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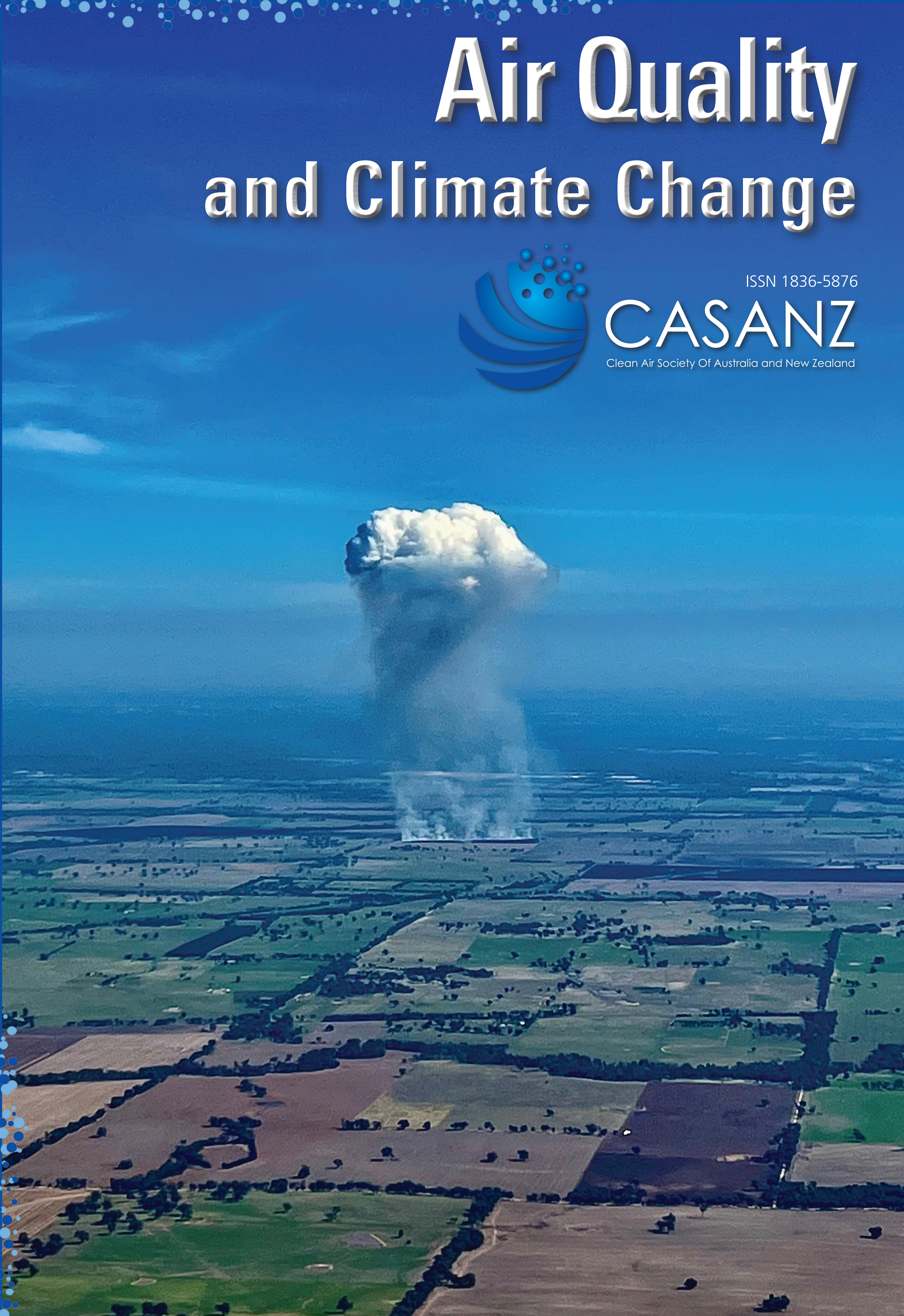

AN INDEPENDENT AND DETAILED ASSESSMENT OF GREENHOUSE GAS EMISSIONS, FUEL USE, ELECTRICITY AND ENERGY CONSUMPTION FROM AUSTRALIAN ROAD TRANSPORT IN 2019 AND 2050

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Abstract

Decarbonising road transport needs to be genuine, rapid and deployed at scale. This paper presents an independent and detailed assessment of well-to-wheel greenhouse gas emissions, fuel consumption, electricity and energy use from Australian road transport in 2019 and 2050, using state-of-the art and Australia-specific software tools and methods. The analysis suggests that Australia will fall short of the net zero target, assuming that we will follow the latest EU scenario with a ten year delay, whilst taking into consideration critical aspects of Australia's unique on-road fleet.

TER estimates a reduction of total GHG emissions (CO_2-e) from Australian transport in 2050 of 35% to 45%, depending on the dominant hydrogen production pathway. This means that significantly more intensified and far-reaching policies need to be developed and implemented if net zero is to be achieved in 2050.

In terms of possible solutions, a combination of electrification and lightweighting of road transport appears to be the most effective and robust way forward. The simulation suggests that an on-road passenger vehicle fleet in 2050 that is dominated by small and light battery electric vehicles may get Australia close to achieving the net zero target. Green hydrogen should be deployed where electrification faces unsurmountable barriers, but it is expected there will not be many cases in the road transport sector.

1. Introduction

Australia needs rapid and genuine reductions in greenhouse gas (GHG) emissions over the coming decades to start addressing increasingly severe and likely non-linear climate change impacts. The road transport sector is one of the most challenging economic sectors to decarbonise. Whereas national GHG emissions have reduced with 22% in 1990-2020, GHG emissions from Australian road transport have increased with 52%. As a consequence, the contribution of road transport to total GHG emissions has increased from 8% in 1990 to 16% in 2020 (DCCEEW, 2023). These trends are expected to continue, roughly in line with population and economic growth (BITRE, 2022), unless there are significant interventions.

In addition to growth in annual travel, there has generally been little progress regarding the average emissions performance of new vehicles sold in Australia in the last decade or so. Previous research (TER, 2019) estimated that on-road fleet-average CO_2 emissions rates (g/km) for new Australian passenger vehicles have been increasing with a few percent each year since 2015, rather than the officially reported annual reduction by the National Transport Commission. The difference is largely explained by the use of an outdated and increasingly unreliable test protocol that underpins these official figures (TER, 2023). The analysis found that a sustained increase in vehicle weight and a shift to the sale of more four-wheel-drive cars (in other words, SUVs and large Utes) are the main factors contributing to the increase in fleet average real-world emission rates of new passenger vehicles in Australia. It is thus important that any GHG emission estimates for road transport capture these shifts and reflect real-world on-road conditions.

The Federal Government publishes emission forecasts out to 2035 (DCCEEW, 2022), but not beyond. This raises the question: will we achieve the net zero target in road road transport in 2050? This paper will present a detailed assessment of current and future real-world GHG emissions for Australian road transport using a number of state-of-the-art and Australia-specific fleet and emission modelling tools. This paper confirms the challenges ahead for sustainable transport and provides an independent and up-to-date estimate of the GHG emissions situation for road transport in 2019 and 2050.

Figure 1. Will Australia achieve net zero emissions in the road transport sector in 2050?

2. Forecasting method

2.1 Overall approach

Vehicle emissions, fuel use, electricity and energy consumption are affected by a range of vehicle and powertrain design factors. Forecasting therefore requires a detailed breakdown and classification of the on-road fleet. In the vehicle emissions software COPERT Australia, the fleet mix (on-road population, annual mileage, accumulated mileage) is represented by 226 fossil-fuelled internal combustion engine vehicle (ICEV) classes. For future years, other fundamental vehicle technologies will increasingly penetrate the on-road fleet and the assumption of a 100% ICEV on-road fleet is becoming less valid. These other technologies include hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV) and (hydrogen) fuel-cell electric vehicles (FCEV). The same level of detail is required in the classification of these vehicle types.

Fleet mix and emissions modelling at this level of detail imposes specific challenges and requires various assumptions. Published fleet or fuel use data are often incomplete or too aggregated to be useful. In addition, available data sets use different vehicle class definitions and different timeframes (financial year, calendar year). TER therefore developed a fleet mix model in 2013 called AFM (Australian Fleet Model), with regular updates to accurately reflect dynamic fleet processes (e.g. changes in purchasing behaviour and preferences). In addition TER developed a new vehicle emissions tool last year called n0vem (net zero vehicle emission model), which fully incorporates COPERT Australia v1.3.5. These three tools work together to create detailed forecasts for current and future years. A schematic of the modelling process is shown in Figure 2. More details on these software tools is provided in the following sections.

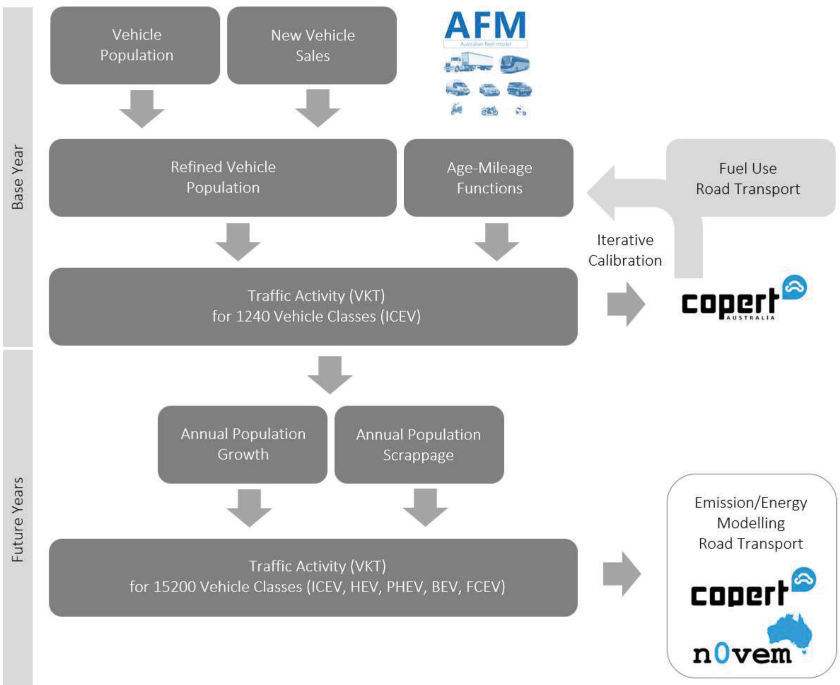

Figure 2. Australian Fleet Model (AFM) simulation method and interaction with Australian vehicle emission models (COPERT Australia and n0vem).

2.2 GHG emission scope

The scope of GHG emissions estimation and the associated terminology can be confusing. For instance, well-to-wheel (WTW) GHG emissions include all emissions related to fuel production – often referred to as the 'fuel-cycle' – in other words, processing, distribution (fossil transport fuels, electricity, hydrogen) and on-road use. An even more comprehensive scope is included in a life-cycle assessment (LCA), which estimates 'cradle-to-grave' emissions and accounts for both fuel-cycle emissions (WTW) and vehicle-cycle emissions (vehicle production as well as end of life, recycling or scrapping). An example of a LCA study is the recent TER study, which compared the life-cycle GHG emissions performance of Australian fossil-fuelled and battery electric vehicles (Smit and Kennedy, 2022).

Scope 1 is defined as the emissions released to the atmosphere as a direct result of an activity. COPERT is traditionally restricted to the estimation of Scope 1 GHG emissions from fossil-fuelled road transport (ICEV tailpipe emissions). Fossil fuels include petrol, diesel, CNG and LPG. This means that COPERT Australia quantifies the use phase or operational (on-road driving) emissions from road transport. It excludes other life cycle aspects such as vehicle manufacturing and fuel production. Previous work has shown that the use phase dominates total life-cycle GHG emissions per kilometre (about 70%) for Australian passenger vehicles. This is the same for both fossil-fuelled ICEVs and BEVs (Smit, 2021; Smit and Kennedy, 2022).

n0vem expands the prediction capability of COPERT Australia to Scope 1 emissions for HEVs, PHEVs, BEVs and FCEVs. BEVs and FCEVs do not emit exhaust or evaporative emissions directly (GHG or air pollutant), but they still generate non-exhaust emissions, for instance tyre, brake and road wear (TER, 2020; Smit, 2021), and indirect emissions related to energy use (electricity, hydrogen). As will be shown later, n0vem provides useful input data for the additional estimation of Scope 2 and 3 emissions such as tank-to-wheel (TTW) electricity use and hydrogen consumption. Scope 2 accounts for indirect emissions related to the generation of purchased energy and Scope 3 for indirect emissions from other upstream and downstream activities (suppliers, extraction, production, etc.).

This paper does not present the results for a complete LCA, as was done elsewhere (Smit and Kennedy, 2022). It provides an estimate of total WTW GHG emissions for Australian road transport, which includes emissions associated with the production and distribution of fossil fuels, electricity and hydrogen. A WTW analysis is expected to capture the bulk of the total GHG emissions (75% to 85%), as compared to a full lifecycle analysis, which also includes emissions associated with vehicle production and disposal (Smit, 2021).

2.3 Australian fleet model (AFM)

The Australian Fleet Model (AFM) is used to simulate future fleet growth and fleet turnover (scrappage) for the on-road fleet out to 2060 and estimates vehicle population and total travel activity, expressed as vehicle kilometres travelled (VKT). AFM is specifically designed to provide fleet data at the level of detail required for vehicle emissions and energy simulation. The software tool has been built and updated over time using a range of relevant datasets from, including but not limited to the Australian Bureau of Statistics (ABS), the Bureau of Infrastructure and Transport Research Economics (BITRE), the Department of Climate Change, Energy, Environment and Water (DCCEEW), the Australian Road Research Board (ARRB) and Gas Energy Australia (GAE). Statistical analysis was conducted separately by TER to develop prediction algorithms.

The AFM tool simulates the on-road vehicle population and total (vehicle) kilometres travelled (VKT) in selected Australian jurisdictions for 15,200 individual vehicle classes for past, current and future base years. AFM is capable of simulating complex patterns in the fleet turnover processes through consideration of vehicle class specific on-road population, vehicle sales data, vehicle usage profiles, population growth and scrappage rates. AFM provides an efficient but comprehensive approach to estimate the (national or specific state/territory) on-road vehicle population and total travel, using a comprehensive vehicle classification.

In this paper the penetration of new vehicle technologies is assumed to occur through a natural fleet turnover process, but the impact of specific interventions (e.g. scrappage programs or ICEV bans) can in principle be simulated. It is also assumed that new vehicles enter the fleet through new vehicle sales (i.e. negligible second hand imports). AFM specifically considers historic vehicle sales data and estimates future sales figures out to 2060 using the AFM scenario builder option, which will be discussed shortly. The on-road population is estimated for each sequential year starting in 2019, using dynamic fleet turnover and scrappage algorithms. This means that the simulation results for one specific year are used as input for the following year.

Since 2022, AFM has incorporated a statistical method to forecast plausible technology penetration trajectories for the on-road vehicle fleet. The starting point is the diffusion of innovation theory, which describes the uptake of new technology over time with a typical sigmoid adoption function (logistic growth curve). This approach has been regularly used to successfully predict the penetration of a broad range of technologies, for instance, EV technology (e.g. Guo *et al*., 2021; Kumar *et al*., 2022). However, the diffusion of innovation can fail for various reasons, for instance, due to a lack of supporting infrastructure, lack of (sustained) government support or simply technological reasons. This means that the typical S-curve is not always the most plausible trajectory for new vehicle technologies entering the on-road fleet.

The method therefore considers a broad range of functions to produce plausible and adaptable penetration trajectories. The plausible trajectory method includes the logistic, modified logistic and Gompertz curves, which represent potential choices for vehicle technologies that are not expected to peak, but instead reach an equilibrium. For situations where a peak is expected, followed by a decline, piece-wise functions are included to allow for the change in direction. The method also includes piece-wise linear, piece-wise quadratic, as well as more flexible curve-types such as the polynomial and natural splines. The best fitting curves are found through parameter optimisation and minimising of the sum of squared errors between the curve trajectories, the sales data and forecasted values, as well as expert judgement.

The penetration trajectories require input data for a few specific future years that guide the fitting process and provide ‘guard rails’. In collaboration with EU colleagues (TU Graz), TER conducted a separate review and analysis of the latest forecasted penetration rates by vehicle type and technology for the European Union (EU-27). The (modified) EU scenario used in this paper reflects the shares of the new vehicle registrations that would be required to meet the latest proposed CO_2-fleet targets in the EU. It has been assumed that Australia will follow the EU with a ten year delay across all vehicle classes.

Some further modifications were made to reflect the Australian situation. For instance, the proportion of PHEVs in EU vehicle sales has been high (due to fiscal measures), but the relative proportion of PHEVs in Australian EV sales is small and falling with increased popularity of BEVs. PHEVs are generally regarded as a transitionary technology for those vehicle segments where fit-for-purpose BEVs are not yet available, or where public charging infrastructure is not yet adequate. Recent overseas research report that the GHG emission benefits of PHEVs have been overstated (e.g. Plötz *et al*., 2020; Bieker, 2021; Farren *et al*., 2021; TER, 2022a). The real-world share of driving in electric mode appears to be about 20-40% of total kilometres driven, which is significantly lower than was originally expected. This means that PHEVs effectively operate as (large) ICEVs most of the time with relatively high GHG emission rates. Future GHG emission mitigation policies may therefore exclude, or at least reduce support for PHEVs, which in turn will affect PHEV sales. PHEVs may also attract ‘bad press’, which may give this vehicle technology an image of being ‘cheaters’ by overstating GHG emission benefits, potentially further affecting PHEV uptake. TER does not expect that there will be a sudden surge in PHEV uptake in Australia, which is reflected in the scenario definition.

Figure 3 presents an overview of the plausible trajectories created for each combination of vehicle type and fundamental technology type for the period 2019 – 2060.

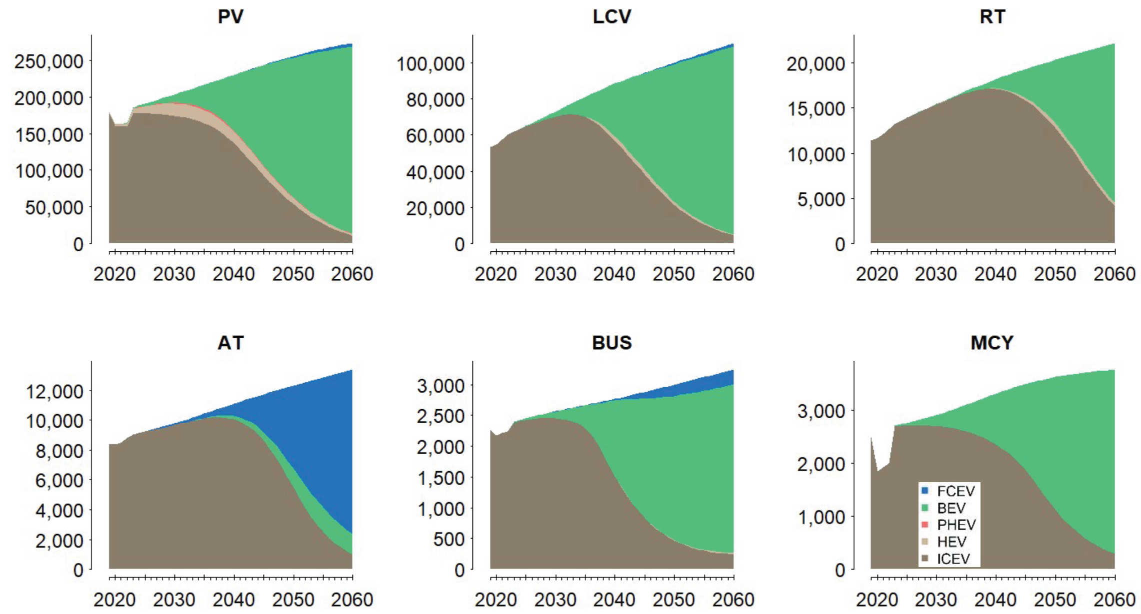

Figure 3. Annual VKT (million km) forecasts for the Australian on-road fleet by main vehicle type and fundamental vehicle technology for the time period 2019 – 2060, using the TER plausible trajectory method and assuming a ten year delay compared with the EU.

Recent emission forecasts by the Federal Government predict that light-duty EV sales (PV and LCV), which includes BEVs and PHEVs, will increase to 23% of new sales in 2030 and 44% in 2035 (DCCEEW, 2022). The TER scenario roughly aligns with these estimates and predicts that the EV share of sales in Australia 2035 will be 43% for passenger vehicles and 41% for light-commercial vehicles, consisting mostly of BEV.

CSIRO (2022) recently projected vehicle EV shares for four different scenarios, and they range from 36% to 94% in 2035, which illustrates the level of uncertainty associated with transport emissions forecasting. Clearly, the forecasted technology penetration trajectories shown in Figure 3 can change significantly due to dynamic changes in policies, regulation or technological and economic factors. It is therefore important to regularly re-evaluate forecasts with empirical data as time progresses. Multiple plausible scenarios could have been defined with AFM, but this is outside the scope of this paper.

Since fleet turnover is simulated with a high level of detail, the impacts of technology specific purchasing behaviour can be assessed. For this paper, the AFM simulation for future years was applied in a ‘like-for-like’ manner. This assumes, for instance, that a specified number of future customers who would traditionally have bought a small and more energy efficient passenger car, would instead buy a similar small non-ICEV passenger car (HEV, PHEV, BEV or FCEV). Similarly, a future customer who would normally have purchased a large ICEV SUV, would instead buy e.g. a large SUV BEV. This is a simplifying assumption as in reality there will be a range of factors that affect purchase decisions, such as upfront costs, total cost of ownership, tax exemptions, vehicle availability, delivery time, access to charging or refuelling infrastructure, to name but a few.

TER analysis of vehicle sales data showed that ICEVs and HEVs currently have similar sales profiles across vehicle size and weight classes, which suggests that a like-for-like assumption is reasonable. In contrast, the PHEV and BEV sales profiles appear to be significantly different from ICEV. At the same time, this finding may not be representative of a typical future sales profile, so further research is needed. Alternative scenarios can be defined at a detailed level to assess the future (policy) impacts of possible shifts in purchasing behaviour across different weight/size classes on total emissions (sensitivity analysis), but this is beyond the scope of this paper. The emission impact of vehicle size and weight are further examined in Section 3.3.

2.4 Net zero vehicle emission model (n0vem)

TER developed a new tool in 2022 called the net zero vehicle emission model (n0vem). This new tool fully incorporates COPERT Australia v1.3.5 – and thus includes all COPERT Australia ICE vehicle categories – but expands GHG emission estimation to include non-ICEV vehicle technology, i.e. HEV, PHEV, BEV and FCEV. It also considers expected emission and energy efficiency improvements for all fundamental vehicle technologies out to 2060.

COPERT (COmputer Program to calculate Emissions from Road Transport) is a globally used software tool used to calculate air pollutant and greenhouse gas emissions produced by road transport. Scientific development is managed by the European Commission. A dedicated Australian version of the software, COPERT Australia, was developed for all fossil fuelled vehicles in 2012-2013 to properly reflect the Australian fleet mix, fuel quality and driving characteristics and to provide accurate vehicle emission estimates for the Australian situation.

The National Pollutant Inventory (NPI) recommends COPERT Australia for motor vehicle emission inventories (Smit, 2014). COPERT Australia is now widely used in Australia for the development of national, state and regional emission inventories, as well as for the computation of fleet average emission factors (e.g. input to air quality impact assessments) and as input for life cycle assessment or LCA studies (e.g. Smit, Cope and Knibbs, 2019; Smit, 2020; Smit and Kennedy, 2022).

The methods and empirical data used in the development of COPERT Australia are transparent and have been comprehensively reported in national and international reports, scientific journals and conference proceedings since 2012 (e.g. Smit and Ntziachristos, 2012; Mellios, Smit and Ntziachristos, 2013). Moreover, particular efforts have been made to assess emission model performance and to conduct model validation using independent empirical data collected from tunnel studies (e.g. Smit *et al*., 2019a), on-road air quality measurements (Smit *et al*., 2019b), remote sensing (Smit and Kingston, 2019; Smit and Kennedy, 2020; Smit *et al*., 2021) and on-board emission measurements (Smit *et al*., 2022).

State-specific COPERT Australia input files were created for the national motor vehicle emission inventory in 2014 (Smit, 2014) and a detailed discussion of the various inputs for Australia is presented in this 2014 report.

COPERT Australia (and n0vem) consider all vehicle types including passenger vehicles (cars, SUVs), commercial vehicles (vans, trucks), buses and two-wheelers. Furthermore, fuel type and emission control standard are used in COPERT Australia to further qualify the on-road fleet, leading to 226 vehicle classes in total. n0vem uses a more refined age description and considers individual years of manufacture. Meteorological input includes average monthly temperature and relative humidity. For this article, meteorological and fuel quality data for NSW were used as a reasonable approximation of representative conditions in Australia. For state-level modelling it is recommended to reflect state-specific inputs for (intrastate) fleet mix, fuel quality and meteorological conditions.

The n0vem tool estimates emissions for 9,558 current and future vehicle technology classes (ICEV, HEV, PHEV, BEV, FCEV). It considers year of manufacture and different weight and size categories, which is important for accurate assessment of electricity consumption, fuel use, energy use and emissions. It estimates GHG emissions (CO_2, CH_4, N_2O, BC, CO_2-e), fuel consumption (petrol, E10, diesel, LPG, hydrogen) and energy/electricity use (kWh consumed). About two million emission factors (g/km), fuel use factors (g/km, MJ/km) and electricity/energy use factors (Wh/km) are generated by n0vem.

These factors are generated for different operational (driving) conditions and different emission types. They include vehicle speed dependencies (driving behaviour and congestion level), hot running emissions and additional GHG emissions due engine start, air-conditioning use, engine oil and NO_x emission control (SCR). The vehicle classification and allocation rules used in n0vem are summarised in Table 1.

Table 1. Vehicle classification used in n0vem.

Main Vehicle type	Subcategory Vehicle type *	Fuel Type	Vehicle class definition ICEV, HEV	Vehicle class definition PHEV, BEV, FCEV	Emission control Standard (ICEVs, HEVs, PHEVs)
Passenger Car	Small	Petrol; Diesel; LPG; E10; Electric; Hydrogen	EC < 2.0 l	GM < 1950 kg (RP < 130 kW) ***	Uncontrolled; ADR27; ADR37/00-01; ADR79/00-05 Year of Manufacture (YoM)
	Medium		2.0 ≤ EC < 3.0 l	1950 ≤ GM < 2150 kg	
	Large		EC ≥ 3.0 l	GM ≥ 2150 kg (RP ≥ 200 kW) ***	
SUV	Compact	Petrol; Diesel; E10; Electric; Hydrogen	EC ≤ 3.0 l AND GM ≤ 2500 kg	GM ≤ 2500 kg AND RP ≤ 150 kW	Similar to PC; +ADR36 (SUV-L); +ADR30; (SUV-Diesel), YoM
	Large		EC > 3.0 l OR GM > 2500 kg	GM > 2500 kg OR RP > 150 kW	
Light Commercial Vehicle (Van)		Petrol; Diesel; Electric; Hydrogen	GM ≤ 3.5 t		Uncontrolled; ADR30 (D); ADR36 (P); ADR37/00-01; ADR79/00-05, YoM
Heavy Commercial Vehicle (Freight Truck)	Medium	Petrol**; Diesel; LPG; Electric; Hydrogen	3.5 t < GM ≤ 12 t AND RP ≤ 155 kW		Uncontrolled; ADR30; ADR70; ADR80/00; ADR80/02-05, YoM
	Heavy		12 t < GM ≤ 25 t		
	Articulated		> 25 t GM OR RP > 300 kW		
Bus	Light Bus	Diesel; Electric; Hydrogen	≤ 8.5 t GM		
	Heavy Bus		> 8.5 t GM		
Moped		Petrol; Electric	2-stroke; 4 stroke		Conventional; Euro 1-3, YoM
Motorcycle			2-Stroke		
			4-Stroke, EC < 250 cm^3		
			4-Stroke, 250 ≤ EC < 750 cm^3		
			4-Stroke, EC ≥ 750 cm^3		

* EC = engine capacity (litres or cm^3), GM = gross vehicle/combination mass (tonne), RP = rated engine power (kW).

** It is noted that Petrol HDVs are a single vehicle class without ADR distinction.

*** GM is the only variable used but if GM info is not available RP can be used (within brackets)

2.5 Model performance and calibration

Independent data on total fuel consumption by fuel type for Australian road transport is required for performance assessment and potentially re-calibration. Fuel consumption and energy data for road transport are available from a number of sources. These include the Survey of Motor Vehicle Use (SMVU) published by the Australian Bureau of Statistics (ABS) until 2020, the Australian Energy Statistics (AES) and Australian Petroleum Statistics (APS) published by the Federal Government. These data have different levels of detail and use different definitions. So further post-processing is required to ensure consistency in the fuel use figures. To create a consistent dataset, the fuel data sets were first converted to a common base (volume in million litres), and subsequently converted to mass units (metric tonne) using consistent fuel parameters (Australia-specific values for commercially available fuels) for each type of fuel (fuel density and lower/higher heating values). Financial year data were converted to calendar year data by taking the average of adjoining financial years. Table 2 shows the estimated total fuel consumption used by road transport in Australia for base year 2019.

Table 2. Fuel consumption by road transport in Australia in 2019 (million litres).

Base Year Source	Petrol	E10	Diesel	Biodiesel	LPG	CNG	Total
2019	14,261	2,254	16,075	22.2	567	404	33,583

n0vem was run with the 2019 input file created with AFM. The performance was then assessed by comparing the predictions of total fuel consumption with the independently estimated total fuel consumption by fuel type shown in Table 2. The difference in total fuel consumption between n0vem and the independent fuel estimate in Table 2 is 0.1%. The differences by fuel type can be slightly larger but lie within ±1.5%. Similar to COPERT Australia, n0vem has a fuel calibration option to achieve full alignment with independent fuel consumption estimates (Table 2). This option was skipped for this paper as the differences in estimated fuel use are acceptable in the light of the significant modelling uncertainties out to 2060.

The Department of the Climate Change, Energy, the Environment and Water maintains and publishes the Australian Greenhouse Emissions Information System (AEGIS). AEGIS can be queried by inventory year, location (jurisdiction), sector and substance. Emission estimates are based on the IPCC classification system used to report Australia's greenhouse gas emission inventory and to track Australia's progress towards its 2030 Paris target. These estimates are compiled using the global warming potentials (GWP) from the IPCC 5th Assessment Report (AR5).

AEGIS (DCCEEW, 2023) reports that total GHG emissions from the road transport sector in Australia for 2019 are 83,725 kt/a (CO_2), 8,159 t/a (CH_4), 2,923 t/a (N_2O) and 84,728 kt/a (CO_2-e, AR5). CO_2-e emission factors are computed through multiplication of greenhouse gas emissions estimated with the 100-year GWP (global warming potential). n0vem uses the latest IPCC AR6 GWP values (6th assessment report) of 1, 29.8 (fossil origin) and 273, respectively. Using AR6 GWP values, total AEGIS CO_2-e emissions are 84,767 (CO_2-e, AR6). TER estimates total 2019 GHG emissions (CO_2-e, AR6) to be 2.1% lower than AEGIS. The largest difference between TER and AEGIS is seen for CH_4 (39% lower) and N_2O (5% lower). However, the combined emissions of CH_4 and N_2O make only a small contribution of about 1% to total GHG emissions (CO_2-e) for road transport. The differences between AEGIS and the TER estimates are explained by differences in the modelling approach and underlying assumptions. For instance, TER understands that the Australian Government (previously) used the COPERT (EU software) rather than the dedicated COPERT Australia software in its calculations. Nevertheless, the comparison between AEGIS and n0vem suggests that the GHG predictions (CO_2-e) compare reasonably well.

3. Results

The AFM-n0vem simulation generates a rich and comprehensive dataset, which can be analysed in various ways. A few examples are discussed in this section.

3.1 What is the forecasted GHG emissions situation in 2050?

When the emission predictions for 2050 are compared with 2019 (Table 3), it is clear that there is a significant reduction in Scope 1 GHG emissions from road transport. Scope 1 GHG emissions are roughly halved in 2050. On the other hand, the situation in 2050 is far removed from achieving the net zero target in 2050. The reduction in total GHG emissions is hampered by a continued increase in total travel, a shift to heavier passenger vehicles and a (naturally) slow penetration of low emission vehicles into the on road fleet (Figure 3).

Table 3. Total road transport GHG emissions in Australia in 2019 and 2050 (Scope 1, TTW).

Year	CO_2 t/a	CH_4 t/a	N_2O t/a	CO_2-e t/a
2019	82,110,515	4,971	2,777	83,016,635
2050	38,182,839	1,040	1,104	38,515,327
Difference	-53%	-79%	-60%	-54%

In contrast to 2019, a significant portion of energy use in 2050 falls outside the Scope 1 emissions definition. Electric propulsion (BEV, FCEV, partly PHEV) generates no direct tailpipe GHG emissions and therefore no Scope 1 emissions. Emissions are generated elsewhere in the production and distribution of fossil fuels, electricity and hydrogen and they need to be accounted for in the assessment.

Table 4 shows current and predicted energy use by fuel type. As expected, the use of fossil fuels has dropped a little over 50%, which is in line with the reduction in GHG emissions (Table 3). Table 4 shows a substantial shift in the use of different energy sources in road transport. Whereas practically all transport energy use in 2019 was fossil fuels, with a negligible portion of electricity (0.01%), the situation is expected to be different in 2050 with 62% of transport energy coming from fossil fuels, 26% from hydrogen and 12% from electricity. In addition, due to efficiency improvements for all vehicle technologies, total on-road energy use by road transport is forecasted to be reduced with 25% in 2050, despite the modelled 54% increase in total travel in the period 2019 – 2050.

Table 4. Total on-road transport energy use in Australia by fuel type in 2019 and 2050.

Year	Fossil TJ	Electricity TJ	Hydrogen TJ	Total TJ
2019	1,118,187	116	0	1,118,276
2050	517,467	216,641	103,001	836,875

However, the picture is significantly richer and more complex than that. First, there are significant differences in energy efficiency between technology types. For instance, battery electric vehicles are roughly twice as energy efficient on the road (TTW) as fuel cell electric (hydrogen) vehicles and roughly three times as energy efficient as ICE vehicles of similar type (Smit, Whitehead and Washington, 2018). This is reflected in the modelling results (Table 5). In 2050, BEVs account for approximately a 70% of total travel, but only 25% of total (on-road) energy use. In contrast, fossil-fuelled vehicles account for about 25% of total travel, but consume 60% of total energy, despite the expected efficiency improvements for ICEVs, which were simulated out to 2060. In 2050, hydrogen vehicles make up only a few percent of total travel, but it was assumed that the bulk will be driven by large trucks. As a consequence, FCEVs use a little over 10% of total on-road energy.

3.2 Including GHG emissions for electricity and hydrogen production (WTW)

The Australian on-road fleet is predicted to require 216 PJ of electricity and 103 PJ of hydrogen in 2050 (Table 4), which corresponds to 60 TWh of electricity and 861 ktonne of hydrogen per annum, respectively. To put this in context, total electricity generation in Australia was 265 TWh in 2019 (DCCEEW, 2020). So the forecasted electricity required for electrified road transport in 2050 is estimated to be relatively modest, with a share of 23% of current electricity production. It is noted that consideration of the temporal distribution of electricity demand is important but outside the scope of this paper (e.g. peak demand over the day, week, months).

Previous TER work (Smit and Kennedy, 2022) has estimated GHG emission intensities (g CO_2-e/kWh consumed) for grid-loss corrected electricity generation by fuel type in Australia for a future 'decarbonised grid' scenario (SC3). SC3 assumes an Australian electricity mix of 5% coal, 5% gas, 30% hydro, 25% wind, 5% biomass and 30% solar. The average emission intensity is 82 g CO_2-e/kWh consumed and this value has been used to estimate total associated GHG emissions for electricity use by road transport in 2050. With a predicted 60 TWh of electricity use in 2050, WTT CO_2-e emissions for electricity consumption (BEVs, PHEVs) are estimated to be 4.9 Mt.

The GHG emission impacts of hydrogen use in transport critically depend on the production and the distribution methods. In fact, a major challenge in analysing the impacts of hydrogen use for transport applications is the large number of combinations and permutations of hydrogen production, transportation, and distribution options, vehicle on-board storage options and fuelling approaches (Frank *et al*., 2021).

Currently, around three-quarters of the annual global hydrogen production is obtained through natural gas reforming (steam methane reforming or SMR, grey hydrogen), and it has been estimated that this process generates 10 tons of CO_2 per ton of hydrogen produced (Fernández and Pérez-Dávila, 2022), plus other air pollutants such as NO_x and PM. With a predicted 861 ktonne of hydrogen use in 2050, CO_2-e emissions for FCEVs are estimated to be 8.6 Mt, but this only includes SMR related emissions and not yet emissions related to hydrogen distribution. Bieker *et al*. (2021) estimates a range of 101 – 134 g CO_2-e/MJ for the SMR hydrogen pathway, which translates to 11.8 Mt, assuming that 115 g CO_2-e/MJ is a reasonable value for Australia.

To reduce the GHG impacts of hydrogen production with fossil fuels, green hydrogen can be used (electrolysis using renewable energy). An initial scan of the scientific literature (e.g. Wong *et al*., 2020; Bieker *et al*., 2021) shows a range of about 10 – 35 g CO_2-e/MJ H_2 for the renewable hydrogen pathway (wind, solar), which translates to 2.3 Mt, assuming that 23 g CO_2-e/MJ – which corresponds with 82 g CO_2-e/kWh used for the future electricity grid – is a reasonable value for Australia.

Finally, extraction, transport, production and distribution of refined fossil fuels such as petrol and diesel require energy and produce GHG emissions. Previous TER work estimated that typically about 20% of the contained energy in fossil fuels is consumed within the production and distribution chain (Smit and Kennedy, 2022). These upstream emissions were added to the operational GHG emissions for fossil fuels. The 2019 baseline (TTW) CO_2-e emissions estimate of 83 Mt (Table 3) is thus increased to 104 Mt to reflect WTW emissions. Table 5 presents an overview of the calculations. It is noted that these are preliminary estimates given the dynamic research situation. Further in-depth research is recommended to throw a wider net, review all available information and update the WTW emission predictions for 2050, if necessary.

Table 5. Summary of forecasted direct and indirect (WTW) road transport energy use and GHG emissions in Australia by fuel type in 2050.

Fuel type	WTW GHG Emissions 2050 Mt CO_2-e	Share of Total GHG Emissions (CO_2-e) %	Share of Total On-Road Energy Use %	Share of Total On-Road Travel (VKT) %
Fossil fuels	48.1	74 – 87%	62%	27%
Electricity	4.9	8 – 9%	26%	71%
Hydrogen	2.3 – 11.8	4 – 18%	12%	2%
Total	55.4 – 64.9	100%	100%	100%

The information presented in Table 5 provides a high level assessment of the expected energy requirements and associated GHG emissions in 2050 and it highlights a number of important considerations for Australian policy makers.

- In 2050, Scope 1 emissions for road transport miss a large portion of the 'upstream' GHG emissions associated with electricity and hydrogen, with a gap varying from about 15% to 25%. It is thus important to include at least the indirect operational emissions for road transport for cost-effective policy development.
- If Australia would follow a (modified) EU scenario with a 10 year delay, the simulation suggests that the net zero target in 2050 is substantially missed. The modelling estimates a reduction of total WTW GHG emissions from Australian transport in 2050 of about 35% to 45%, depending on the hydrogen production pathways (104 Mt in 2019 to 55 – 65 Mt in 2050). This finding suggests that significantly more intensified and far-reaching policies need to be developed and implemented in Australia to achieve net zero emissions in 2050.

- BEVs have a significant advantage over the other technologies in terms of energy efficiency, which means that their carbon footprint is small compared with fossil fuelled (ICEV, HEV, PHEV) and hydrogen vehicles. This is clearly demonstrated in Table 5 where BEVs make up the bulk of total travel, but only a quarter of total energy use. This result indicates that aggressive new policies to increase BEV shares in the Australian on-road fleet across all vehicle classes as soon as possible should be seriously considered.

3.3 Lightweighting of the on-road fleet

The modelling in this paper shows that Australia is expected to fall short in achieving net zero emissions in road transport. This is still the case with a significant penetration of electric vehicles in the on-road fleet and approximately 70% of total kilometres travelled by BEVs in 2050. Electrification and the use of hydrogen alone are not going to be enough.

One issue that has not yet received much attention is the sustained and increasing proportion of large and heavy passenger vehicles (SUVs, Utes) in on-road fleets around the world and particularly in Australia. These vehicles have a detrimental effect on energy efficiency and GHG emissions. SUVs and Utes are larger and heavier than conventional passenger cars and the laws of physics dictate they need substantially more energy and fuel per kilometre of driving, when compared with smaller and lighter vehicles.

Whereas a large diesel SUV typically drives 3 kilometres to emit a kilogram of CO_2, it will take about 15 and 200 kilometres for a light electric vehicles and an e-bike, respectively, to do the same. A battery electric car will currently drive about 7 kilometres before emitting one kilogram of CO_2, but in 2050 this is expected to be in the order of 60 kilometres due to a decarbonised grid. Lightweighting a battery electric car will more than double the distance again to 125 km per kilogram of CO_2 (TER, 2022b). TER therefore expects that lightweighting and energy efficiency optimization in transport will be critical to reach significant reductions in GHG emissions and meet our targets.

To illustrate the potential impact of lightweighting of the Australian on-road fleet, all passenger vehicles (cars, SUVs, Utes) were instantaneously converted to small cars in the simulation, while keeping all other vehicle types (light and heavy commercial vehicles, buses, motorcycles) the same.

If Australians would have driven only small passenger cars in 2019, then total GHG emissions from road transport would have been approximately 15% lower, a significant reduction. This equates to about 11.3 Mt of CO_2-e (TTW) and 14.1 Mt of CO_2-e (WTW). This reduction in GHG emissions is similar to total annual emissions for domestic aviation and domestic shipping combined, which was reported to be 10.8 Mt in 2019 (DISER, 2021), simply by shifting to smaller cars. The relative reduction in emissions, fuel and energy use in 2050 by lightweighting the fleet is similar to 2019 and about 15%. This is estimated to result in a reduction of about 5.5 Mt of CO_2-e (TTW) and 7.0 Mt of CO_2-e (WTW). It is emphasized that lightweighting is beneficial for all vehicle and technology types. So it will be equally important to lightweight fossil-fuelled and electric vehicles.

3.4 Hydrogen for road transport – elevated risk and uncertainty

The modified EU scenario used in this study reflects a significant uptake of hydrogen vehicles in 2050, but it is clear that the proportion of FCEVs or H_2-ICEVs (direct combustion of hydrogen) in future EV sales is by no means guaranteed. The main reasons for a negligible uptake of hydrogen vehicles in Australia to date are costs (both vehicle and fuel), the need for new hydrogen fuel infrastructure, the lower level of technology maturity (compared to BEVs) and limited vehicle availability. These are not expected to change in the short to medium term and hydrogen uptake (and similarly for e.g. e-fuels) is therefore not expected to be significant in the foreseeable future, as is also clear in Figure 3.

Global sales data for cars and light commercial vehicles, along with statements from corporate leaders, suggest many vehicle manufacturers do not seriously consider hydrogen to be a viable and lucrative road transport fuel. For example, the Honda Clarity hydrogen fuel cell vehicle ceased production in August 2021 when Honda trimmed underperforming models from its line-up. Truck makers such as Daimler, MAN, Renault, Scania and Volvo have indicated they see an all-electric future. Some manufacturers are even lobbying for a faster transition to electric cars (Smit, Zhao and Dia, 2021).

In the longer term (2040 – 2060), hydrogen vehicles may or may not make up a significant to large portion of future vehicle sales in the long-haul truck sector, but TER expects they are unlikely to generate significant sales volumes in market segments where electrification (BEVs) is feasible (passenger vehicles, light-medium commercial vehicles, buses and motorcycles). Even for the long-haul trucking sector, hydrogen vehicles will have to compete with alternative technological solutions, such as battery swapping (short refuelling times) and overhead charging cables (catenary BEVs, e-highways), as well as annual improvements in battery energy density and battery prices.

There are a number of unresolved aspects to hydrogen in transport (risk factors) that do not seem to be broadly discussed and would be worthwhile to point out here. First, hydrogen vehicles have a lower overall energy efficiency than BEVs, as was noted before. Hydrogen is not an energy source, it is an energy carrier. This means it needs to be generated, compressed or liquefied, transported and converted back into electricity – and each step of the process incurs an energy loss. The more energy required for transport, the more renewable energy needs to be generated, and the higher the cost and more difficult it becomes to decarbonise the economy rapidly and at scale.

Second, there is potential for significant leakage of hydrogen during production, transport and use. Hydrogen is a more potent greenhouse gas than the main greenhouse gas carbon dioxide, and any loss of hydrogen also reduces the overall energy efficiency. Hydrogen emissions from leakage may also add to local and regional air pollution, and they may deplete the ozone layer in the stratosphere, but further research is needed in this space.

Hydrogen in fuel cells also needs a significant amount of clean fresh water. A single hydrogen fuel cell car requires about 9 litres of clean, demineralized water for every 100 km driven. For a large truck, this would be over 50 litres per 100 kilometres. If sea water and desalination plants were used to produce the water, another energy loss would be added to the production process, penalising overall energy efficiency (and costs) even further.

And, finally, there is a general consideration of what is the best value for consumers. Consumers are able to generate and store their own renewable electricity (decentralised system), but they are generally not able to produce hydrogen. Hydrogen production and distribution requires a specialised and centralised system, which is likely the reason that industry has a strong interest in (and lobbies for) hydrogen, as it sustains the profit making business models of the current (fossil) fuels industry.

Although this paper has generally followed the latest EU scenario, the simulated penetration of hydrogen vehicles and the hydrogen on-road fleet in 2050 is uncertain and may be overestimated, given the points raised in this section. So it would be useful to consider the GHG emission impacts of a more electrified scenario.

4. Conclusions

Decarbonising road transport needs to be rapid, deployed at scale, and requires a holistic strategy that promotes shifts in everyday travel behaviour and freight movements. This study presented an independent assessment of direct and indirect greenhouse gas emissions, fuel and energy use (WTW) by Australian road transport in 2050, using state-of-the art software tools and methods. The analysis suggests that Australia will significantly fall short of the net zero target, assuming that we will follow the EU low and zero emission technology penetration trajectory with a ten year delay and taking into consideration Australia's unique on-road fleet and energy use.

TER estimates a reduction of total GHG emissions (CO_2-e, WTW) from Australian transport in 2050 of only 35% to 45%, depending on the dominant hydrogen production pathway. This means that significantly more intensified and far-reaching policies need to be developed and implemented if net zero is to be achieved in 2050.

In terms of possible solutions, BEVs have a substantial advantage over the other technologies in terms of (WTW) energy efficiency and emissions, which means that their carbon footprint is relatively low compared with fossil fuelled (ICEV, HEV, PHEV) and hydrogen vehicles. This result indicates that aggressive new policies to increase BEV shares in the Australian on-road fleet across all vehicle classes could be seriously considered.

In addition, lightweighting of new vehicles and promotion of the sale of small and light vehicles will have significant beneficial impacts on greenhouse gas emissions and energy use in road transport. The evidence suggests that an on-road passenger vehicle fleet in 2050 that is dominated by small and light battery electric vehicles may get Australia close to the net zero target.

Betting on the future large-scale availability of hydrogen for the transport sector risks locking in fossil-fuel dependency, and its additional greenhouse gas and air pollutant emissions, if upscaling clean hydrogen falls short of expectations. Transport policies need to minimise energy demand and improve energy efficiency in transport as much as possible and as fast as possible. For a rapid reduction in greenhouse gas emissions, electrification of transport appears to be the most cost-effective and most robust way forward. Green hydrogen should be deployed where electrification faces unsurmountable barriers, but this is unlikely to be the case in the road transport sector. Other transport sectors such as long-range shipping and aviation could be more plausible candidates.

5. Disclaimer

The research presented in this article is independent and has not been funded by an external organisation. This article has been prepared with due diligence and care, based on the best available information at the time of publication. TER holds no responsibility for any errors or omissions in this article. Any decisions made by other parties based on this article are solely the responsibility of those parties.

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