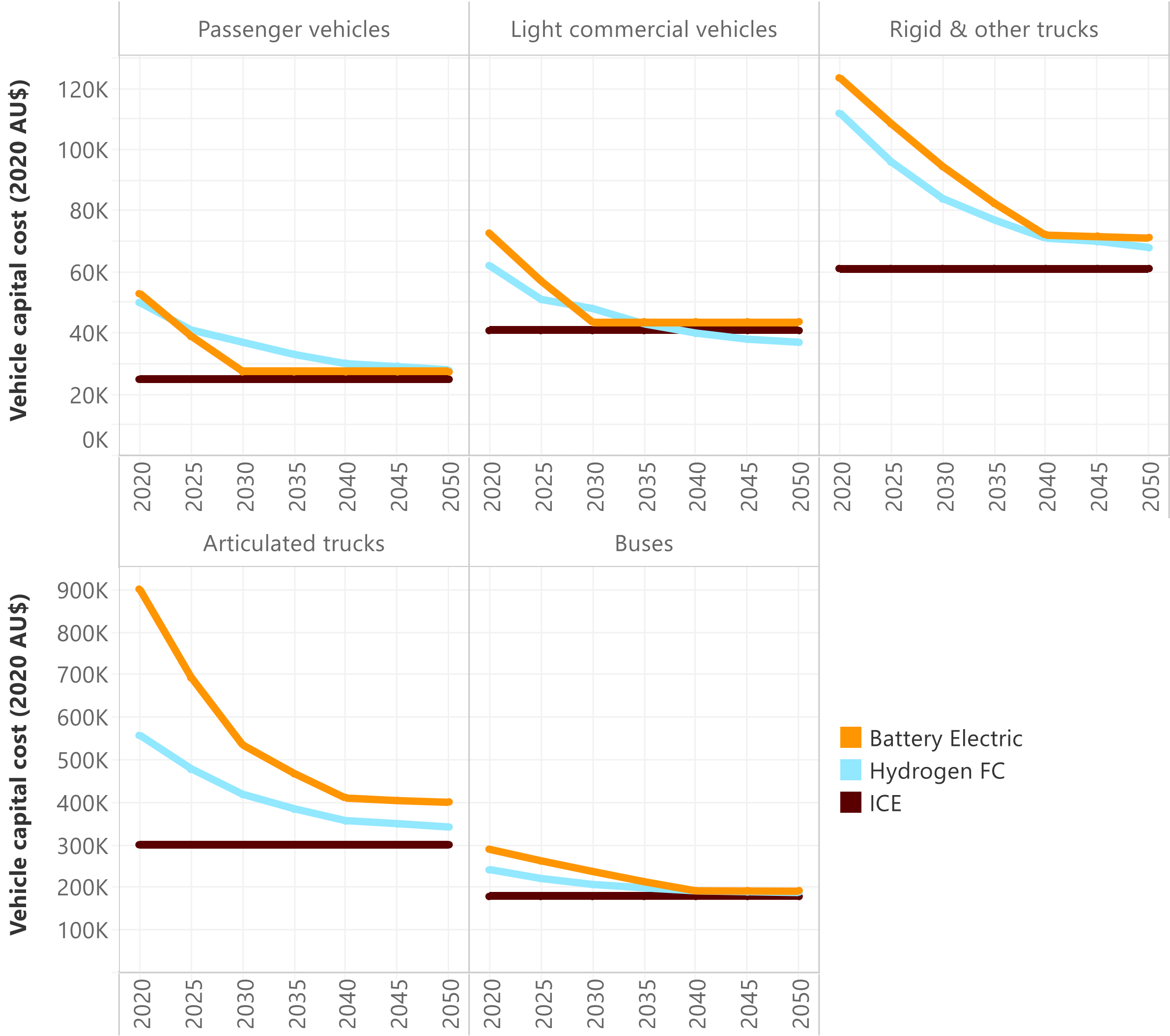
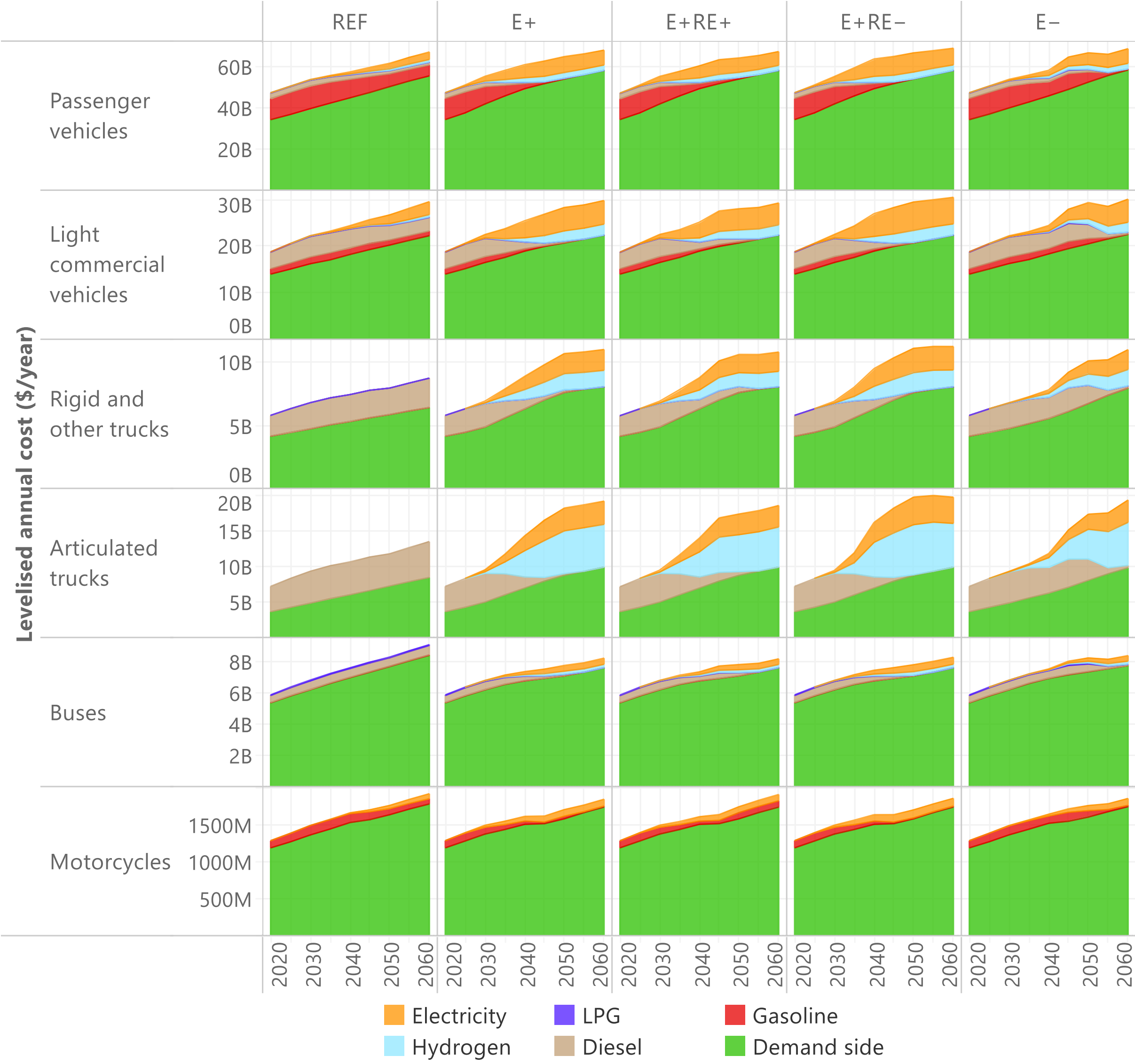


Figure 23 presents the levelised annual on-road transport system costs modelled for NZAu's Core Scenarios. This shows the levelised cost of supplying final energy demand for five final energy types and each vehicle class. Also shown are the levelised demand side costs, which include: vehicle capital costs levelised over the lifetime of a vehicle (and therefore incurred in each year from the sale of a vehicle until the end of its economic life); rewiring and charger costs associated with switching to BEVs; and annual non-energy operating costs. Figure 23 shows that demand side costs account for the majority of the on-road transport sub-sector costs, with fuel/energy costs having a 13-27% share of light-duty transport costs. This share is ~30% and ~50% for the larger rigid & other trucks and articulated trucks vehicle classes.

It is noteworthy that the modelled net-zero Scenarios do not exhibit significantly increased cost over the reference (REF) Scenario, with the light-duty vehicle classes having ~$5B./year greater demand side cost in the 2040s, which is partially counteracted by lower fuel costs. This higher demand-side cost can be attributed to the greater capital cost of BEVs and HFCVs than ICEVs in the 2020s whose levelised costs are still incurred later in the transition. We note that we model vehicle replacements to occur at the economic end-of-life. More rapid replacement of existing vehicle stock may be possible and would accelerate the road sub-sector transition. However, this would lead to some vehicles becoming stranded assets and corresponding increased demand-side transition costs.

The biggest departure of the net-zero Scenarios from REF can be seen for the heavy-duty vehicle classes whose demand-side and fuel costs are greater than those of REF by a combined $8-11 B./year (39-56%) in 2050.

Figure 23 | Levelised annual on-road transport system costs, disaggregated by demand side costs (capital, operating and infrastructure costs) and the cost of supplying final energy demand, for all supply-side Scenarios, except for E+ONS, which has similar trend to E+. Note different vertical axis scales.



We examine costs at the individual average vehicle level in Figure 24, Figure 25, and Figure 26, by normalising the levelised total annual costs for each vehicle type (size class and propulsive energy type) by the number of those vehicles (stock) operating in that year. In these figures capital costs include the vehicle capital cost, a home rewiring cost, and the cost of installing both residential and non-residential EV charging infrastructure; operating costs do not account for insurance costs, which are a small component of total costs and are not significantly different between vehicle fuel types; and we emphasise that fuel/energy costs are modelled *cost* outputs and are not any inferred *prices*.

Figure 24 shows that battery electric passenger vehicles incur capital & operating cost premiums early in the transition, but that this converges to a similar annual cost per vehicle to gasoline passenger vehicles. Annual passenger vehicle fuel/energy costs are similar across gasoline and battery electric vehicles and scenarios, until the system emissions constraint becomes binding near to 2050 when electricity costs are significantly less than gasoline.

Figure 25 exhibits similar trends for light commercial vehicles, comparing diesel LCVs with battery electric and hydrogen FC vehicles. Zero tailpipe emissions LCVs have higher capital and operating costs early in the transition which converge to diesel LCV costs. Here however, battery electric LCVs have lower fuel/energy costs than diesel LCVs, while hydrogen FC LCVs have higher fuel costs.

Taken together, these results suggest that a capital cost subsidy – or other transport sector decarbonisation policy – may be required to incentivise the initial uptake of BEV light-duty vehicles, given their lower energy costs may not sufficiently offset initially higher capital costs. Note that the average vehicle capital and operating costs of gasoline and diesel vehicles in Figure 24 and Figure 25 show significant decline from 2040 in E+. This is attributed to the majority of those vehicles reaching end of economic life (their capital costs entirely amortised) but with some portion remaining in service for a few years beyond their economic life.

Figure 24 | Levelised average annual passenger vehicle cost per vehicle, by cost component, for gasoline and battery electric vehicles in the E+ and E– Scenarios.

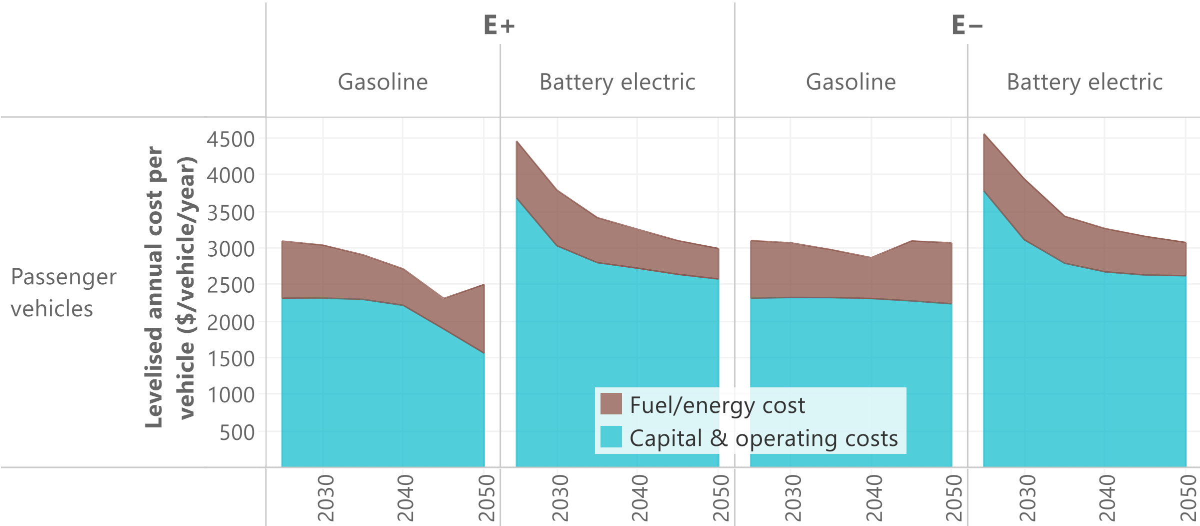
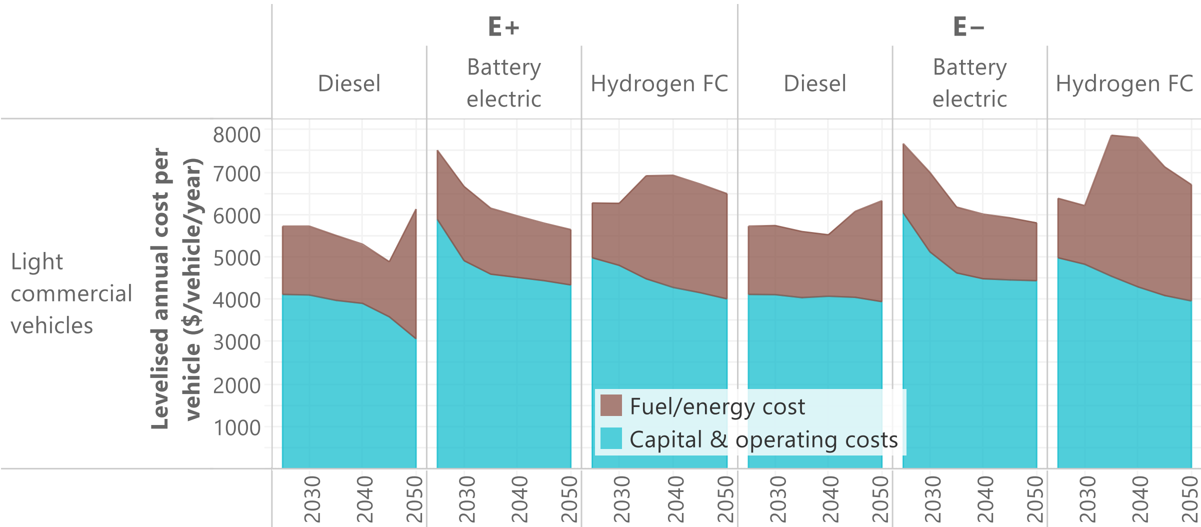


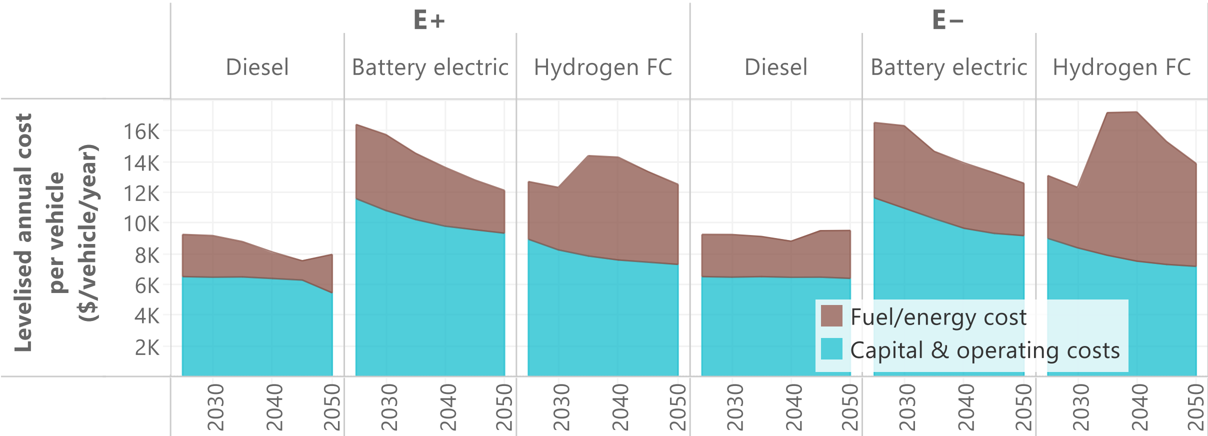
Figure 25 | Levelised average annual light commercial vehicle cost per vehicle, by cost component, for diesel, battery electric and hydrogen FC vehicles in the E+ and E– Scenarios.



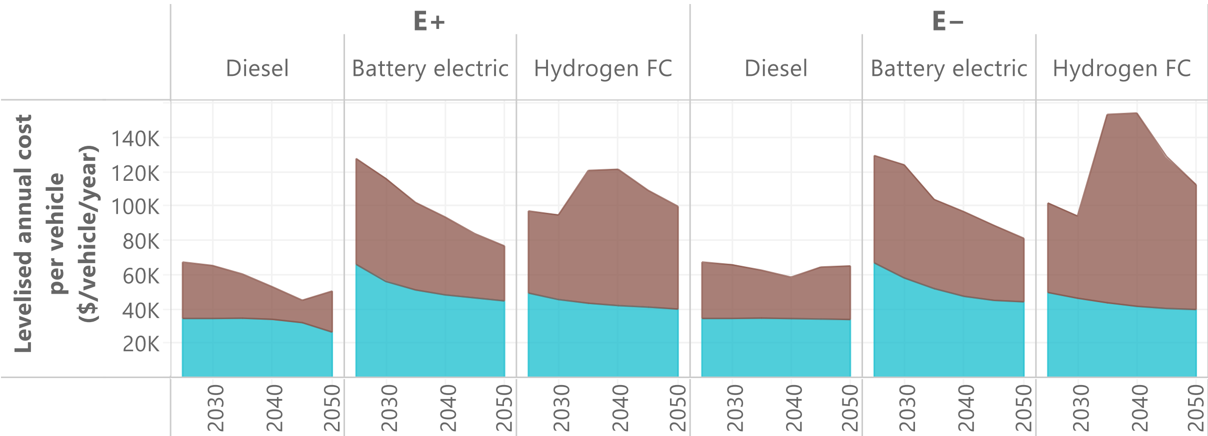
The levelised costs of heavy-duty vehicles (Figure 26) shows that both capital & operating, and fuel/energy costs of zero-tailpipe-emissions HDVs are greater than those of incumbent diesel vehicles. While capital costs of battery electric and hydrogen FC HDVs reduce with time, these never reach cost parity with diesel vehicles. Battery electric energy costs are initially almost double diesel costs and reduce slightly over time to be only slightly more costly than diesel. Hydrogen energy costs, however, are on average about 3 times the annual fuel costs of diesel HDVs.

Figure 26 | Levelised average annual heavy-duty vehicle cost per vehicle, by cost component, for diesel, battery electric and hydrogen FC (a) rigid & other trucks; and (b) articulated trucks in the E+ and E– Scenarios.

(a) Rigid & other trucks



(b) Articulated trucks



4 Aviation

Historical Australian domestic and international aviation activity data is presented in Figure 27, showing fuel consumption and energy efficiency metrics, sourced from the *Australian Energy Statistics* (DISER, 2021a) and the *Australian Infrastructure and Transport Statistics* (Bureau of Infrastructure and Transport Research Economics, 2021a). These show sustained growth in aviation fuel use until the impacts of the COVID-19 pandemic in FY2020. The aviation energy efficiency metrics also do not show significant improvement over recent years, with no apparent downward trend in international aviation fuel use per flight or per seat in the last decade, and a slight increase in domestic aviation fuel use per available-seat-kilometre over the same timeframe.

We project future energy demand for the aviation sub-sector based on drivers of population and gross domestic product, as outlined in our MASS document (Net Zero Australia Project, 2022). For domestic aviation we project energy-service demand in units of available-seat-kilometres, and use historical data for energy-service efficiency (fuel use per available-seat-kilometre) with an assumed 1.5% (1% for the REF Scenario) annual efficiency improvement. The resulting energy-service and energy demands are shown in Figure 28. It can be seen that the reduction in energy use per available-seat-kilometre in E+ avoids 146 PJ/year of fuel use in 2060 compared with the REF Scenario. However, this would require significant technological and logistical effort to improve energy efficiency at rates that are significantly greater than recent historical trends (Figure 27).

For international aviation we project only energy demand (and not energy-service efficiency) to grow in proportion to population, with an assumed 1.5% (1% for the REF Scenario) annual efficiency improvement. Again this energy efficiency gain is significantly greater than recent historical trends (Figure 27), and avoids 237 PJ/year of fuel use in 2060, relative to REF.

Note that we do not assume any aviation fuel demand switching to alternative final energies, such as electricity and hydrogen. This is due to the uncertain prospects of those alternative energy carriers to decarbonise aviation due to their less favourable gravimetric and volumetric energy density, and also because new aircraft designs require many years of flight testing before being permitted for commercial aviation. The result of this assumption is that final demand for aviation fuels will need to be decarbonised either by the supply of bio- or synthetic drop-in fuels, or through atmospheric CO_2 removal in other modelled energy sectors.

Figure 27 | Historical aviation activity data for (top) total annual domestic & international aviation fuel use, and domestic aviation energy-service demand; and (bottom) domestic & international flights, fuel use per flight, fuel use per available seat, and fuel use per available seat kilometre (Bureau of Infrastructure and Transport Research Economics, 2021a; DISER, 2021a).

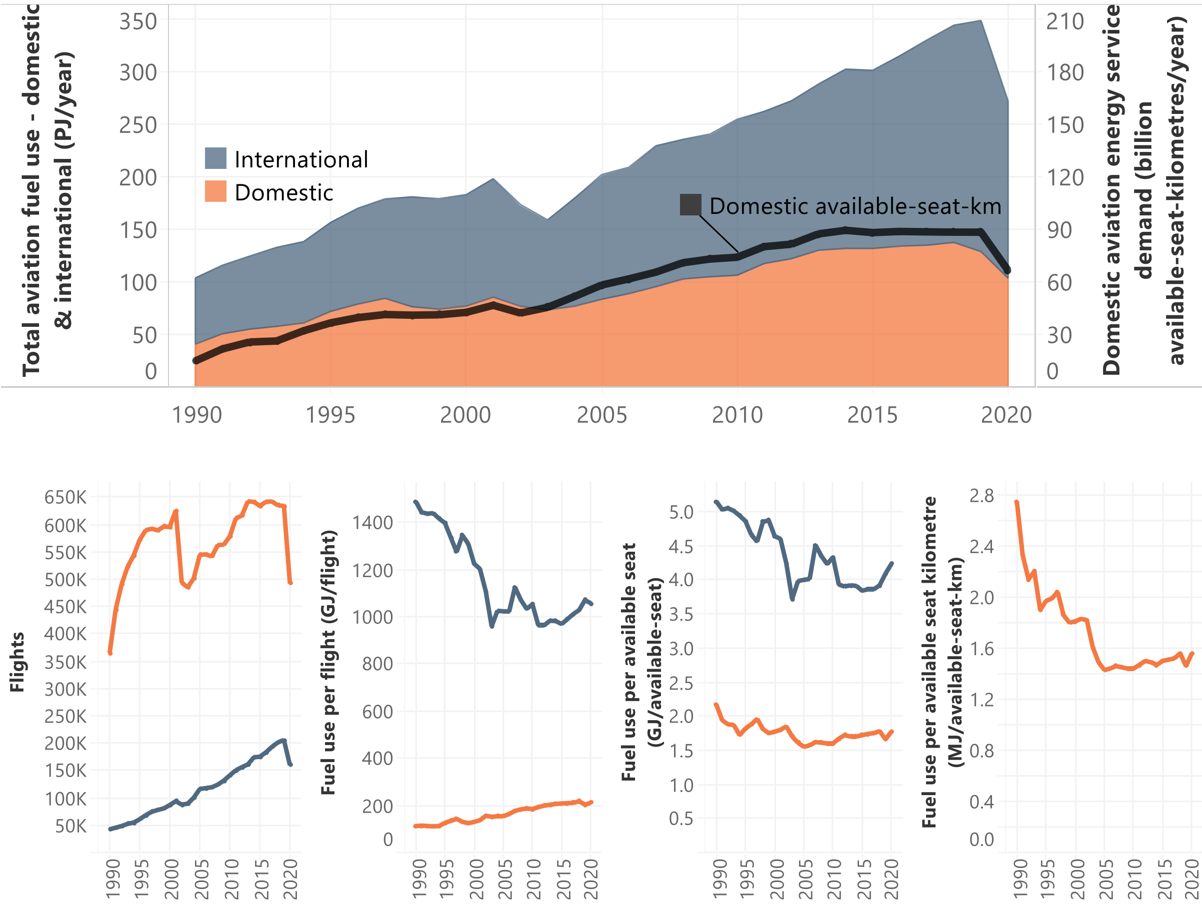


Figure 28 | (a) domestic aviation energy-service demand projection; and (b) final energy demand for both domestic and international aviation.

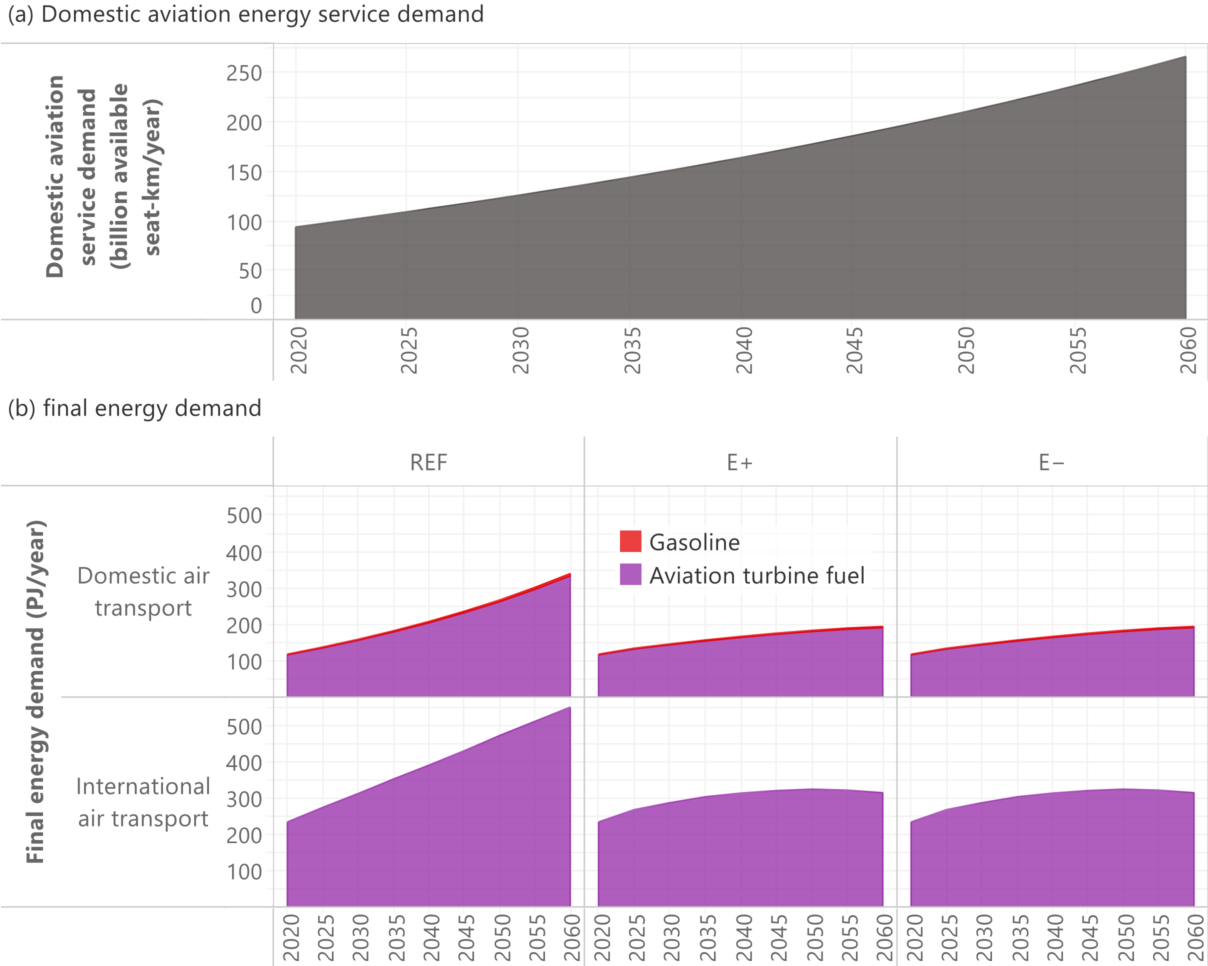


Figure 29 presents the supply of aviation turbine fuel by source, for the modelled supply-side Scenarios, showing that in most core Scenarios aviation fuel largely remains an imported refined fossil liquid. This results in the aviation sub-sector continuing to be a source of GHG emissions, contributing 29–35 Mt-CO_2e in 2050 (Figure 29), and therefore requiring CO_2 offsets in another modelled sector. The one exception to this trend is evident for the E+RE+ full renewable rollout Scenario, in which fossil fuels are prohibited from 2050. In this Scenario, aviation turbine fuel is decarbonised through the supply of synthetic aviation fuel via the Fischer-Tropsch process. The E+ and E− Scenarios also feature some limited use of synthetic aviation fuel.

Currently the most common grades of aviation fuels used are Jet A and Jet A-1, derived from crude oil with main chemical components being alkanes, isoalkanes, cycloalkanes and aromatic compounds (Wei et al., 2019). The need for alternative aviation fuels has led to the establishment of a new fuel standard specification – ASTM D7566 (ASTM International, 2022) – for jet fuels containing synthetic hydrocarbons. This standard approves various pathways producing synthetic paraffinic kerosene (SPK), including hydroprocessing vegetable oils and animal fats, Fischer-Tropsch synthesis and alcohol oligomerisation. Currently ASTM D7566 stipulates that SPK fuels may be blended up to a maximum of 50% with conventional jet fuels. This suggests that rigorous testing of SPK fuels for airworthiness is required (Gray et al., 2021) before a change to the standard could be made to enable the 100% synthetic jet fuels that we have found would be required in the E+RE+ Scenario (Figure 29).

Figure 29 | Supply-side modelling for the aviation sub-sector showing (a) the supply of aviation turbine fuel by source; and (b) the annual embodied GHG emissions in fuels used across the aviation sub-sectors.

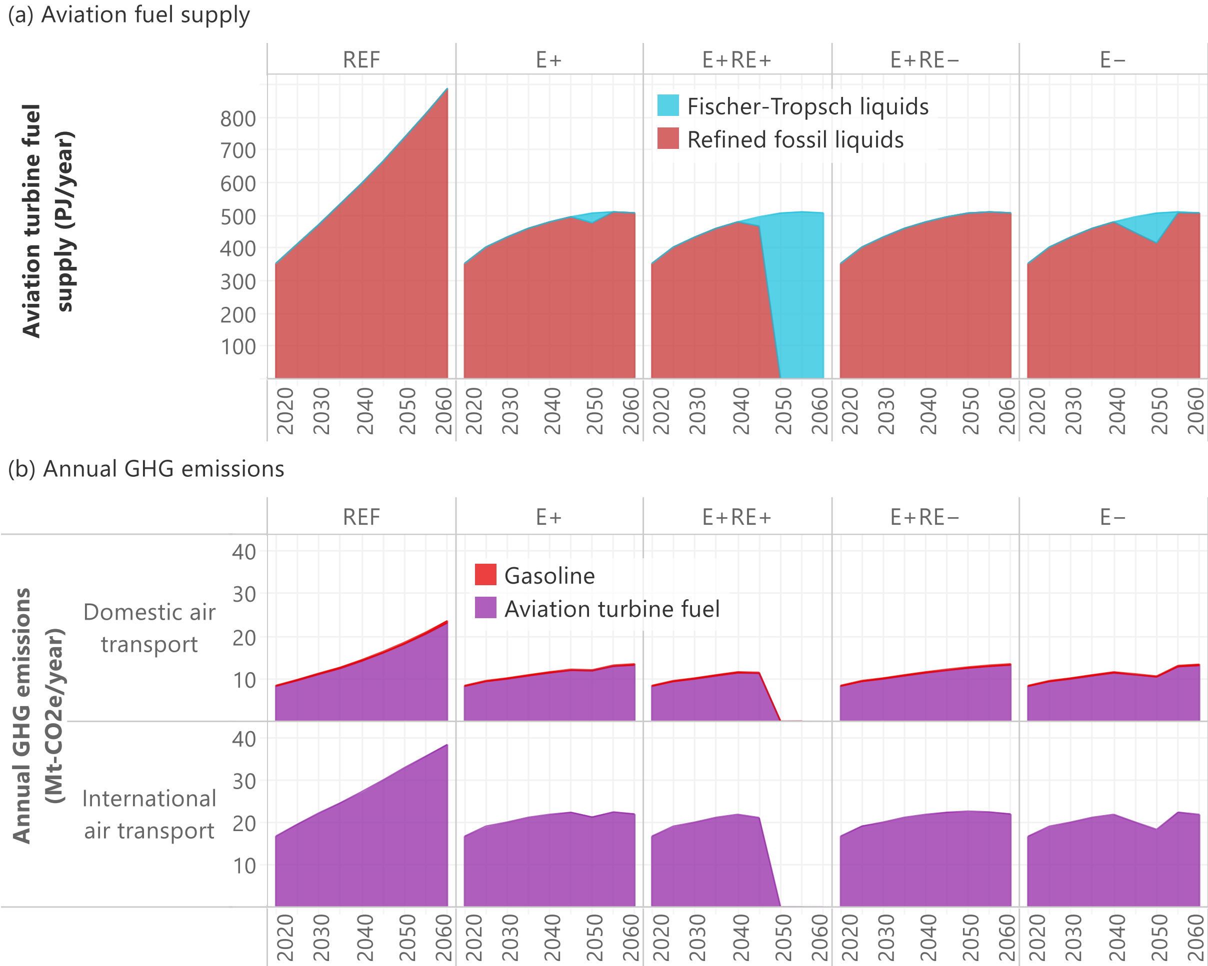
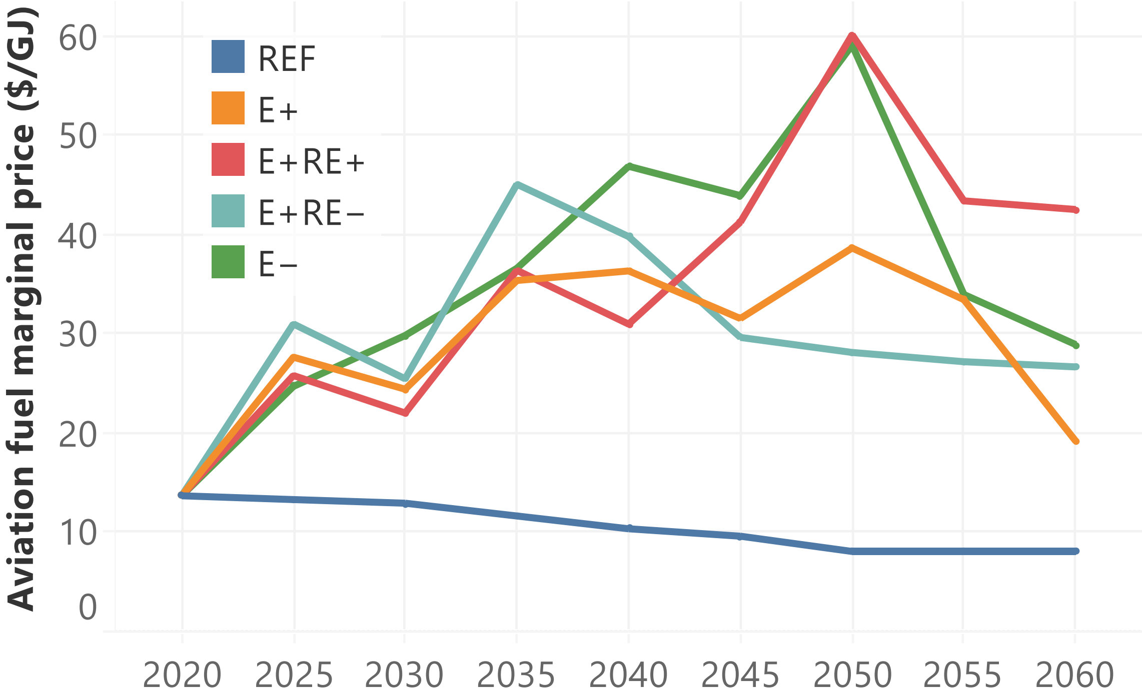


Figure 30 presents the marginal price for aviation fuel derived from the energy system supply-side optimisation, across the modelled horizon and Core Scenarios. These marginal prices reflect the modelled cost of supplying an additional increment of this fuel, with the 2020 prices and those of the REF Scenario out to 2060 corresponding to assumed global oil prices. Figure 30 shows that the marginal price of aviation fuel increases with the application of the system-wide emissions constraint, reflecting the cost of producing one more unit of zero-carbon fuel for the Scenarios with synthetic fuels, or similarly, the cost of using fossil fuels and their associated cost of offsetting fossil fuel combustion emissions.

The E+RE− constrained renewable rollout Scenario has the lowest marginal price of aviation fuel between 2045 and 2055 due to the greater availability and implicit lower marginal cost of geologic CO_2 sequestration in that Scenario. That is, residual fossil fuel use for aviation can be more cheaply offset with CO_2 sequestration (via direct air capture or bioenergy with CCS). Scenarios without this greater sequestration potential rely to some extent on synthetic fuel production, which has a capital-intensive value chain consisting of hydrogen production plant, CO_2 supply facilities and Fischer-Tropsch synthesis plant.

Figure 30 | Aviation fuel marginal prices, by Scenario.



The volume of aviation fuel supply across Australian states/territory and by the source of that fuel is shown in Figure 31. In 2020, QLD and VIC supply small portions of aviation fuel via their existing oil refineries: the Lytton and Geelong oil refineries. The remaining aviation fuel is supplied mainly via imports. As the net-zero transition progresses, the two oil refineries are shut down with all aviation fuel supply replaced by imports. Then, as the domestic net-zero emissions constraint binds in 2050 the widespread supply of synthetic aviation fuel via Fischer-Tropsch plant is established in the E+RE+ Scenario. Figure 32 then shows the geospatial and temporal transition of aviation fuel *demand*. This is distributed roughly in proportion to population and does not change significantly across the net-zero transition.

We note here that it may be more likely that the production of synthetic fuels in Australia will occur in a few designated locations, rather than with Fischer-Tropsch plants broadly distributed across the country. For example, it is possible that Australia's existing (or recently retired) oil refinery locations could be used for synthetic fuels production, with those fuels then transported across the country to locations of need. It is also possible that refined fossil liquid imports could be replaced by synthetic liquid fuel imports. Further detail on the downscaling of Fischer-Tropsch fuel synthesis plants and their supply of fuels to all sectors is provided in the companion downscaling report *Hydrogen & synthetic fuel production, transmission & storage*.

Figure 31 | Regional supply of aviation fuel by source and year, for the REF, E+ and E+RE+ Scenarios.

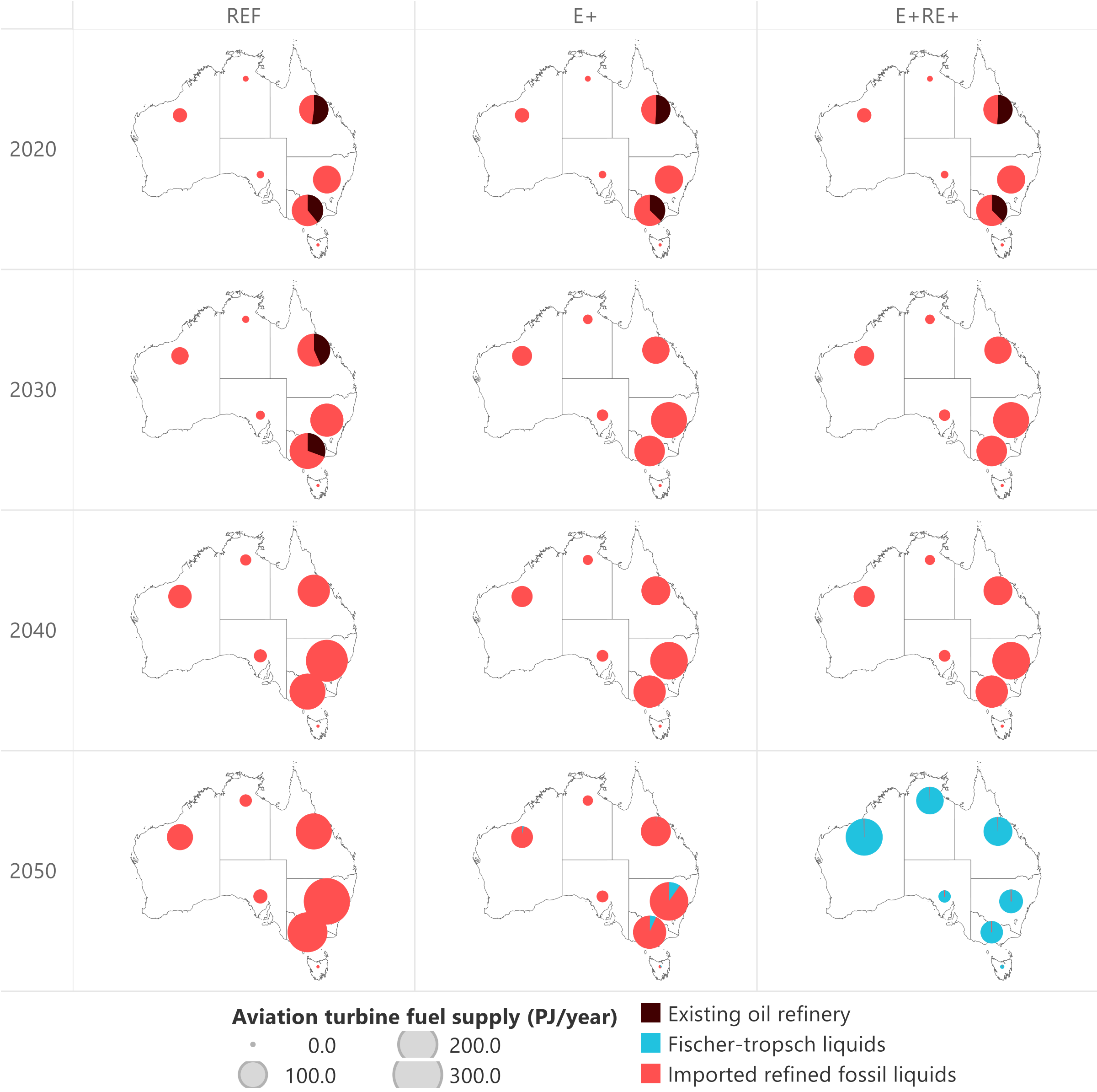


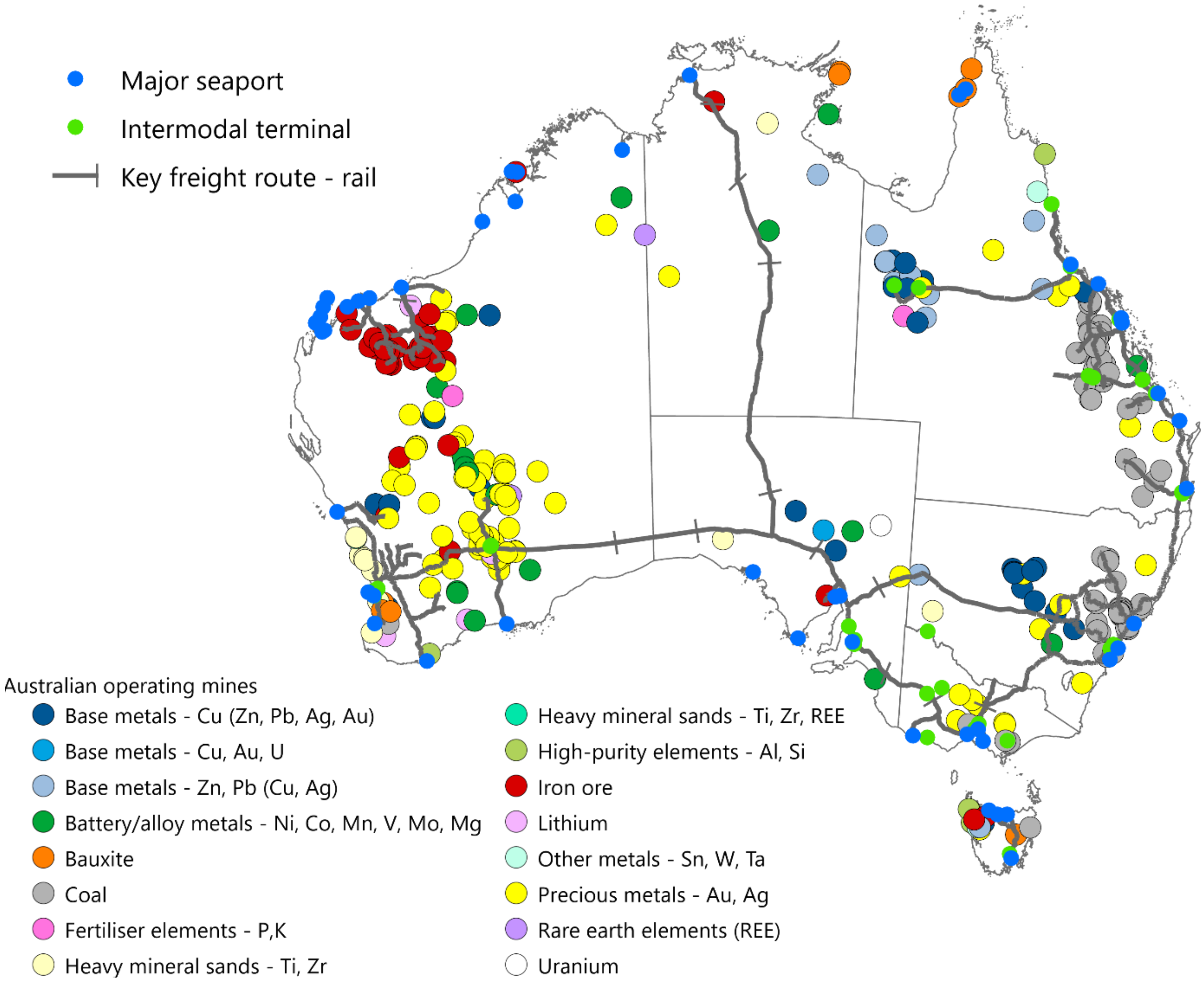
Figure 32 | Regional final demand for aviation fuel by year, for the REF, E+ and E+RE+ Scenarios.

5 Rail

The majority of bulk freight in Australia is transported by rail systems to ports, as was previously shown in Figure 20. This is illustrated by Figure 33, which shows Australia's key rail freight routes along with locations of currently operating mines. The coincidence of these rail freight routes with clusters of mines is evident, particularly for iron ore in Western Australia's northwest, for precious metals in Western Australia, and for coal in Queensland and New South Wales. This highlights the significant importance of rail transport as a component of Australia's mining and export value chain.

In addition to rail freight networks shown in Figure 33, most Australian states/territories have regional passenger train networks and most major cities have urban rail networks. However, the majority of absolute energy consumption in the rail transport system is attributed to bulk freight transport.

Figure 33 | Australia's key rail freight routes and locations of air and seaports (Department of Infrastructure, 2022), along with Australia's operating mines by type (Geoscience Australia, 2022).



In this work we have modelled the decarbonisation of rail energy consumption through fuel switching, with 90% of fossil fuel use switched to hydrogen and 10% switched to electricity by 2050 in the E+ demand-side Scenario and 20 years later in E−, as outlined in our MASS document along with projected energy demand growth (Net Zero Australia Project, 2022).

Figure 34 presents the supply-side optimisations of primary energies that supply the three modelled rail transport final energy carriers, diesel, electricity, and hydrogen, along with the trends in final rail transport energy demand and associated GHG emissions. We find, for the E+ supply-side scenarios, that diesel that is largely imported as a refined liquid currently is rapidly replaced by electricity and hydrogen produced with wind and solar PV renewable electricity generation. This has the effect of reducing the associated GHG emissions to zero by 2050.

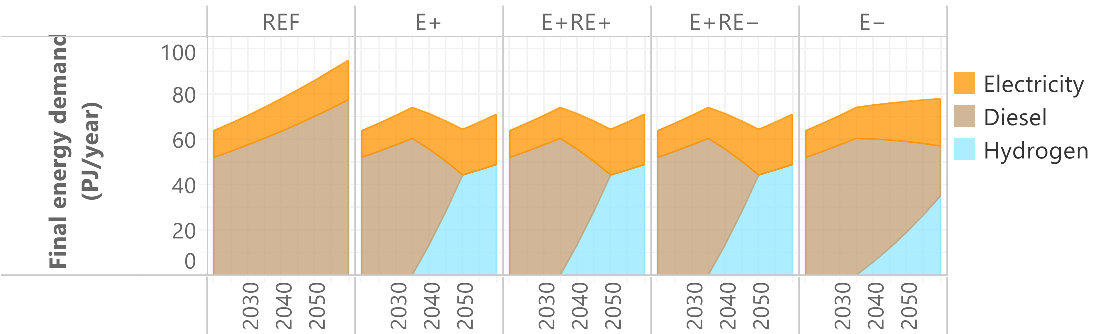
The slower electrification E− Scenario projects some residual demand for diesel beyond 2050 due to the slower fuel switching assumptions in that scenario. Consequently E− shows a residual 2 Mt-CO_2e GHG emissions from the rail transport sub-sector in 2050, which continues to reduce towards 2060. Interestingly, some of the residual diesel demand in 2050 in E− is decarbonised through the provision of renewable primary energy (top band in Figure 34), which is converted to synthetic diesel by Fischer-Tropsch synthesis.

Figure 35 shows the regional distribution of rail transport final energy demand over the net-zero transition. Demand is largest in WA, QLD and NSW, which each have significant bulk-freight rail networks for exporting different commodities. The E+ Scenario shows that diesel use reduces to approximately 60% of total rail final energy in 2040, and is no longer used in 2060. However, the Net Zero Australia project models pathways in which both domestic and export use of coal is almost entirely eliminated from our energy system. This will have a corresponding effect of reducing rail transport energy demand in those privately operated rail networks that transport coal in Central Queensland and the Hunter Valley, NSW. Simultaneously there will be significant growth in demand for many critical minerals and metals, such as copper, lithium and nickel (International Energy Agency, 2021). Australia is well placed to supply some of this demand, which may increase the demand for bulk rail freight and consequently, low-emissions rail transport fuels in some regions. The secondary feedback effects that a changing mining industry supply chain may have on demand for energy is, however, outside the scope of this work.

Figure 34 | Rail transport (a) primary energy supply for various final energy types; (b) total final energy demand; and (c) annual GHG emissions by final energy.

(a) Primary energy supply for various final energy types

(b) Final energy demand



(c) Annual GHG emissions

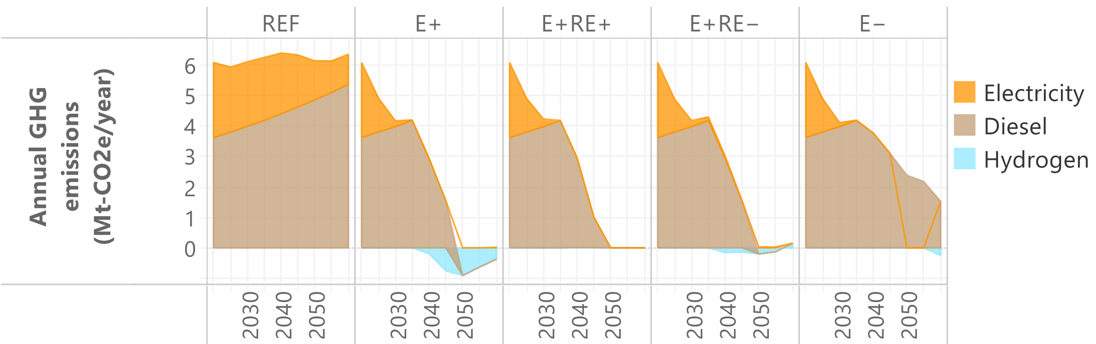
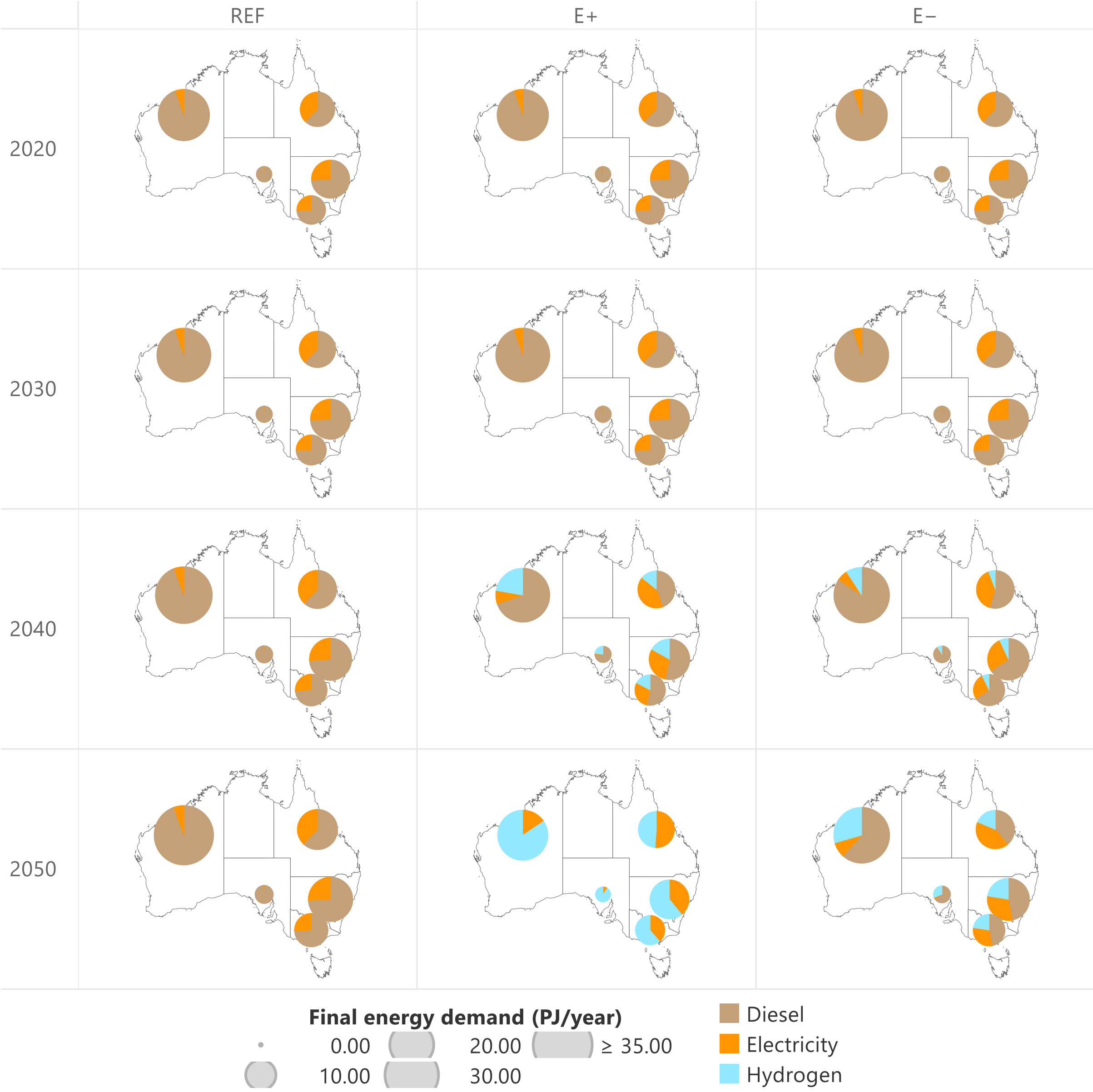


Figure 35 | Regional distribution of rail transport final energy demand, over selected years.



6 Water transport

Various commodity supply chains rely on the transport of bulk-freight via ships (Figure 20). For domestic water transport, the two most significant supply chains are the transport of bauxite from Weipa and Gove in northern QLD and the NT to Gladstone, and the transport of iron ore from Port Hedland, WA to Port Kembla, NSW (Bureau of Infrastructure and Transport Research Economics, 2021b). Domestic shipping freight, however, accounts for less than 5% of total freight passing through Australian ports. This implies that international shipping freight activity is also a significant source of demand for shipping fuels, with major ports in northern WA (Port Hedland, Dampier, Port Walcott), QLD (Hay Point, Gladstone) and Newcastle accounting for more than 80% of the total Australian export freight volume by weight (Bureau of Infrastructure and Transport Research Economics, 2021b).

Here, we use the Australian Energy Statistics as the basis of examining the decarbonisation of shipping energy consumption, disaggregated by domestic and international shipping sub-sectors (DISER, 2021a). Decarbonisation of water transport energy consumption has been modelled through assumed energy efficiency improvement of 1%/year, and through fuel switching measures. These fuel switching measures are:

- 100% of international shipping switching to ammonia by 2050 in E+ and 20 years later in E−; and
- 33% of domestic shipping switching to ammonia, 33% to hydrogen and 33% switching to electricity by 2050 in E+ and 20 years later in E−.

The process of projecting shipping final energy demands is detailed in our MASS document along with projected energy demand growth (Net Zero Australia Project, 2022).

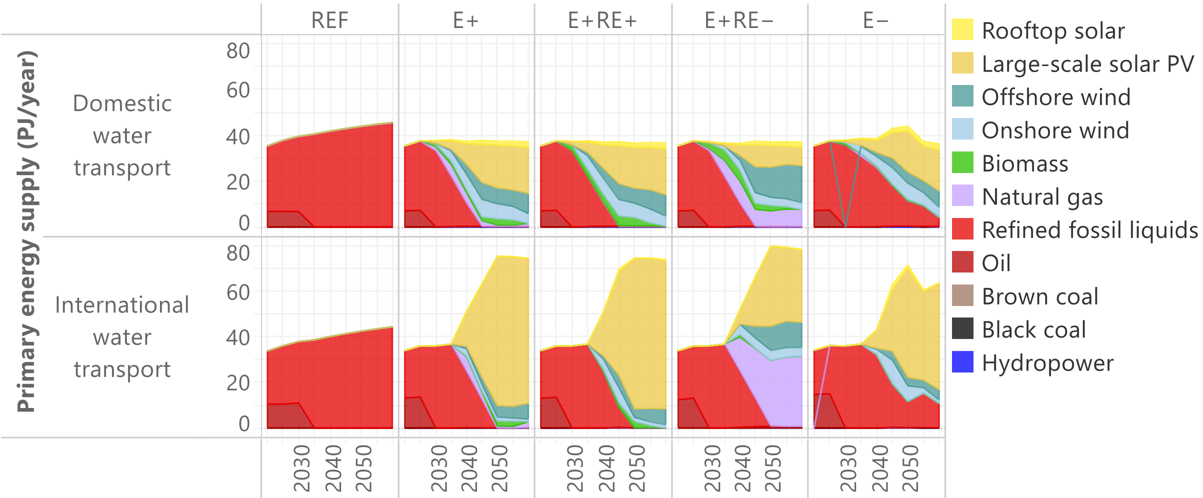
Figure 36 presents the supply-side optimisations of primary energies that supply the various modelled water transport final energy carriers, along with trends in final water transport energy demand and associated GHG emissions embodied in final energies. This shows that the transition of shipping fuels to ammonia, hydrogen and electricity across domestic and international shipping sub-sectors results in a significant reduction in the need for oil and refined fossil liquid imports of approximately 80 PJ/year. This coincides with an increase in supply of renewable primary energy, which is converted to the modelled final energy carriers via renewable electricity generation, electrolysis, Haber-Bosch synthesis and bio-gasification. The E+RE− Scenario also uses natural gas for hydrogen and ammonia production, as this Scenario has greater prevalence of natural gas across all sectors, which is due to the greater geological CO_2 sequestration potential assumed in this Scenario.

Figure 36 also shows that the E− Scenario demonstrates a transition of primary and final energy that is similar to the other core Scenarios but has a slower rate of change. This results in a residual ~40 PJ demand for fuel oil, diesel and gasoline in 2050, which is mostly met by synthetic renewable liquid fuels via Fischer-Tropsch synthesis, as indicated by the mix of renewable primary energy. This has the effect of reducing water transport emissions to 1.5 Mt-CO_2e in 2050, which reduces further out to 2060.

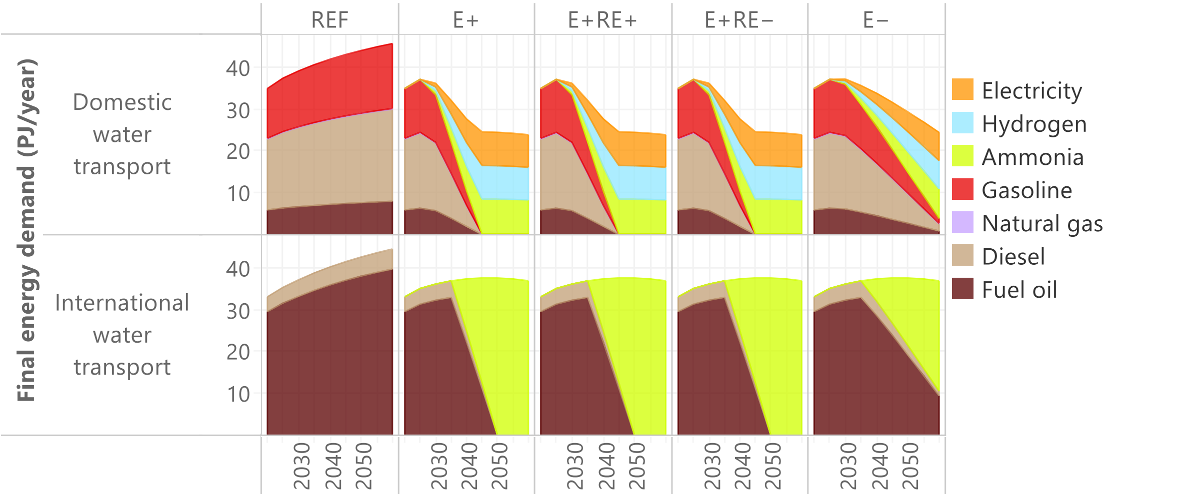
Note also that Figure 36 shows, for some Scenarios, that ammonia production for shipping transport fuels has small net negative levels of embodied emissions. This is possible through the use of biomass feedstock for hydrogen production via biogasification with carbon capture, followed by the subsequent permanent sequestration of that captured *biogenic* CO_2.

Figure 36 | Domestic and international water transport (top) primary energy supply; (middle) total final energy demand; and (bottom) annual GHG emissions by final energy.

(a) Primary energy supply



(b) Final energy demand



(c) Annual GHG emissions

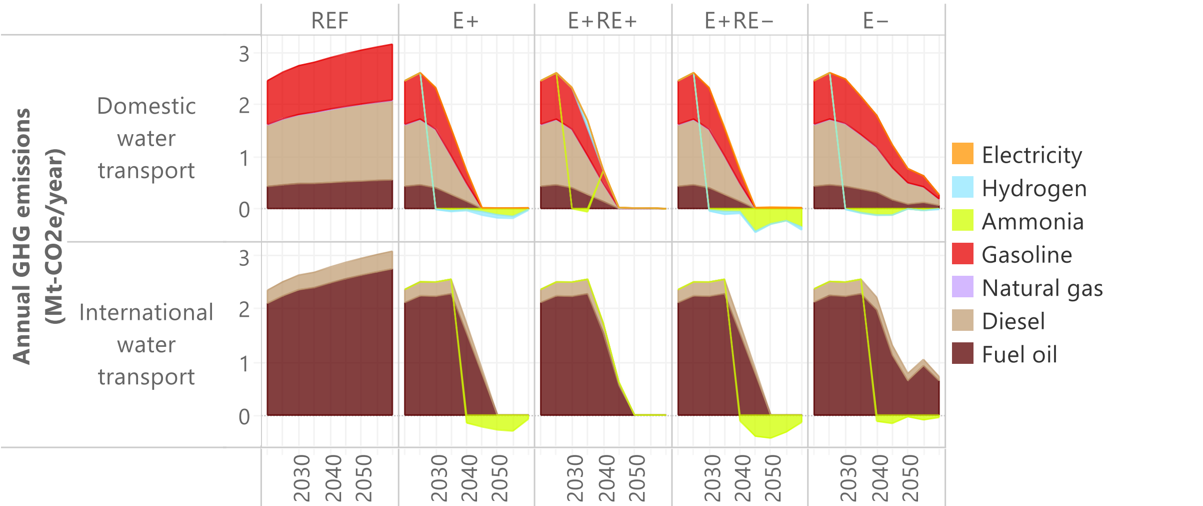


Figure 37 shows the regional distribution of water transport final energy demand over the net-zero transition. Demand is largest in WA, QLD and NSW, from which much of Australia's bulk-freight commodities originate.

It is also worth noting that the present analysis of international water transport energy demand is based on the energy accounted in the Australian Energy Statistics (DISER, 2021a). However, some fuels used in international shipping may be provided by overseas bunkering operations. The future supply chain for alternative marine fuels and logistics of fuel distribution and bunkering at a network of shipping ports will therefore be highly dependent on the international maritime industry and its pursuit of the net-zero transition. This may also be a significant National opportunity given the large distances from Australia to our export partners and the global significance of very large ports in the region, such as Singapore.

Figure 37 | Regional distribution of water transport final energy demand by type, over selected years.

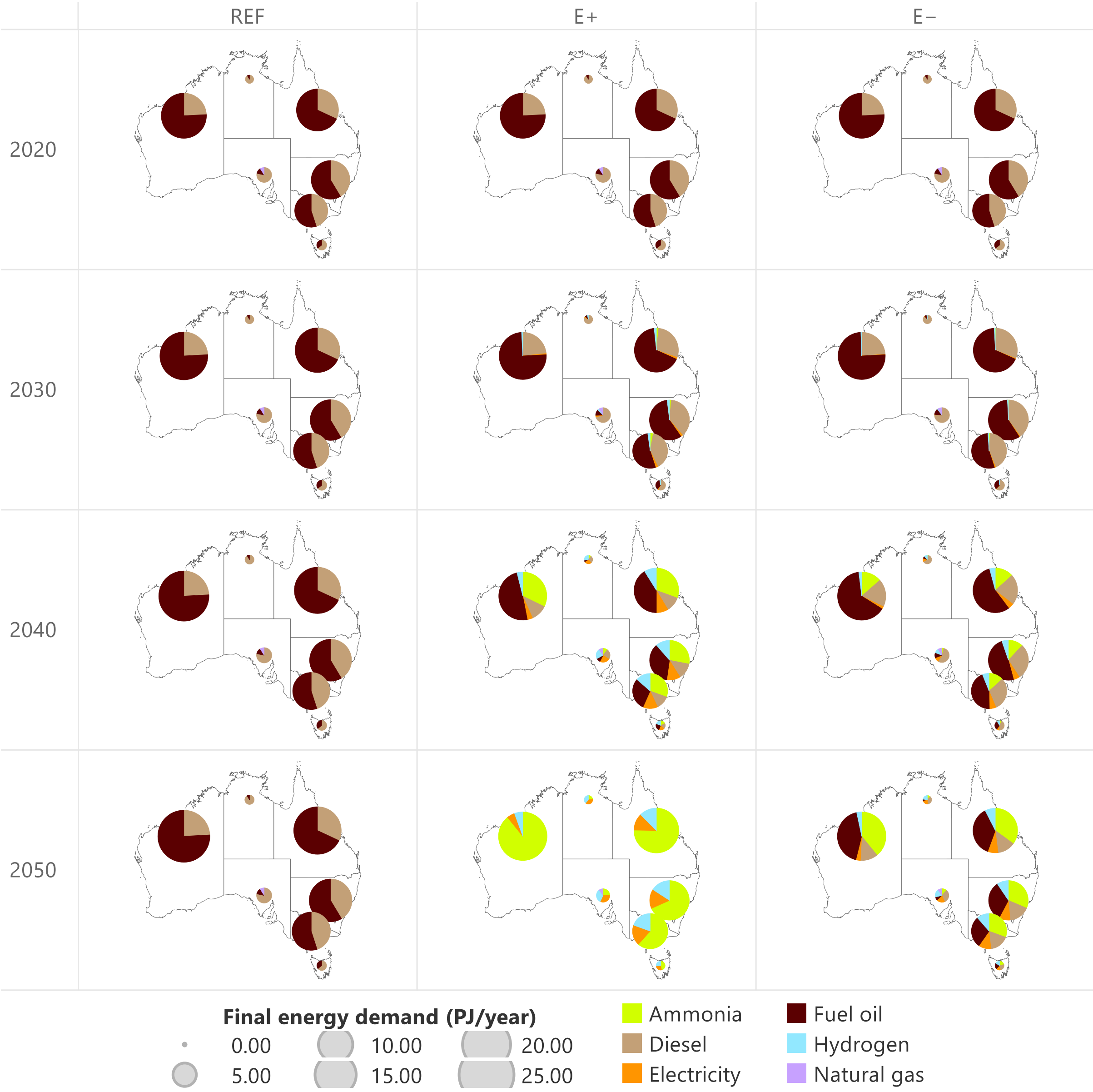
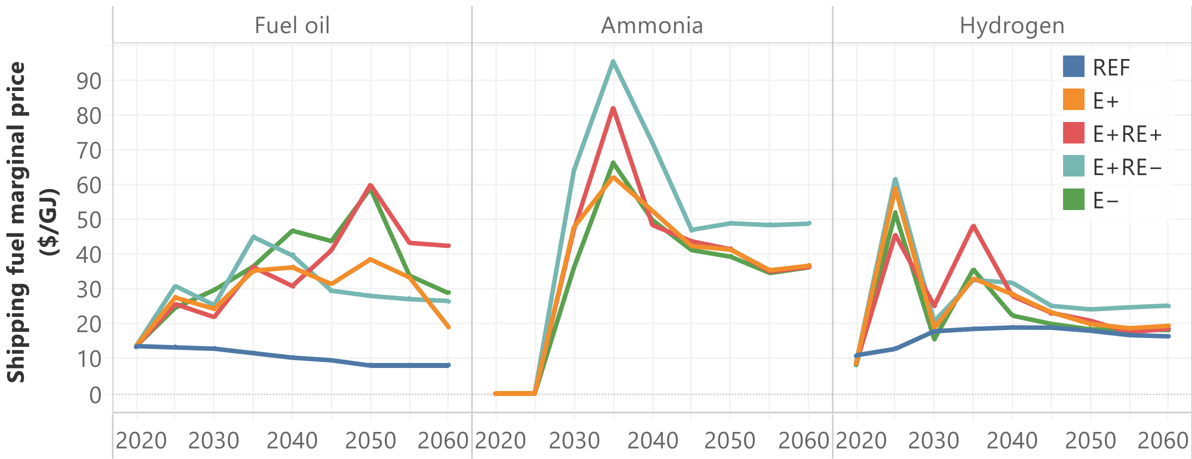


Figure 38 presents the marginal price for selected modelled shipping fuels derived from the energy system supply-side optimisation, across the modelled horizon and Core Scenarios. Figure 38 shows that the marginal price of fuel oil increases in the net-zero Scenarios with the application of the system-wide emissions constraint.

Figure 38 also shows that the marginal prices of ammonia and hydrogen peak before 2040 at higher prices than that of fuel oil, which indicates pinch point between the project's assumed renewable compound annual build rates and GHG emissions constraints. However, as the net-zero transition progresses domestic ammonia marginal prices converge to values close to that of fuel oil (with implicit carbon price), while hydrogen prices converge to low marginal prices of 19 – 25 $/GJ. Notably, the long-run marginal price of hydrogen in the E+RE− Scenario has the highest marginal prices for ammonia and hydrogen, which can be attributed to the more restrictive renewable build rate constraints applied in that scenario, leading to the more costly production of hydrogen.

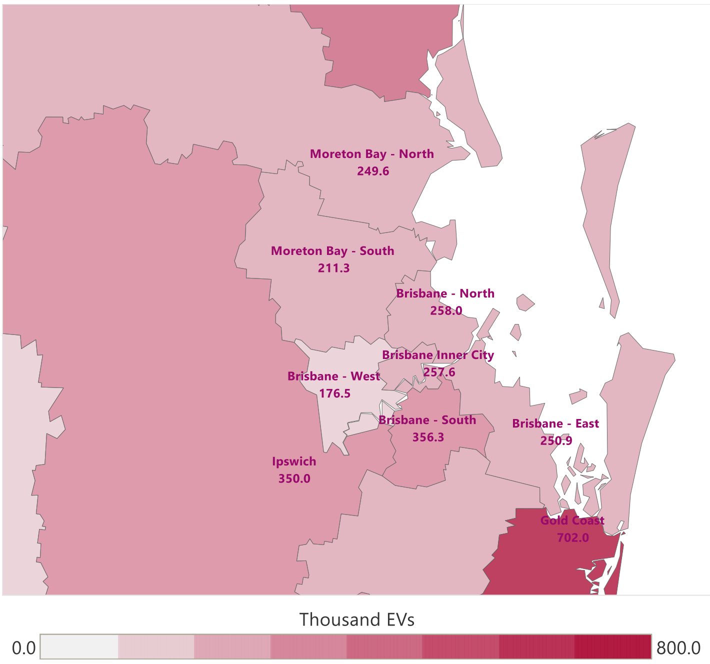
Figure 38 | Marginal prices for selected modelled shipping fuels, by Scenario.



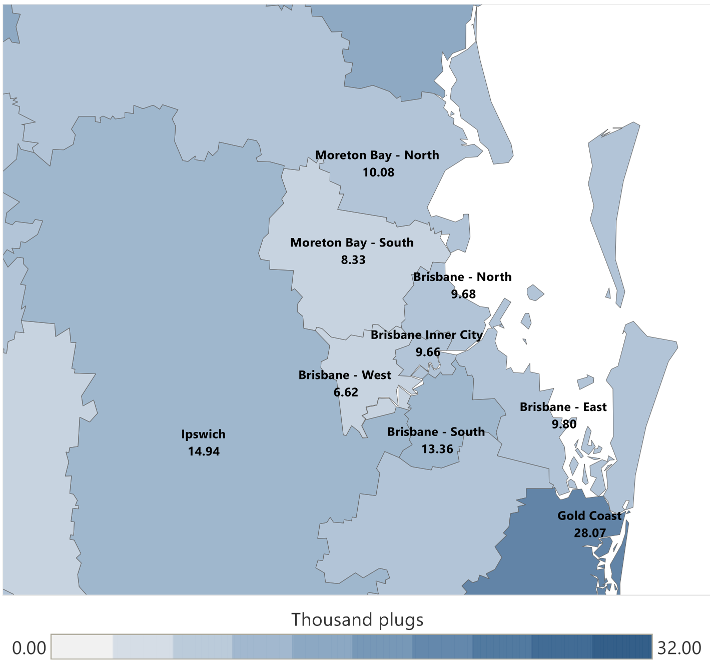
Appendices

Appendix A: Spatial distribution of the light-duty vehicle fleet and estimated number of public EV chargers

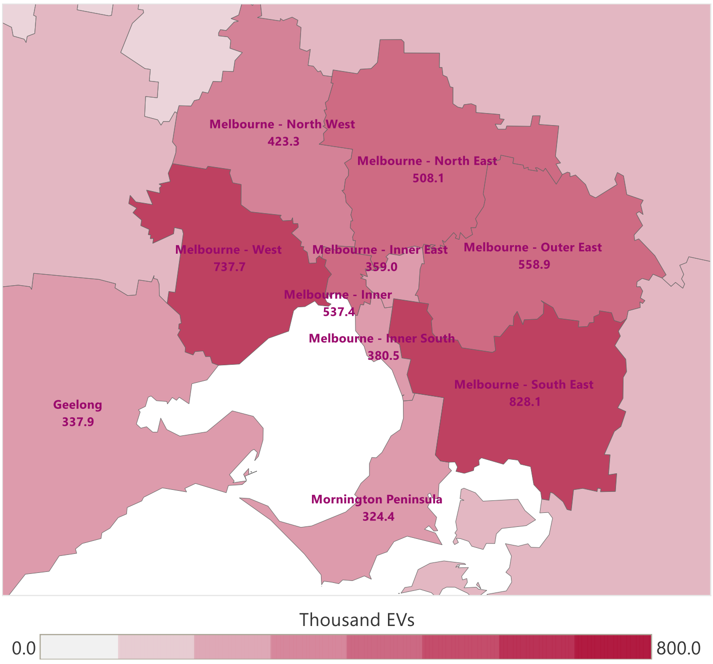
Number of Light Duty EVs, **E+ 2050**, by SA4 region (thousand EVs)



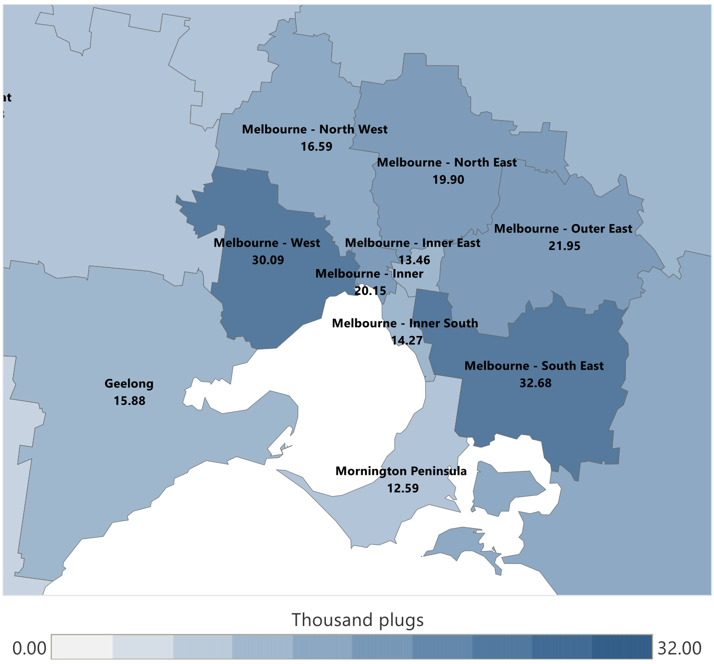
Public EV charging plugs, **E+ 2050**, by SA4 region (thousand plugs)



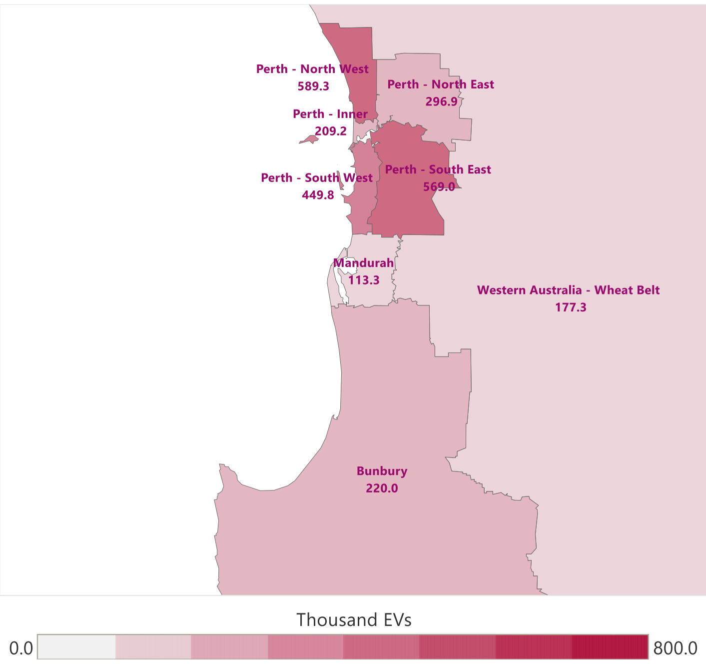
Number of Light Duty EVs, **E+ 2050**, by SA4 region (thousand EVs)



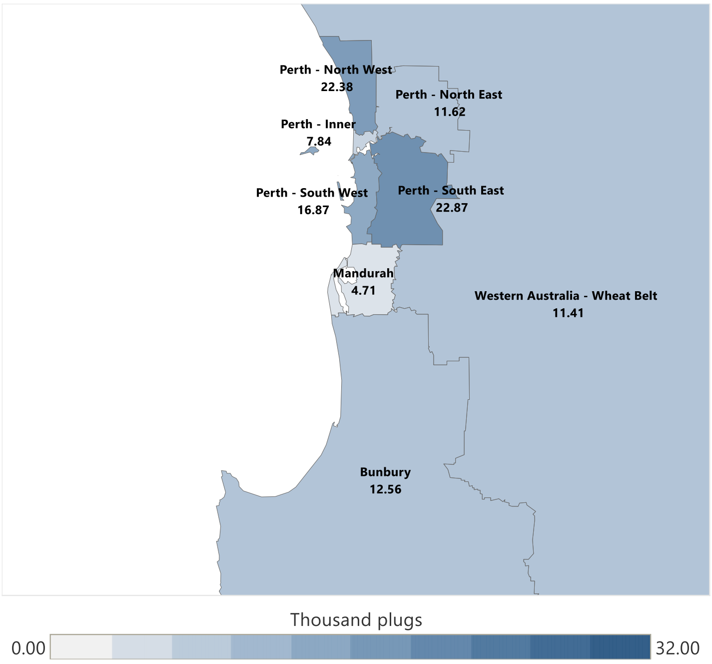
Public EV charging plugs, **E+ 2050**, by SA4 region (thousand plugs)



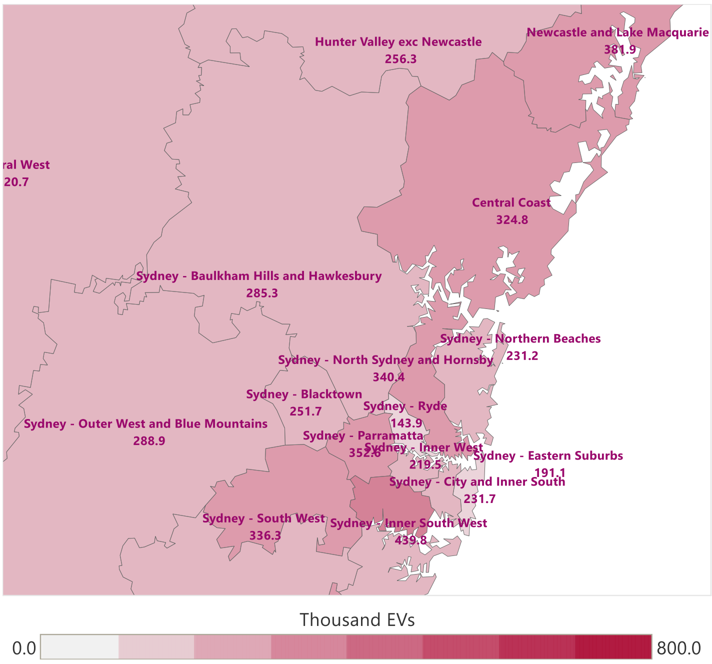
Number of Light Duty EVs, **E+ 2050**, by SA4 region (thousand EVs)



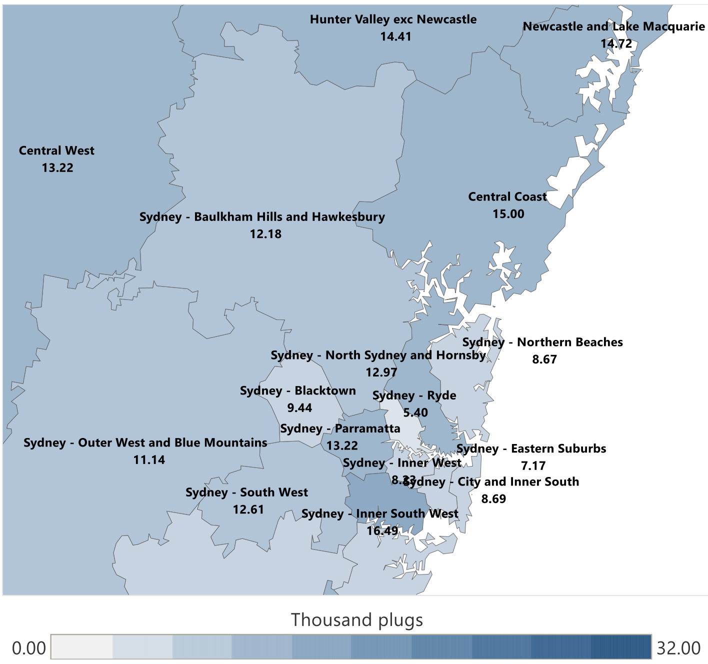
Public EV charging plugs, **E+ 2050**, by SA4 region (thousand plugs)



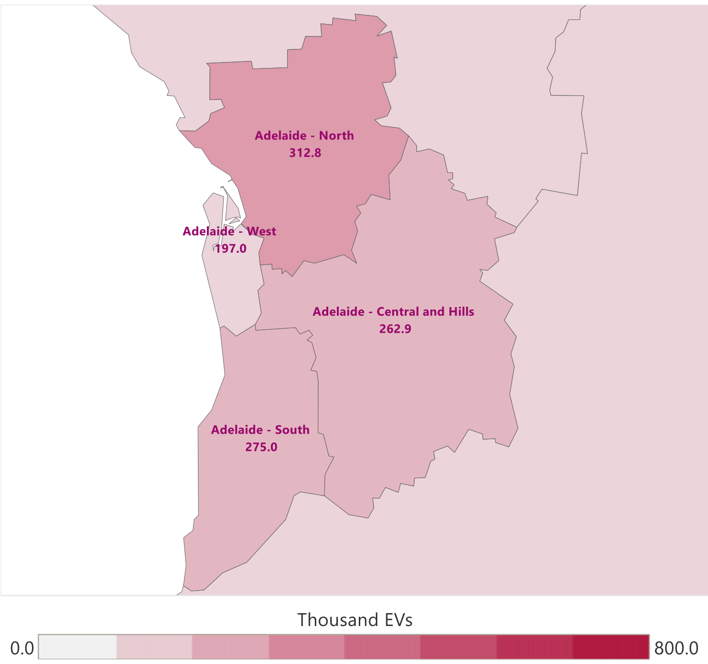
Number of Light Duty EVs, **E+ 2050**, by SA4 region (thousand EVs)



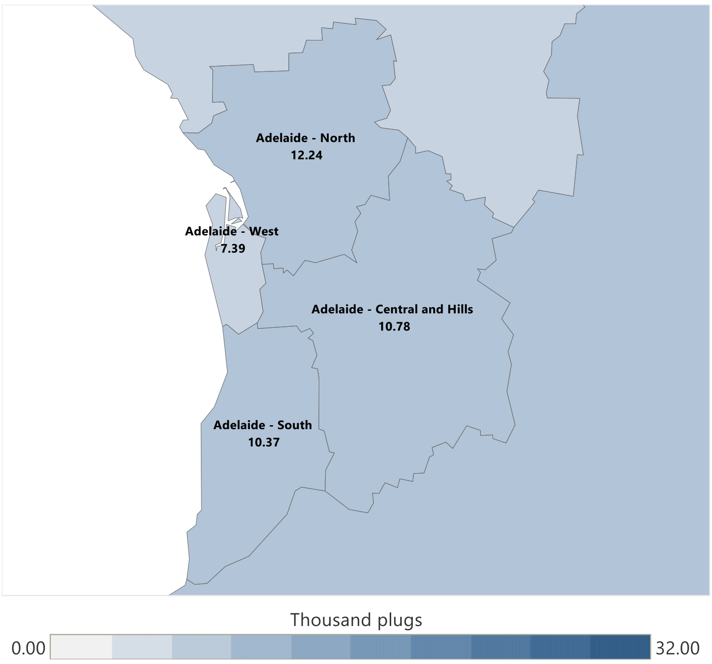
Public EV charging plugs, **E+ 2050**, by SA4 region (thousand plugs)



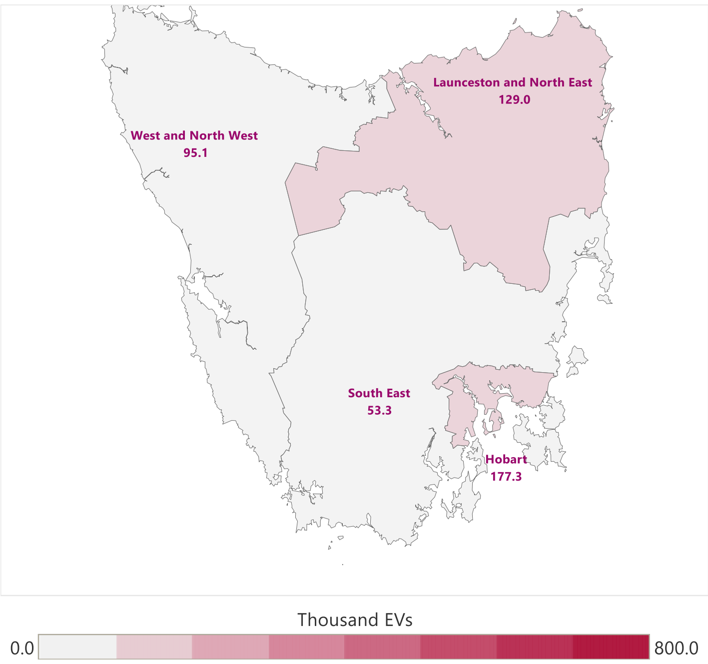
Number of Light Duty EVs, **E+ 2050**, by SA4 region (thousand EVs)



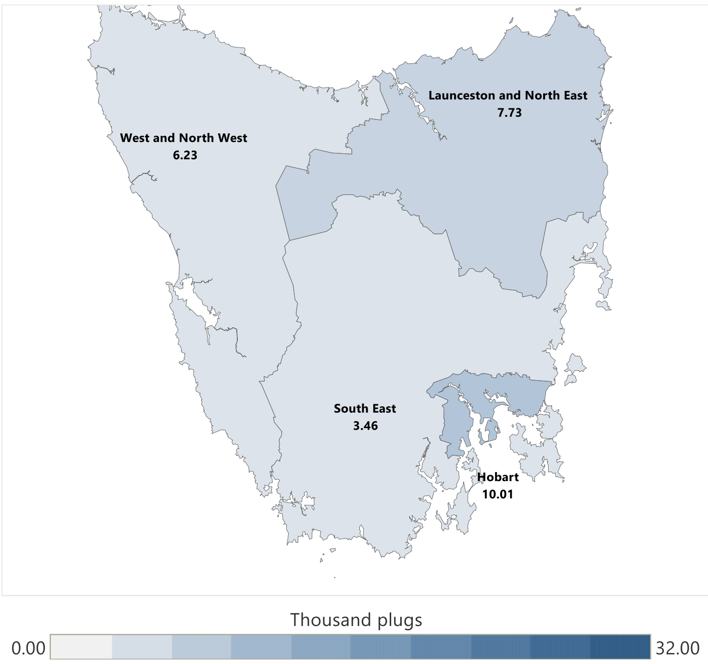
Public EV charging plugs, **E+ 2050**, by SA4 region (thousand plugs)



Number of Light Duty EVs, **E+ 2050**, by SA4 region (thousand EVs)

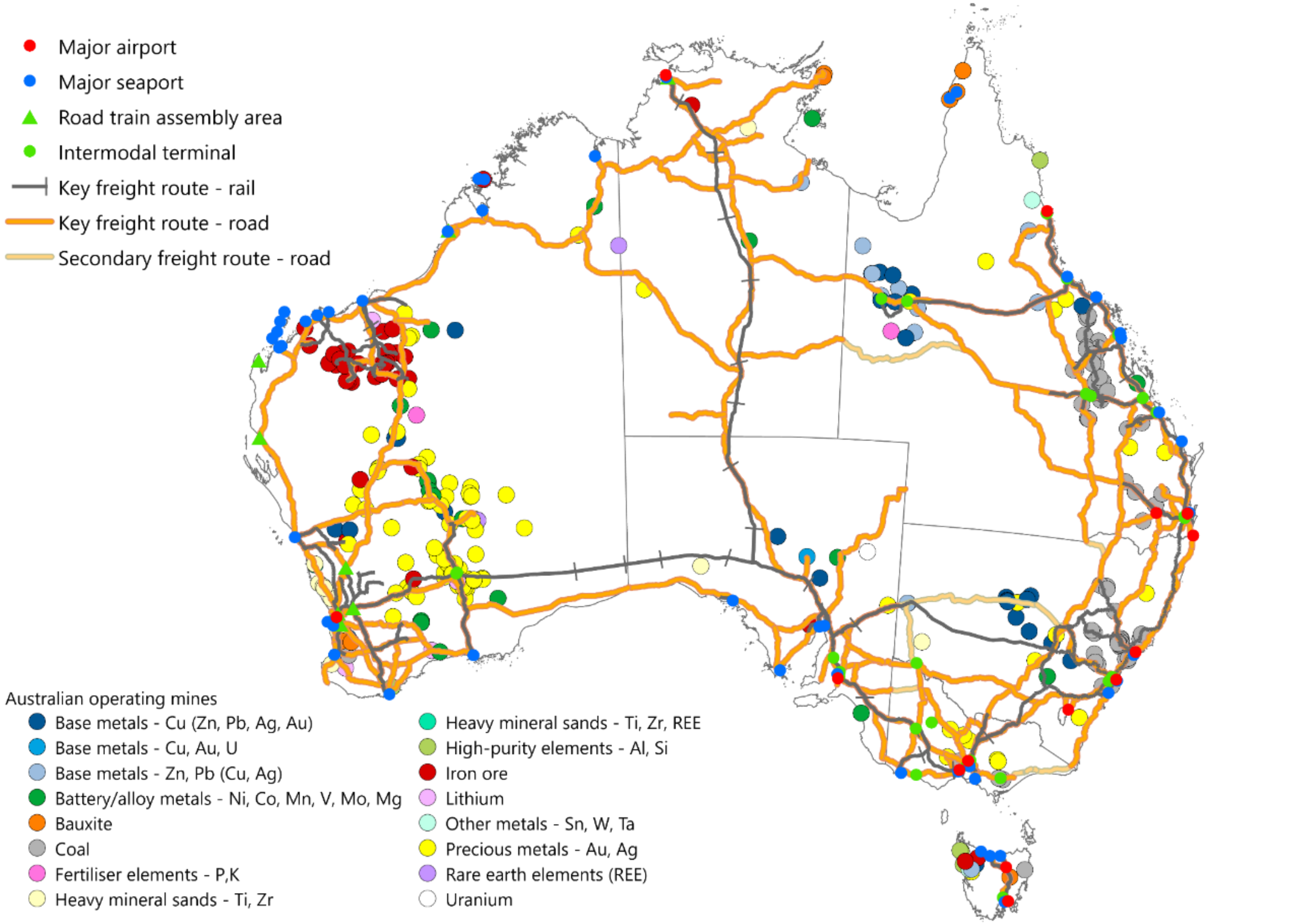


Public EV charging plugs, **E+ 2050**, by SA4 region (thousand plugs)



Appendix B: Key road and rail freight routes

Figure 39 | Australia's key road and rail freight routes, locations of air and seaports, and road freight infrastructure (Department of Infrastructure, 2022), along with an underlay of Australian operating mines by type (Geoscience Australia, 2022).



References

ASTM International, 2022. ASTM D7566-21 - Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. Book of Standards 05.04, https://doi.org/10.1520/D7566-21.

Australian Bureau of Statistics, 2020a. Motor Vehicle Census. https://www.abs.gov.au/statistics/industry/tourism-and-transport/motor-vehicle-census-australia/.

Australian Bureau of Statistics, 2020b. Survey of Motor Vehicle Use, Australia, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2010, 2012, 2014, 2016, 2018, 2020. https://www.abs.gov.au/statistics/industry/tourism-and-transport/survey-motor-vehicle-use-australia.

Australian Bureau of Statistics, 2021. Australian Statistical Geography Standard (ASGS) Edition 3. https://www.abs.gov.au/statistics/standards/australian-statistical-geography-standard-asgs-edition-3/jul2021-jun2026.

Bauer, G., Hsu, C.-W., Nicholas, M., Lutsey, N., 2021. Charging up America: assessing the growing need for US charging infrastructure through 2030. International Council on Clean Transportation,

Bureau of Infrastructure and Transport Research Economics, 2020. Australian Infrastructure Statistics: Yearbook 2020. Department of Infrastructure, Transport, Regional Development and Communications, Australian Government,

Bureau of Infrastructure and Transport Research Economics, 2021a. Australian Infrastructure and Transport Statistics: Yearbook 2021. Department of Infrastructure, Transport, Regional Development and Communications, Australian Government,

Bureau of Infrastructure and Transport Research Economics, 2021b. Australian sea freight 2018–19. Department of Infrastructure, Transport, Regional Development and Communications, Australian Government,

Department for Transport, UK Government, 2021. UK confirms pledge for zero-emission HGVs by 2040 and unveils new chargepoint design. https://www.gov.uk/government/news/uk-confirms-pledge-for-zero-emission-hgvs-by-2040-and-unveils-new-chargepoint-design.

Department of Infrastructure, Transport, Regional Development and Communications, 2022. National Key Freight Routes Map. https://data.datahub.freightaustralia.gov.au/ne/dataset/national-key-freight-routes-map.

DISER, 2021a. Australian Energy Update 2021, Australian Energy Statistics. Department of Industry, Science, Energy and Resources, Canberra

DISER, 2021b. National Inventory Report 2019: The Australian Government Submission to the United Nations Framework Convention on Climate Change. https://www.dcceew.gov.au/climate-change/publications/national-greenhouse-accounts-2019/national-inventory-report-2019.

Geoscience Australia, 2022. Australian Operating Mines. http://services.ga.gov.au/gis/rest/services/AustralianOperatingMines/MapServer.

Graham, P., Havas, L., 2021. Electric vehicle projections 2021. https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/csiro-ev-forecast-report.pdf.

Gray, N., McDonagh, S., O'Shea, R., Smyth, B., Murphy, J.D., 2021. Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Advances in Applied Energy 1, 100008, https://doi.org/10.1016/j.adapen.2021.100008.

Hall, D., Lutsey, N., 2017. Emerging best practices for electric vehicle charging infrastructure. Washington DC

Hall, D., Lutsey, N., 2020. Electric vehicle charging guide for cities. International Council on Clean Transportation,, Washington DC

International Energy Agency, 2021. Net Zero by 2050. Paris, https://doi.org/10.1787/c8328405-en.

International Energy Agency, 2022. Global EV Outlook 2022. Paris

Lynskey, R., Rowe, H., Ashfaq, M., 2022. Accelerating EV uptake: Policies to realise Australia's electric vehicle potential. Climateworks Centre,

Net Zero Australia Project, 2022. Net Zero Australia - Methods, Assumptions, Scenarios & Sensitivities. https://www.netzeroaustralia.net.au/mass-document-aug-2022/.

NSW EPA, 2019. 2013 Calendar Year Air Emissions Inventory for the Greater Metropolitan Region in NSW. https://www.epa.nsw.gov.au/your-environment/air/air-emissions-inventory/air-emissions-inventory-2013.

Szinai, J.K., Sheppard, C.J.R., Abhyankar, N., Gopal, A.R., 2020. Reduced grid operating costs and renewable energy curtailment with electric vehicle charge management. Energy Policy 136, 111051, https://doi.org/10.1016/j.enpol.2019.111051.

Terrill, M., Burfurd, I., Fox, L., 2021. The Grattan car plan: practical policies for cleaner transport and better cities. Grattan Institute,

Terrill, M., Burfurd, I., Fox, L., 2022. The Grattan truck plan: practical policies for cleaner freight. Grattan Institute,

Tietge, U., Díaz, S., Yang, Z., Mock, P., 2017. From Laboratory to Road International: A Comparison of Official and Real-World Fuel Consumption and CO_2 Values for Passenger Cars in Europe, the United States, China, and Japan. The International Council on Clean Transportation, Berlin

Wei, H., Liu, W., Chen, X., Yang, Q., Li, J., Chen, H., 2019. Renewable bio-jet fuel production for aviation: A review. Fuel 254, 115599, https://doi.org/10.1016/j.fuel.2019.06.007.

Williams, J.H., Jones, R.A., Haley, B., Kwok, G., Hargreaves, J., Farbes, J., Torn, M.S., 2021. Carbon-Neutral Pathways for the United States. Agu Adv 2(1), e2020AV000284, https://doi.org/10.1029/2020AV000284.

Wood, E.W., Rames, C.L., Muratori, M., Srinivasa Raghavan, S., Melaina, M.W., 2017. National plug-in electric vehicle infrastructure analysis. National Renewable Energy Lab. (NREL), Golden, CO (United States).

Yang, Z., Bandivadekar, A., 2017. Light-duty vehicle greenhouse gas and fuel economy standards. The International Council on Clean Transportation, Washington DC