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# Transforming Australia's road fleet with electric vehicles: Strategies and impediments affecting net-zero emissions targets for 2050

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ABSTRACT

A complete and rapid transition to electromobility can minimise road fleet emissions. Electric vehicles (EV) will be essential for decarbonising road transport, which in 2022 generated 19% of Australia's total emissions. Unlike New Zealand, which implemented multiple policies since 2016, limited policy support in Australia for EVs means uptake lags. Creating opportunities for decarbonising road transport and the electricity supply could accelerate the clean energy transition and reduce fossil-fuel dependence. This paper's primary purpose is to suggest policy mechanisms to expedite Australia's road fleet electrification by 2050. Results show that implementation of evidence-based policies, and ensuring their ongoing functionality, will be necessary to achieve the goal. We provide recommendations for the future direction of Australia's federal government policy to enhance a rapid transition to EVs. Its role is critical in supporting the transformation by adopting appropriate targets and policies to encourage EV uptake, transitioning electricity completely to renewable sources, deploying adequate charging infrastructure and maintaining it and the forced-phase out of residual fossil-fuelled cars. A faster transition means fewer emissions and less likelihood of exceeding the emissions budget.

## 1. Introduction

Modern modes of travel have enabled increased trade and a shrinking of the time taken to reach a destination, but the continued use of oil has come at a price (Banister et al., 2011). Decarbonising road transport will be an essential component in the quest for net-zero emissions by 2050 as per the Paris Agreement (UNFCCC, undated) to which Australia is a signatory nation (UN, 2016). In 2020, road transport through the consumption of fossil fuels as an energy source contributed about 23 % of total global emissions (IEA, 2022a). In March 2022, Australia's road transport generated 18.7 % of the country's total emissions, 48 % greater than in 1990, and passenger cars accounted for more than half of road transport emissions, about 10 % of the country's total (DCCEEW, 2022a). In neighbouring New Zealand (NZ), transport's contribution to the country's total emissions is far greater: 39 % of domestic emissions in 2020, of which 90.5 % was from road transport, an increase of more than 80 % since 1990 (Ministry for the Environment (NZ), 2022). These statistics show the significant opportunities that road transport offers for reducing greenhouse gas (GHG) emissions in absolute terms, rather than continue on a growth trajectory (IEA, 2023). Consideration must also be made about the renewables content of any country's electricity supply as this will affect the ability for road transport to reach net-zero emissions. However, very few countries have an electricity supply that has insufficient renewable energy for BEVs to make a positive contribution when they are driven in preference to Internal Combustion Engine Vehicles (ICEV) (Broadbent, 2018). Additionally, more specific information about the impact of EVs on emissions and electricity supply in Australia can be found at Mills and MacGill, 2017.

A transition to EVs can reduce GHG emissions from transport, in tandem with a reduction in a suite of other environmental, social and economy-wide harms such as air pollutants, noise and the resulting health issues (Broadbent et al., 2017). Concurrent with prior research (e.g. Dovers and Hussey, 2013), we argue that governments have a role to play in transitions, especially in the early stages through the adoption of suitable policies, which can be based on regulations, information provision, be directed at the market, or a combination thereof (see Section 2. 1). As an example, scenarios developed for Europe (Krause et al., 2020) have previously demonstrated that a full electrification of the vehicle fleet is required to achieve the full potential of emissions reductions along with the proviso that all accompanying policies must

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perform at the best possible level.

With the importance of the road transport sector in the quest towards net zero emissions, this paper intends to suggest a range of potential policy options that Australia could adopt if the aim is to reduce road transport emissions to net-zero by 2050. As such, the paper provides a synthesis of the results of our previous research into factors affecting adoption of EVs (Broadbent et al., 2021a; Broadbent et al., 2021b) and the development of modelling to test a range of scenarios and policy pathways (Broadbent et al., 2022a; Broadbent et al., 2022b) to ascertain benefits that can accrue, in particular from a transition to plug-in only battery electric vehicles (BEV). Our research provides unique insights into consumer thinking about EVs in NZ and applies these to our original modelling of scenarios and the impact of various combinations of potential policy options. The insights could be useful to policy makers and researchers in countries that are considering the introduction of measures to encourage uptake of EVs.

Section 2 of this paper provides relevant background information, outlining the state of play in the Australian and New Zealand markets, two countries with similar socio-economic conditions, but with very different government approaches to EV adoption. Section 2.1 discusses the importance of government intervention to achieve change, Section 2.2 outlines research into the factors that affect the transition away from oil, and Section 2.3 provides further detail about Australia and NZ, the changes NZ made to their policies, and the impact this has made on EV rates of uptake in NZ. Section 3 synthesises lessons gained from research we conducted in NZ, and then in Section 4 we investigate potential Australian BEV adoption rates, GHG emissions changes and costs to government by modelling various targets and policy options that could be adopted, but assuming no vehicle supply shortages and no mode shift to public and active transport, which otherwise can contribute to emissions reductions. Finally, in Section 5, based on the lessons learned from New Zealand and other international successes, and our modelling results, we make recommendations for the future direction of road transport related policies in Australia.

## 2. Background

### 2.1. Government intervention

Albeit the efficacy of individual policy instruments is debateable (Coffman et al., 2017) and can vary by jurisdiction, government policies can encourage the purchase of EVs through financial and/ or soft incentives (e.g. providing the necessary public charging infrastructure, a necessary market co-condition, especially on major routes (Lieven, 2015)), and by raising awareness of current policies and associated benefits. In any sector better policy outcomes can be achieved by addressing market pinch points through direct government participation in the market (e.g., through vehicle procurement), or indirectly (e.g., by regulation, taxation, subsidies), while being mindful of unexpected consequences that can lead to inefficiencies (UK OFT, 2009). Many studies have illustrated the importance of government policies to support market establishment, particularly in the early stages before EVs become profitable (e.g., Rietmann and Lieven, 2019; Narassimhan and Johnson, 2018; Lutsey et al., 2018); and the importance of governments in accelerating transitions and tipping points in transforming systems (Sharpe and Lenton, 2021).

Government policies can employ a carrot and/or stick approach to facilitate changes in vehicle fuel sources. There is a range of incentives that can act as carrots to encourage EV adoption and the following provide examples that have shown demonstrable success in encouraging consumers to change.

Measures that can reduce vehicle purchase price such as tax deductions and rebates are important as higher vehicle capital costs for EVs, compared to operational costs, can deter buyers (Bjerkan et al., 2016; Gass et al., 2014);

Ensuring the supply of publicly accessible charging stations are available for both destination charging and fast chargers for long distance trips as adequate charging infrastructure provision, especially fast chargers on major transport routes, has been assessed as an essential component of the shift to EVs (Mersky et al., 2016; Lieven, 2015);

Provision of a range of soft incentives that appeal to various niches of the motoring market such as toll relief on roads and ferries, access to bus lanes, free parking, priority parking for EVs (Mersky et al., 2016).

Demonstrating the critical role of governments in engendering sales, research in different Nordic countries (Zarazua de Rubens, 2019) showed consumers had similar behavioural characteristics, but it was differences in government policies that accounted for differing EV purchase rates among the five countries. By contrast, Switzerland's low EV sales may be a result of limited policies that otherwise might increase the appeal of EVs to mainstream consumers (Brückmann et al., 2021).

Furthermore, governments that fail to adopt mandatory vehicle fuel emissions regulations (European Commission, 2022), which act as a stick approach due to the application of fines on manufacturers who fail to sell enough EVs from their total offerings, can discourage EV purchasing in the long term, even when infrastructure deployment is supported (Harrison and Thiel, 2017). A further example of the stick approach has been applied by the Norwegian government to buyers of fossil-fuelled cars. Norway is the world's leading EV market where the taxes applied to s ICEVs are punitive thus rendering EVs relatively cheaper (Figenbaum, 2017). This approach provided government revenue that led a successful shift in the composition of Norway's fleet and did not require dependence on expenditure of other government revenue to achieve the result (Fridstrøm, 2020).

It is worth noting that having good policy intentions can be undermined by weak instruments and poor attention to detail (Broadbent et al., 2017). For example the UK aimed to install a large network of chargers, which is an essential policy, but ensuring the downtime for out-of-order chargers is minimised will be essential to prevent market failure where consumers fear a lack of reliability and turn away from EVs (Broadbent et al., 2017). Furthermore, the number of chargers installed would need to keep pace with predetermined targets such as per the European union's target of one destination charger per ten EVs in the fleet and one fast charger per 100 vehicles (IEA, 2020a). Similarly, a useful network of chargers must be well dispersed, including in rural areas, easily accessible and well signposted (Falchetta and Noussan, 2021). Thus, to have any measure of success policy instruments must be implemented with care and assure ongoing functionality of measures while trying to avoid unintended consequences.

One co-benefit that governments can reap from the introduction policy fostering EVs uptake is a reduction in air and noise pollution, which leads to reductions in health costs and a healthier society. South Korea is one of many nations developing policy to reduce air pollution through measures to limit diesel vehicle pollution, which combined with targeted rebates for EVs could reduce air pollution significantly (Choi and Koo, 2021). Furthermore, the transition to EVs is expected to markedly reduce noise especially in urban areas, which causes multiple health problems (UNEP, 2022), greatly improving the well-being of those living near major roads (Walker et al., 2016).

The IEA (2022) has developed scenarios showing that the current pledges by countries to reach net-zero emissions by 2050, even if implemented perfectly, are insufficient to meet their respective goals. More will need to be done by governments and it is worth noting that many automakers are more ambitious than policy targets overall, particularly in Europe, which may reflect the EU's commitment to transition to net-zero emissions by 2050 (IEA, 2022b).

### 2.2. Making the transition away from oil: Factors affecting change

The transition away from oil will be driven by multiple factors such as government policies, consumer choices, and preferences for the status quo including by incumbent industries. Urry (2004) predicted a transformation of the transport system away from steel vehicles and oil-based propulsion back in 2004, but could not say how this would occur, and given the dominance of individual freedom of mobility he argued that public transport could not completely substitute for current modes of transport demand. Furthermore, Struben and Sterman (2008) suggested that a transition away from fossil-fuelled vehicles would be difficult to transition arguing that efforts to reduce the dominance of conventional cars would need to be sustained for decades due to vehicle longevity, customer perceptions, resistance to change, and the power of vested interests. More recently, Sheller and Urry, (2016) discussed the need for more research into mobility as a system, considering that current social practices and institutions are reliant on mobility, which is a complex system that is path dependent. Following an investigation of the scandal surrounding automotive emissions performance standards, Haas and Sander, (2020) warned it is necessary to recognise the structural power of automotive system incumbents, especially vehicle and parts manufacturers, and oil producers, and they also noted dependency on existing system pathways.

To change the current pathway patterns where there is continued economic growth, de Blas et al., (2020) instead suggested that a degrowth paradigm is pursued to reduce materials and energy consumption. The authors encouraged a mode shift to active and public transport in order to overcome potential deficits in emissions reductions from a transition to electric vehicles, and that rapid electrification of transport vehicles will require investment in key minerals to avoid materials shortages. Indeed, the European Commission (2020a) recommends that all policy levers are pulled to make transport more sustainable, including transportation that reduces dependency on fossil fuels, encouragement of greater use of public and active transport modes, and using polluters pay mechanisms.

Changes in government policies that seek to reduce emissions from road transport could expose difficulties that could hamper progress and reduce the opportunity for optimal outcomes. It will be important that such difficulties are considered and addressed. For example one challenge for the decarbonisation of the road transport sector is the required rapid restructuring of the automotive industry and the complete supply chain, including an adequate supply of the necessary components (IEA, 2022b), including component recycling and raw material extraction (Danielis et al., 2022). However, the lithium-ion batteries used in current model EVs can result in some harm, for example if the lithium and cobalt is sourced from countries with environmental and human exploitation concerns (Olivetti et al., 2017). Recycling of lithium ion batteries is an emerging field (Neumann et al., 2022) that can reduce some of the issues (Reinhardt et al., 2019) and provide alternative sources of these essential materials, helping develop a circular economy (Baars et al., 2021). However, with soaring global demand for lithium, recycling will not be able to supply sufficient quantities for some time to come (Shekhar et al., 2022; Habib et al., 2020). Furthermore, some battery chemistry types may not be as profitable to recycle and may require government assistance (IEA, 2022b).

Moreover, there are other impediments that can thwart the introduction of policies to encourage EV uptake, which are well documented in sustainability transitions literature (e.g. Geels, 2019). Examples include: institutional inertia such as existing regulations and standards and where policy networks favour incumbents, which create an uneven playing field; vested interests using their access to policy networks to dilute regulatory change and hinder innovation.

### *2.3. From intentions to action: Uptake of EVs in Australia and New Zealand*

New Zealand and Australia have many similar socio-economic and cultural characteristics (UNDP, 2018), including high rates of car ownership (Ministry of Transport NZ, 2018; Australian Bureau of Statistics, 2019), a Westminster system of government and importantly both are right-hand drive countries, which can affect availability of vehicle models from producer countries. These two countries have had divergent approaches and outcomes to the electrification of road transport. Back in 2011 both OECD countries had a similar rate of EV uptake (Fig. 1), however, that situation began to change in 2016, with New Zealand (NZ) evidencing a higher rate of EV uptake from that time. The successful transition from good intentions to actions achieved by NZ offers a suitable case study to understand the effects of various policies adopted to encourage EV uptake. Here follows a summary of the baseline situation in Australia and New Zealand back in 2011, and the different policy pathways adopted since then in NZ. While the Total Cost of Ownership was canvassed in the survey, and it is an attribute that can influence consumer intentions to buy an EV (Liao et al., 2017), for example, motorists in South Korea (Lashari et al., 2021) and NZ (Broadbent et al., 2021a) did not consider it as important as the upfront cost of the vehicles. However, further study on Australia's tax regime that encourages the purchase of certain classes of vehicles would be beneficial to determine the impact of tax regulations on purchasing preferences and total cost of ownership.

By 2011 EVs were utilising lithium-ion batteries, thus rendering them as a practical alternative to fossil-fuelled vehicles, and importation of EVs increased in both Australia and NZ after that. In 2016 the NZ national government introduced a suite of policies to encourage the uptake of EVs (as per the list at the end of this Section 2.3), with the explicit intention of reducing road transport related emissions and reducing the burden of importing petroleum fuels on the nation's economy (Minister for Transport NZ, 2016). Since then, the NZ government added two more policies, the Clean Car Standard (NZ Transport Agency, 2021), which is a mandatory vehicle fuel emission standard, and the Clean Car Discount (NZ Transport Agency, 2022) with the Clean Vehicle Act coming into force in February 2022 (Ministry of Transport NZ, 2022a). The Clean Car Discount is a bonus-malus scheme designed to encourage EV uptake by making polluters pay more for vehicle registration and provide cost savings for those buying low emission vehicles, a scheme that is cost neutral to government. Now Australia is only one of two OECD countries without a mandatory vehicle fuel emission standard (Broadbent et al., 2022b).

Over the same time period, the then conservative government of Australia expressed little interest in encouraging the sale of EVs or ensuring that EV travellers could traverse the country and charge all along the way (DISER, 2021). A new Labor government, following elections in 2022, has sent signals that they intend to take more action (DCCEEW, 2022b). Meantime, some Australian state and territory governments have provided minor purchase incentives and undertook some programs to deploy charger networks (Wood et al., 2021), yet not enough to appeal the population at large, rather enthusiasts who could afford the higher price of imported new EVs and who were prepared to spend time charging their vehicles on long trips and who had easy access to 'at home' charging on a day-to-day basis (Broadbent et al., 2019).

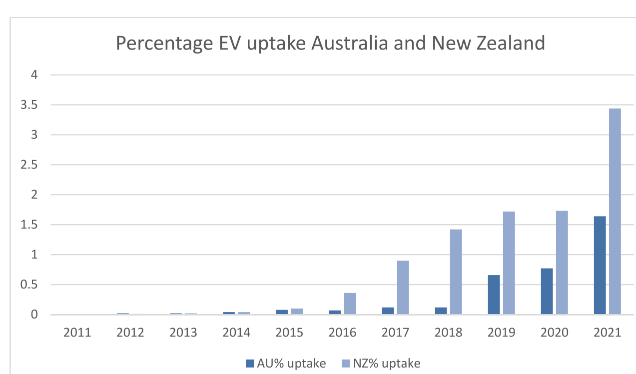


**Fig. 1.** Percentage of EVs in the light vehicle category purchased new in Australia and New Zealand from 2011 to 2021 (data source: Ministry of Transport (NZ) and FCAI).

The New Zealand government implemented a target to reduce emissions by 41 % from 2019 levels by 2035. To achieve this reduction the NZ government introduced specific targets and policies in 2016, (Ministry of Transport NZ, 2022a; Ministry of Transport NZ, 2020) as per the following list.

**Targets for 2035**

- to reduce total kilometres travelled by 20 %;
- to increase zero emission light vehicles to 30 % of the fleet;
- reduce emissions from freight transport by 35 %;
- reduce the emissions intensity of transport fuel, for example, by using some sustainable biofuels

**EV policies from 2016**

- To implement an information / promotion campaign focused on businesses and households
- To encourage business and public procurement
- To implement a contestable fund for project developments
- To implement a target of the fleet being EVs by end of 2021
- To improve the regulatory framework for charger deployment
- To extend the exemption from the road-user charge for EVs to the end of 2021
- To revise the tax rules to ensure equity for EVs
- To enable access to bus and High Occupancy Vehicle lanes
- To form a leadership group with industry and government

Further to the above actions the NZ government enacted the Clean Vehicle Act in 2022 to provide a Clean Car Discount. This discount was a bonus / malus scheme to reduce registration costs for low emission vehicles and increase registration costs for higher emission vehicles so that polluters paid more, however, following a change of government this law was repealed at 31 December 2023 and the rebate is no longer available (NZ Transport Agency, 2024). Also, the Clean Car Standard was introduced in 2023 to effect a vehicle fuel emissions standard that would be tightened over time with fines for non-compliance for vehicle importers (NZ Government, no date. Clean Car Standard Explainer [WWW Document]. URL https://www.beehive.govt.nz/sites/default/files/2021-01/Clean%20Car%20Import%20Standard%20Explainer_0.pdf (accessed 02.02.2024).).

Fig. 1 shows that since 2016, when the policies were introduced, New Zealand's rate of EV uptake has grown significantly, although during the pandemic lockdowns in 2020 the market was flat, then growth in 2021 surged.

The contrast between the resulting rates of EV sales in Australia and NZ from 2011 to 2021 (Fig. 1) is striking. The much more rapid rate of uptake in NZ compared to Australia could be explained by the positive impact of government policies on consumer behaviour. In 2022, in NZ BEV uptake has grown since the introduction of additional policies that make EV purchase cheaper (Minister for Transport NZ, 2022). In NZ one action of particular importance was enabling the widespread importation of second-hand EVs from other right-hand drive markets, notably Japan and the UK, which are much better value vehicles (Hasan et al., 2021). The NZ Ministry of Transport has previously noted that supply of these vehicles could become limited in the future if Japan's EV uptake and production remained low (Ministry of Transport NZ, 2021). Although Australia belatedly allowed such grey imports, the rules have been quite restrictive and relatively few second-hand EVs have been imported (My Electric Car, 2024).

The following Section 3 synthesises the findings from our investigations into New Zealand's efforts to facilitate a transition to electromobility and presents the lessons learned.

## 3. Lessons from New Zealand

To gain constructive insights into consumer thinking that, if addressed by government policy, could encourage EV uptake in early 2020 we conducted a survey, by questionnaire and interviews, of motorists of both fossil-fuelled and electric passenger vehicles, using a large panel of New Zealanders (n = 893) who planned on buying a car at some time in the future, with regional, gender and age quotas. Results of this consumer-demand focused survey (Broadbent et al., 2021) indicate lack of awareness about EV policies among the cohort of survey respondents who were ICEV motorists. These motorists tended to perceive EVs as expensive with inconvenient charging characteristics and they were worried about the longevity and cost of replacing the battery. By contrast, the EV owners surveyed had a much greater knowledge of policies, regarded EVs as economical and fun, and were not as concerned about the availability of public chargers. Our research also evidenced that the most popular incentives were those designed to reduce the cost of buying an EV relative to ICEVs and to increase nation-wide deployment of publicly accessible chargers.

Consistent with our NZ research, and our earlier Australian research (Broadbent et al., 2019) Liao et al., (2017) found that financial and vehicle attributes have significant impacts on people's understanding of EVs. Indeed, other research suggests that people struggle to consider factors other than vehicle cost and range, and that such neoliberal consumerism will influence their perspectives of cars as consumer products, thus people may find it difficult to heed communications about the emissions reduction potential of EVs (Esmene et al., 2020). Such results suggest that policies that effect cheaper EV purchase prices and facilitate vehicle charging, within the constraints of available vehicle range (dictated by each vehicle's battery), ought to be the focus of government attention. Also popular with our NZ survey participants was the anticipated incentive of cheaper EV purchase prices with the introduction of the Clean Vehicle Act by the NZ government (see above list), which would also effect mandatory vehicle fuel emissions standards. Mandatory emissions standards have been found to be important mechanisms in the electromobility transition, and only strong incentives could achieve large sales shares of EVs in the vehicle market in Norway and The Netherlands (Deuten et al., 2020).

Our survey also demonstrated a need to improve communication strategies, including by using the print media to enhance EV sales (Broadbent et al., 2021b). That fewer motorists read the print media's motoring sections to research about cars than did consult them, indicates that messaging could benefit from increasing coverage in the general sections of the papers, rather than the motoring sections. Such exposure could increase informational and social conformity assisting in the normalisation of EVs (Cherchi, 2017; Axsen and Kurani, 2012). Developing a social marketing campaign would be advantageous as it would consider factors that could increase EV appeal for the niche of motorists next-most-ready to purchase. However, research indicates that the media can be biased against EVs, such as the finding that conservative media outlets continue to mislead motorists about electric cars, trying to portray then as environmentally harmful and as unsafe, which are false claims (Fong and Theel, 2012). Such false representations continue until the present day e.g., (MediaMatters, 2022). It is possible that such communications influence consumers' values and attitudes, and hence purchase intentions (Liao et al., 2020), although we did not find that the case in NZ (Broadbent et al., 2021b) where the media are considered to be relatively unbiased (Media Bias Fact Check, 2022), although that may be starting to change (Crawford, 2021).

As discussed in our previous research (Broadbent et al., 2021b) additional broadening of communication channels can be achieved via procurement policies, as implemented by the New Zealand government, as it increases the opportunity for employees of government and businesses to increase motorists' first-hand experience in driving EVs, without having to buy, thus providing avenues to inform more of the population about EVs, which are characteristic means to diffuse an innovation (Rogers, 2003). Moreover, such procurement would provide opportunities for increasing publicity about EVs in the general news pages, rather than in the motoring sections of newspapers to disseminate knowledge helping normalise the technology in the community. In addition, by guaranteeing bulk purchase of EVs, governments and large businesses can help increase the availability of more models that can satisfy more market niches and expanding EVs' appeal (Broadbent et al., 2021a).

In the current geopolitical climate, there is a supply shortage of EVs generally relating to supply chain issues, such as the doubling of the cost of steel, rising costs of battery components and chip shortages, as EVs require double the number compared to conventional cars (IEA, 2022d), which may hamper the fulfilment of orders for EVs. New Zealand has a long history of allowing the importation of second-hand cars from other right hand drive markets and the ability to bring in second-hand EVs has proven more popular among EV owners than buying more expensive new EVs (Ministry of Transport NZ, 2022b), providing opportunities for the main stream market to go electric in addition to early adopters. While the NZ government has introduced measures for mandatory vehicle fuel emissions standards there may be difficulties in obtaining sufficient vehicles, especially second-hand EVs from Japan and the UK.

The results of our New Zealand research, and other international research provide a basis to inform the development of scenarios for fulfilling Australia's aspirations to increase EV uptake and for the concepts used in the modelling of potential policy options for Australia. Our results align with those of many other countries, indicating that in addition to undertaking measures to achieve price parity of EVs with ICEVs and more consumer awareness programs, continuing to deploy publicly accessible chargers should be a priority to attract more customers to EVs.

## 4. Testing policies for Australia

Mindful of the findings from our New Zealand research and other international research as already described, we undertook two scenario modelling exercises, as described in Broadbent et al., 2022a and Broadbent et al., 2022b. Our aim was twofold: to ascertain if it is possible for Australia's road transport sector to reach net-zero emissions by 2050 and what level of policy ambition would be required; and what combination of Australian price and infrastructure support policies could best achieve net-zero emissions for road transport by 2050, and at what cost.

Our first scenario modelling used an integrated assessment model (iSDG-Australia, Allen et al., 2019) in the system dynamics modelling language (Broadbent et al., 2022a). Here we modelled five different scenarios by applying various levels of ambition to simulate the scale and pace of change required and compared it to business-as-usual (BAU) to determine if net-zero emissions could be achieved for road transport by 2050, and the role of BEVs in achieving such an outcome. Our results, see Fig. 2 in Broadbent et al., 2022a, showed that under BAU the share of BEVs would be 27.8 % by 2050, including all vehicle types in the Australian road fleet. Of the scenarios tested only the highly ambitious High-Stretch scenario, which includes the forced phase-out of remaining ICEVs from 2045, projects a 100 % BEV fleet by 2050. Without the forced phase-out of remaining fossil-fuelled vehicles, by scrapping them or by converting them to electric drivetrains to reduce the loss of embodied energy, it would not be possible to reach net-zero emissions by 2050. This can be explained by the long life of vehicles, with passenger vehicles lasting about 20 years, while heavy rigid trucks can still be on the road after 30 years, suggesting those ICEVs purchased new after 2030 for passenger cars and 2020 for heavy rigid trucks that remain in the fleet could still be producing GHG emissions in 2050.

In addition to these residual fossil-fuelled vehicles, the sensitivity analysis done to test the robustness of the modelling showed that the ability to reach net-zero was subject to the proportion of renewable electricity available to charge vehicles, see Fig. 5 in Broadbent et al., 2022a. Only when 100 % renewable electricity is used to generate electricity could net-zero emissions be achieved by 2050. While this is logical it does demonstrate the usefulness of the model used.

The second round of modelling used the conditions for the most ambitious scenario and BAU, and we employed an additional transport module to test the effect of different combinations of policies that made vehicles cheaper to buy and to support the ongoing deployment of charging infrastructure (Broadbent et al., 2022b) and to project possible quantities of emissions reductions (see Fig. 4 in Broadbent et al., 2022b) that could be achieved, and at what cost to government (see Fig. 6, 7a and 7b in Broadbent et al., 2022b).

We applied eight potential combinations of policies (including BAU) that are practical and feasible to project possible quantities of emissions reductions that could be achieved, and at what cost to government. These policies focused on reducing the price of EVs by various changes in taxation and rebates, specifically exemptions from stamp duty (ownership transfer tax), vehicle goods and services tax and a purchase rebate. The modelling also accounted for loss of revenue from fuel excise and money expended on infrastructure, and for providing support for the ongoing increasing deployment of charging infrastructure around the country (Level 3 chargers) and at the local level (Level 2 chargers), particularly in areas where there is limited access to off-street parking by residents. There is varying support for infrastructure installation by many state and local governments and what is required is federal government support to ensure ongoing deployment as the EV fleet grows. The trajectory for emissions declined most steeply for the pathway that provided the best purchase support, in effect speeding up the point at which price-parity occurred, and which also provided the best support for infrastructure. While emissions from all pathways declined by 2050, the BAU pathways continued to grow until 2032, and failed to reduce emissions below 2001 levels, showing that small increases in EV uptake were overwhelmed by increases in emissions from growth in the total fleet accompanying higher total population growth and concomitant increases in the fossil-fuelled fleet. The total avoided emissions of the best pathway compared to BAU was 623 738 kilotons. The total cost to government grew to AUD312 per person per year in 2034 and declining thereafter. By comparison in 2020–21 a rebate of AUD7.8b subsidised the purchase of petroleum products in Australia (Campbell et al., 2021), approximated AUD309 per person in 2020, which is high by international standards (Coady et al., 2019). The IEA has recommended the phase out of such subsidies (IEA, 2020b).

The declining government revenue from fuel taxes could be offset by changing how polluting vehicles are charged, for example the tool employed in New Zealand, that is a "cost-free" policy of a bonus-malus scheme for first registration and consideration of the declining health costs associated with transport related pollution. An important effect was noticed in Pathway 2 where support for EV purchase was suddenly stopped at 2030, the results show EVs sales suddenly declined, and took 10 years to recover to sales levels that might be achieved if the support is gradually reduced. A similar effect occurred in Denmark when the government changed policies engendering immediate plummeting EV sales (European Commission, 2020b). The IEA (2022c) have commented that governments should not abruptly change incentive and subsidy structures but gradually transition to more targeted and financially sustainable tools.

In addition to the modelling, sensitivity analyses were performed to test the robustness of the main parameters that had high levels of uncertainty: population (as a key driver of vehicle demand), government subsidies for passenger BEVs, costs for charging stations, desired target levels for charging stations, base price for passenger BEVs, government share of charging infrastructure investment, and the maximum saturation effect of insufficient public charging infrastructure investment. Each of the parameters were shown to be robust, although the actual base price of vehicles, and when price-parity of BEVs to fossil-fuelled vehicles is achieved, had the greatest impact on the share of BEVs by 2050, emphasising that the sooner the vehicles become affordable to the mainstream market the more quickly they will be adopted. This effect suggests that government policies will need to be designed carefully to ensure suitable vehicle models are affordable to mainstream consumers.

Importantly, the results also show that unless the charger deployment targets of one destination charger (Level 2) per 10 BEVs and one fast charger (Level 3) per 100 BEVs (see Alternative Fuels Infrastructure Directive in IEA, 2020a) are maintained to keep pace with the growing fleet then achieving net-zero by 2050 could not be achieved. This can be explained by consideration of motorists who are unable or unwilling to adopt EVs due to charging inconveniences, such as a lack of handy public chargers that can be accessed close to home for those without off-street parking, which has been demonstrated to engender abandonment of the technology by potential second-time EV purchasers (Hardman and Tal, 2021). It would also take into account that some motorists may be unwilling to queue to charge on long distance trips and could avoid EVs for that reason, such an effect has been noted by Figenbaum (2018).

Furthermore, unless 100 % of new car sales are BEVs by 2030 then it will not be possible to reach net-zero emissions for cars by 2050. This outcome is to be expected because of the long life of vehicles (about 20 years), that is, some new fossil-fuelled cars purchased after 2030 will still be in the fleet at 2050, continuing to emit the same GHG emissions for every kilometre travelled over their entire life unless they are retired early, converted to an electric drivetrain or offsets purchased, which may become increasingly expensive. By contrast, as the electricity supply increases its level of renewables then the emissions from EVs decreases for every kilometre travelled (Broadbent, 2018). Our results show that even under the best combination of policy support to ensure affordable vehicles and adequate government support to supplement private investment in infrastructure, net-zero emissions are not possible by 2050. This result is because of residual fossil-fuelled cars in the fleet and the late commencement of the transition of heavier vehicles to electric because of delays in availability of suitable vehicle options.

## 5. Policy pathways for action in Australia

The following points summarise options for actions that Australia could undertake if the aim is to achieve the goal of net-zero emissions from road transport by 2050. Policies are needed to drive change to overcome the status quo, especially measures that will attract consumers, such as policies to make vehicle purchase cheaper and to ensure an adequate supply of fully functioning public charging stations that are distributed where people need them. Importantly, no one measure can achieve the goal and it is by implementing the range of measures, with ongoing monitoring to ensure the measures continue to work well, that the goal of reaching net-zero for road transport emissions, especially for passenger cars could be met:

1. *Set targets to ensure all tiers of government work together.* The level of ambition to ensure transport achieves net-zero emissions by 2050 ought to be high. Our modelling demonstrates that unless the target for a very high ambition is set, aiming to ban new sales of fossil-fuelled passenger cars by 2030 and including early retirement of polluting vehicles from 2045 as a forced phase-out, then it will not be possible to achieve the goal. One example is to ensure all tiers of government have procurement targets (Section 3), this will increase the speed of exposure to EVs by government employees, assisting with diffusion of innovation helping normalise the technology in the community, and increase the speed of turnover to create a sizable second-hand EV market, which will be important for many mainstream consumers unable to afford a new car.
2. *Enact appropriate legislation, regulations and ensure policy coherence.* It is recommended that legislation and regulations support the planned targets and goals. Implement a mandatory "Clean Car Standard" i.e., vehicle fuel emission standard (Section 3) that over time reduces the allowable $CO_2$ emissions per kilometre of travel per vehicle, based on an average for all vehicles sold by any particular brand. This measure would mean that manufacturers would need to sell higher volumes of low emissions vehicles, especially EVs, with fines applying for non-compliance. There should be consistency between the federal and state/territory governments.
3. *Overhaul the tax system* to ensure low emission vehicles are not penalised and that polluting vehicles pay for the harm they cause (Section 2). One means to achieve this could include a bonus / malus scheme for first time registration of vehicles where polluting vehicle fees are charge more and there is a sliding scale of the fee based on the emissions per kilometre for the vehicle (Section 3).
4. *Implement measures to ensure BEVs are attractively priced compared to similar ICEVs.* This can be achieved by a number of measures such as removing the goods and services tax (GST), import taxes, and stamp duty (ownership transfer tax) and providing purchase rebates dependent on emissions reductions (Section 4). The earlier that price parity with ICEVs can be reached the earlier the tipping point for sales and greater possible emissions reductions.
5. *Deploy adequate charger infrastructure that continues to grow as the BEV fleet grows.* To overcome a significant impediment to EV uptake, our modelling shows that to cater for vehicle range, inability for some to charge locally on a day-to-day basis and anxiety about potential queues at charging stations, unless charger installation keeps pace with one destination charger per 10 vehicles and one fast charger per 100 vehicles then it will not be possible to achieve the net-zero goal (Section 4).
6. *Implement measures to ensure BEV supply and infrastructure can meet demand* (Sections 2,3,4), for example by enacting mandatory vehicle fuel emissions standards, which encourages importers to bring in more EVs to avoid any fines it helps ensure customer demand for vehicles can be met; and setting targets for infrastructure deployment to keep pace with EV uptake.
7. *Implement measures that promote the availability of additional vehicle models and that quickly grow the second-hand market* (Sections 3 and 4) to attract mainstream consumers e.g., by enacting appropriate emission standards and ensuring governments procure BEVs in preference to ICEVs, which guarantees business for EV importers as well as post-sales operations.
8. *Implement communications and social marketing strategies to promote electromobility* as lack of up-to-date knowledge about an innovation is a major impediment to the uptake of the technology (Section 3).

Government involvement in the transition to electromobility is essential and adoption of the above recommendations will help ensure the response is comprehensive. The time for debate on the necessity of decarbonisation is over, and all necessary measures will need to be taken to ensure the transition rate accelerates if the goal of net-zero emissions from the road transport sector is to be met by 2050. The interface between science and policy needs to continue to address the knowledge gaps that are beyond the scope of this paper. To build on the recommendations of this paper, future research could focus on determining specific and measurable targets for each of the policies mentioned. Additionally, it would be beneficial to explore the potential impact of the transition to electric vehicles (EVs) on employment in the car industry.

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## CRediT authorship contribution statement

**Gail Helen Broadbent:** Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Writing – original draft, Writing – review & editing. **Graciela Metternicht:** Supervision, Writing – review & editing. **Thomas Wiedmann:** Supervision, Writing – review & editing, Funding acquisition. **Cameron Allen:** Data curation, Formal analysis, Methodology, Resources, Software, Validation, Writing –

original draft, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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