Achieving a Timely, Efficient, Equitable and Orderly Transition to Net-Zero Emissions for Transport and Heating in New Zealand: Part 1 – Framing the Challenge

Discussion Paper for

Vector Limited, Powerco Limited, and First Gas Limited

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Richard holds a PhD in Industrial Organisation and Regulation from Toulouse School of Economics. His research includes analysis of competition and regulation issues in imperfectly competitive sectors such as electricity sectors, including how different forms of ownership (e.g. vertical integration, customer ownership) affect strategies, incentives and behaviours.

Richard has taught industrial organisation, environmental economics, and corporate finance, at various universities. He has also been a peer reviewer for the International Journal of Industrial Organization, Journal of Institutional and Theoretical Economics, Economic Modelling, New Zealand Economic Papers, and New Zealand Treasury Working Papers.

His research outputs include books, book chapters for edited volumes, peer-reviewed journal articles, academic working papers, and commissioned studies. He regularly presents his research to academic and practitioner/policy audiences.

Of particular relevance to this study, Richard has contributed to electricity sector research, advice, analysis and transactions for over 30 years. Richard was also a co-author of MBIE's 2017 study into the reasonableness of fuel pricing in New Zealand, and has researched the welfare impacts of coordinated infrastructure investments in transport. He has undertaken major futures-focused studies of optimal regulation in transport and electricity sectors, given the advent of disruptive new technologies, business models and players in those sectors.

Richard's most recent research includes analysing the uptake of distributed energy resources and the contributions of different organisational types in supporting that uptake, as well as policies and factors affecting the uptake of low-emissions vehicles. He has also undertaken a number of studies assessing the socio-economic impacts (especially for Māori) of emissions pricing, and transitioning to a low-emissions economy.

A full list of Richard's publications can be found at: https://www.cognitus.co.nz/publications.

Abbreviations

5G	Fifth generation mobile network technology standard
BEV	Battery electric vehicle – see also EV
BOOT	Build, own, operate, transfer scheme
CCS	Carbon capture and storage
CNG	Compressed natural gas
CO_2	Carbon dioxide
DNE	Direct network effect
EV	Electric vehicle – see also BEV
eVTOLV	Electric vertical take-off and landing vehicle – i.e. electric flying vehicle
FCEV	(Hydrogen) fuel cell electric vehicle – see also H_2V
GHG	Greenhouse gas
H_2HV	Hydrogen hybrid (electric) vehicle
H_2ICEV	Hydrogen internal combustion engine vehicle – see also H_2V
H_2V	Hydrogen vehicle – e.g. FCEV, H_2ICEV, etc
HV	Hybrid vehicle – e.g. fossil fuel and electric, or hydrogen and electric, etc
ICEHV	Internal combustion engine hybrid (electric) vehicle
ICEV	Internal combustion engine vehicle using fossil fuels (petrol, diesel, LPG, CNG)
INE	Indirect network effect
LPG	Liquid petroleum gas
P2P	Peer-to-peer
PHEV	Plug-in hybrid electric vehicle
PV	(Solar) photovoltaic
UFB	(Fibre-based) ultra-fast broadband
V2G	Vehicle-to-grid

Executive Summary

New Zealand shares the global challenge of achieving net-zero greenhouse gas emissions by 2050, in order to limit the risk of potentially devastating climate change. The country's electricity sector is already predominantly based on renewable resources, and the agricultural sector's emissions are difficult to abate other than through reduced production, given current technologies. This means emissions reductions in transport (land, sea and air), space/water heating and cooking, and in process heat, are priority areas for the country.

Transitioning from fossil-fuel based technologies in transport, heating/cooking and process heat to low-emissions alternatives is not a simple matter. Where people have chosen to live, work and play strongly affects decisions they have made about the heating and transport technologies they use. Likewise, industries often locate where suitable energy supplies are located and tailored their processes to those energies. This naturally creates inertia in transitioning to alternative, low-emissions technologies.

That inertia is only harder to overcome if low-emissions technologies are not clearly superior – i.e. either significantly cheaper, or substantially better in other dimensions, than existing options. And even if low-emissions alternatives were comparable or even superior to existing technologies, there is no guarantee that those benefits can be realised without a high degree coordination between the 1.7 million households,[1] thousands of small businesses, and perhaps hundreds of larger industrial concerns in New Zealand.

Such coordination is critical to unlocking the benefits of low-emissions technologies, and to induce these many decision-makers to relinquish their existing technologies. This is because the existing fossil fuels ecosystem powering transport, many forms of heating/cooking, and process heat – like clean energy ecosystems that might constitute an alternative – are essentially "platforms". For example, the fossil fuel supply chain can be thought of as an energy platform.

On one side of the platform are hardware (e.g. vehicle, appliance and equipment) suppliers and others supporting the use of that hardware. On the other are buyers of that hardware, which they combine with energy to provide the transport, heating and other services they rely on. The scale economies and network effects associated with platforms mean that benefits of migrating from one energy ecosystem to another cannot be fully realised unless a sufficiently large number of other users (suppliers and consumers) also make that migration.

[1] Based on 2018 Census data, available at www.stats.govt.nz.

Such platforms commonly feature significant economies of scale, and network effects. Economies of scale refer to things like the ability to supply energy at lower unit cost when energy supply infrastructures are operated at scale. Network effects refer to the benefits or costs enjoyed by or created for platform users by the decisions of other platform users, whether those users are on the same side (direct network effects), or on different sides (indirect network effects).

Even with just one clean-energy platform to rival the current fossil fuels platform, convincing literally millions of individual decision-makers to transition from one to the other is a fraught undertaking. For most, the status quo provides a high level of service at an affordable price, whereas the alternative is currently unaffordable, and currently promises lower service levels. Consumers will naturally hesitate to migrate, making it less viable for hardware suppliers to also migrate, and therefore for low-emissions energy platform providers to find it profitable to make the substantial and risky platform investments needed to support the transition.

The challenge of migrating to a low-emissions platform is considerably more difficult if there are competing low-emissions alternatives. The problem of coordinating on any given alternative is then so pronounced that any migration to low-emissions technologies can be delayed or deterred, to the benefit of the status quo, fossil fuel energy platform.

Transitioning to low-emissions technologies in private road transport is a case in point – battery electric vehicle technologies are currently the leading alternative to fossil fuel vehicles. But hydrogen-based technologies are developing hot on that technology's heels, and offer potentially much wider energy ecosystem benefits (e.g. being suitable for a wider range of transport applications, but also for many non-transport applications). These offer exciting possibilities, but also create significant strategic uncertainties for vehicle suppliers and consumers, and hence for providers of the low-emissions fuel supply chains needed to support either technology. These strategic uncertainties could materially delay the net-zero transition.

The history of major technology transitions in transport (roads to canals, canals to rail, and horse-drawn vehicles to motor cars) holds many key lessons for the current transition. The first is that transitions are highly path-dependent – where you get to is strongly influenced by where you start. The second is that major transitions occurred when the new technologies offered compelling benefits (such as reduced travel times and costs, increased travel speeds and reliability, and the freedom to travel when and where you want). This was particularly the case when new transport technologies (like bicycles, and automobiles after Ford revolutionised car-making with mass production and standardisation) were affordable to the mass-market.

The third major lesson is that there is a “chicken and egg” problem plaguing most major technology transitions. Users of new technologies are reluctant to adopt them until the required infrastructures are in place. But infrastructure providers can be reluctant to invest without knowing users will migrate to their technology. Large vested interests – often industrialists that benefited directly from new infrastructures, and had the resources and capabilities to build them – have historically been pivotal in leading the development of those infrastructures. Having taken the first step, they paved the way for other users to benefit by adopting their technology platforms, creating additional platform uses and value streams.

History, as well as substantial research, points to other complications in transitioning to new technologies. This is because competition between new platform technologies that feature significant network effects is no guarantor of socially-desirable outcomes. It is common for platform competition to result in dominance by one – or only few – technologies (though typically to the benefit of users, since scale economies and any beneficial network effects are then maximised).

However, experience as well as research points to platform competition often resulting in inferior technologies remaining dominant – “locked in” – for longer than they should, even when superior platforms emerge. Currently dominant platforms enjoy a strong incumbency advantage that makes then hard to dislodge. New platforms face the substantial challenge of convincing enough users and suppliers of the existing platform to migrate to theirs. Simply being better does not guarantee that they will win. Being inferior to the existing platform makes winning even harder.

Also, simply dismantling an existing energy platform does not guarantee that a new, low-emissions one will grow to take its place. Even if a low-emissions platform emerges, there is no guarantee that it will maintain overall service levels (e.g. of transport, heating/cooking, and process heating services). Synchronising any transition will require careful management.

New Zealand faces significant policy challenges and questions in transitioning to low-emissions technologies in transport, heating/cooking and process heat – especially if the transition is to be timely, efficient, equitable, and orderly. Strategic decisions need to be made regarding whether it is best to simply let competing technology platforms vie for ascendancy, or to commit to a certain technology path.

The former risks delaying the required transition, without necessarily ensuring that ultimately dominant technologies are not disrupted by others (or by themselves, where they spur the development of superior technologies). The latter risks “picking the wrong horse”, but gets New Zealand in the race to net-zero much faster (and possibly with wider benefits).

Table ES.1 – Policy Levers that might be used to Accelerate the Transition to Net-Zero Emissions

<table>
<tr><th></th><th>“Push” levers (Discouraging emissions)</th><th>“Pull” levers (Encouraging low-emissions)</th><th>General levers</th></tr>
<tr><td>Demand-side levers (interact with supply-side due to indirect network effects)</td><td>Price measures:
• Emissions pricing (reflecting network effects as well as environmental costs)
• Levies on emitting hardware</td><td>Price measures:
• Clean fuel subsidies
• Clean hardware subsidies
• Parking or toll road subsidies for clean transport users</td><td rowspan="4">• Creating coordination focal points for hardware suppliers, consumers/users, and infrastructure providers
• Increasing commitment power of long-term policies (e.g. independent policy-making and implementation)
• Wider regulatory/ policy coordination – urban design, transport, energy, etc
• Safe harbours from competition law prohibitions on desirable industry coordination
• Regulatory forbearance for whole-of-life infrastructure pricing – e.g. sub-cost initial pricing to accelerate uptake, followed by higher later pricing to achieve required lifetime fair returns)</td></tr>
<tr><td></td><td>Non-price measures:
• Sunset clauses (hard, soft)
• Technology targets/ mandates</td><td>Non-price measures:
• Sunset clauses (hard, soft)
• Technology targets/ mandates
• Certification/consumer information
• Hardware leasing, or guaranteed buy-backs/trade-ins
• Solutions for new technology end of life (e.g. battery recycling)</td></tr>
<tr><td>Supply-side levers (interact with demand-side due to indirect network effects)</td><td>Price measures:
• Emissions pricing
• Levies on emitting hardware</td><td>Price measures:
• Subsidies or co-investments for new infrastructure</td></tr>
<tr><td></td><td>Non-price measures:
• Sunset clauses (hard, soft)
• Technology targets/ mandates
• Progressive bans on emitting uses of fossil fuels, or on fossil fuel exploration
• Coordination/cooperation measures</td><td>Non-price measures:
• Targets/mandates for minimum clean infrastructure capacity and service levels
• Franchise bidding for monopoly rights to develop clean infrastructure(s)</td></tr>
</table>

New Zealand faces particular challenges in unleashing the power of vested interests to resolve the "chicken and egg" problems likely to delay the development and uptake of low-emissions energy platforms. The country lacks the large industrial bases of many other countries, including any significant car manufacturing capacity. It has few large organisations in general with the capacity to undertake major infrastructure investments alone, let alone with the technical capabilities to do so.

The country's existing major energy companies are strong contenders to take the necessary lead, especially if their existing infrastructures can be repurposed for low-emissions fuels (though other contenders cannot be ruled out, and might play complementary pivotal roles). Harnessing the incentives of suitable large vested interests, or changing their payoffs to ensure they find supporting the transition more beneficial (or less disadvantageous) than maintaining the status quo, are likely to be key in accelerating the net-zero transition.

Many policy levers exist to influence competition between low-emissions technologies, and the transition to those technologies from fossil fuels, as summarised in Table ES.1. These include measures that make spearheading the transition to net-zero more attractive to incumbent energy providers than maintaining the status quo. It also includes measures that best make use of incumbents' existing infrastructures and capabilities where that is more expedient than creating new competing infrastructures. The many available policy levers need to be carefully deployed to ensure New Zealand's net-zero transit is timely, efficient, equitable and orderly.

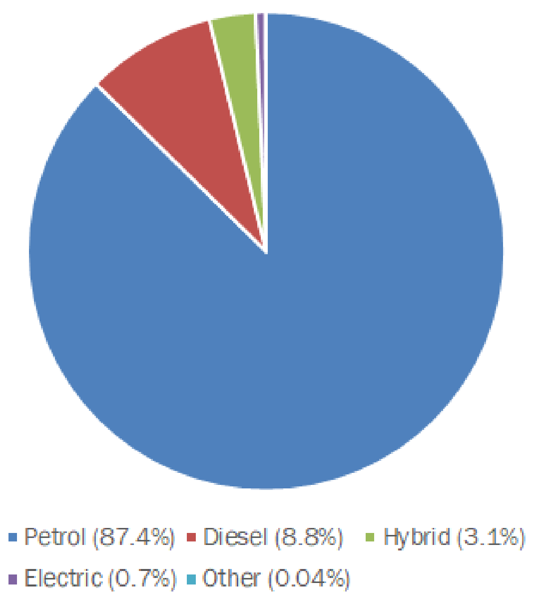
1. Introduction

1.1 Context

1. New Zealand, like many other advanced countries, has committed itself to achieving net-zero greenhouse gas (GHG) emissions by 2050 in order to help combat climate change. This will require major changes to things we currently take for granted, like how we travel and heat ourselves, and how we make things in processes requiring large amounts of energy. Such changes are challenging in and of themselves. They are especially challenging if we wish to achieve them in a timely (i.e. urgent), efficient, equitable and orderly way.

2. The enormity of the challenge should not be underestimated. Transitioning the country's current fleet of 3.5 million passenger cars and vans to low-emissions technologies, by itself, will be a Herculean challenge. As shown in Figure 1.1, the vast majority of that fleet – 96% – runs exclusively on fossil fuels (i.e. petrol and diesel), while another 3% (hybrids) relies on fossil fuels to some degree. As of September 2021, less than 1% of the vehicle fleet (23,245 vehicles) runs on electricity. Only four passenger cars or vans run on hydrogen.

Figure 1.1 – Composition of New Zealand's Fleet of Passenger Cars and Vans, September 2021



Source: based on data from New Zealand Transport Agency.[2]

[2] https://www.nzta.govt.nz/resources/new-zealand-motor-vehicle-register-statistics/national-vehicle-fleet-status/.

3. However, there is cause for optimism. Technology breakthroughs mean renewable energy and low-emissions transport solutions are feasible and increasingly attractive (even if they are not yet widely affordable). Continuing breakthroughs and innovations will make these solutions both increasingly attractive and increasingly affordable, meaning they will naturally start to displace existing technologies.

4. Despite this, simultaneously transitioning consumers, producers, and network providers from existing, polluting technology platforms (i.e. those based around fossil fuels) to low-emissions platforms (i.e. those based around renewable electricity, hydrogen and biofuels/e-fuels) creates its own set of challenges . This is especially so if we wish to transition in a way that is timely, efficient and equitable, and also which avoids undesirable or unintended collapses in service availability (i.e. is orderly too).

5. Such simultaneous transitioning by multiple types of actor raises extremely challenging coordination issues. These issues are not novel – for example, at the turn of the 20th century, petrol and electric motor vehicle technologies (as well as steam road vehicles) were all vying for supremacy. However, history teaches us that technology revolutions such as the eventual dominance of internal combustion engine vehicles (ICEVs) over these competing transport technologies often take decades, and proceed in a messy way – commonly resulting in dominance by just one or only few technologies.

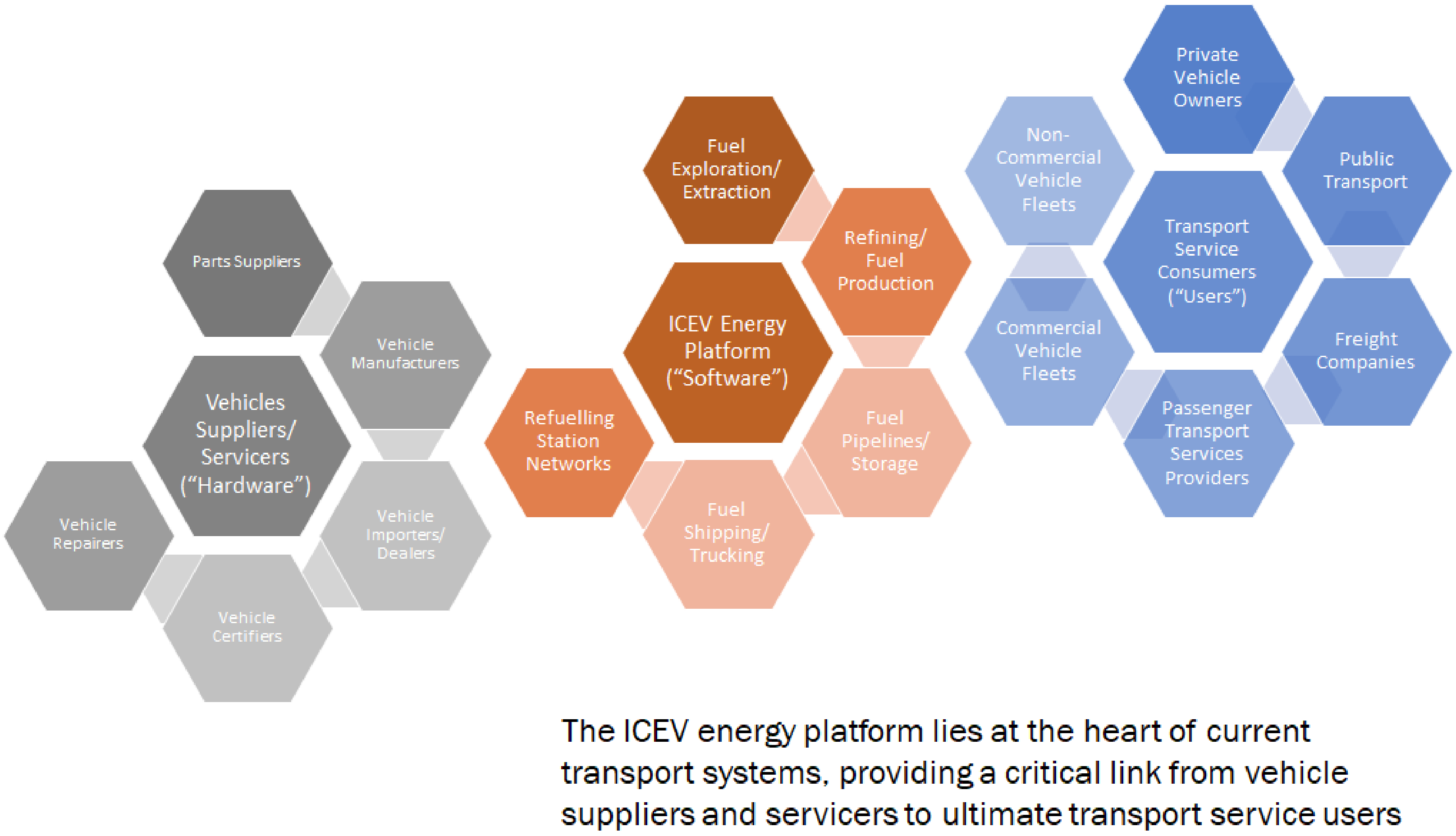
6. These messy dynamics arise because new technologies often represent “platforms” about which suppliers and consumers gravitate. Figure 1.2. represents the ICEV energy platform, comprising the fossil fuel supply chain that links vehicle suppliers and servicers to the users of transport services provided using ICEVs.

7. The benefits enjoyed by suppliers and consumers using a platform depend on the nature and number of other consumers and suppliers on that same platform, and the interactions between them – so-called “network effects”. Moreover, platforms often require physical networks – such as the fossil fuel supply chain, or supply chains for clean energies like biofuels, or hydrogen made from renewable energy sources. Such networks can also exhibit economies of scale, meaning the unit costs of network services decline when networks are large:

   7.1. Both network effects and economies of scale can incline competition between platforms – competition “for the market” – to be “winner takes all”;

   7.2. This often means dominant platforms eventually emerge at the expense of rival platforms, until they too, in turn, are eventually fully or partially displaced.

Figure 1.2 – Representing the Fossil Fuel Supply Chain as a "Platform" Linking Vehicle Suppliers and Servicers on the One Hand, with the Users of Transport Services Provided using Internal Combustion Engine Vehicles on the Other



8. Achieving a timely, efficient, equitable and orderly transition to one or more low-emissions technology platforms may therefore require key decisions to be made that either shortcut this process, or expedite it in a socially desirable way.

1.2 About this Study

9. This study provides insights from the history of major technology transitions, and scholarly research on such transitions, to highlight the key challenges and decisions they give rise to. It does so to stimulate considered and reasoned debate on the key, long-term decisions that will affect how New Zealand can achieve its net-zero goals in a timely, efficient, equitable and orderly way. Because the purpose of the study is to stimulate debate, it deliberately focuses on posing key questions, rather than reaching specific findings or conclusions about the merits or otherwise of any given technology or policy approach.

10. This study has been written by an independent economic consultant and researcher who has no stakes in existing or new energy technologies (aside from being a car owner and occasional user of public and active transport, a user of electricity and gas for domestic purposes, and one of the 346,000 families and businesses that are customer-owners of Vector, one of the parties commissioning this study).[3]

11. That said, a reader might naturally be curious about the interests of the parties that commissioned this study, specifically of:

    11.1. Vector and Powerco – each being regulated electricity distribution businesses (Vector majority-owned by its customers, Powerco owned by investors), with electricity generation and retailing interests limited by regulation, and also with interests in gas distribution networks and retailing (to commercial and residential customers); and

    11.2. First Gas – the owner and operator of gas transmission/storage and regulated distribution network assets, and with interests in gas wholesaling (to industrial customers) and retailing (to retail and commercial gas customers).

12. As such, these parties have a variety of possibly diverging interests (about which the author has no inside information). In principle, all should wish for their gas network assets and

[3] As a residential customer-owner of Vector, the author receives a dividend of about $300 per year from Entrust, the 75.1% shareholder in Vector representing customer-owners, which receives annual dividends from Vector on consumers' behalf.

wholesaling/retailing businesses to have a viable economic future as we transition away from using fossil fuels like natural gas – a leading contender would involve adapting their gas network infrastructure assets to transport hydrogen, which:

12.1. Can replace natural gas for things like electricity generation and heating (and be used in certain industrial processes, such as steel making); and

12.2. Can also be used in low-emissions transport via fuel cells in hydrogen fuel cell vehicles (FCEVs) or hydrogen internal combustion engine vehicles (H_2ICEVs; together with FCEVs, Hydrogen Vehicles, H_2Vs), but can be used to make electricity directly for non-transport purposes as well.

13. However, in principle Vector and Powerco might also wish for greater uptake of battery electric vehicles (BEVs) supplied with electricity from the New Zealand electricity system, and increasingly from distributed renewable technologies like solar photovoltaic (PV) generation:

13.1. This is because their electricity distribution networks will play a key role in integrating and facilitating such new technologies – e.g. via BEV recharging in homes and at public or commercial rechargers; and

13.2. First Gas might also see a role for itself in using hydrogen to ensure reliable clean electricity supply to BEVs – e.g. by using hydrogen to provide energy storage to buffer intermittent PV supply, or simply for electricity generation using gas turbines.

14. Hence, taken as a whole, it is not clear that the parties that commissioned this study should wish to resist the transition to a low-emissions economy (supposing they could), or for any one low-emissions technology to thrive relative to another:

14.1. This further underscores the independence of this study, and that the purpose of this study is to stimulate reasoned and considered debate on key long-term decisions affecting the transition to a low-emissions economy.

15. The author expresses his thanks to Vector, Powerco and First Gas for commissioning this study to contribute to reasoned and considered debate, despite them having possibly divergent interests in terms of the study's conclusions. Naturally this means the study's conclusions are the author's, and not necessarily those of Vector, Powerco or First Gas.

1.3 Scope of this Study

16. We are starting our transition to a low-emissions economy from an existing "ecosystem" – or "platform" – that intertwines the following inter-dependent domains:

    16.1. Where we live, work, play and get/give stuff;

    16.2. The energies and complementary technologies we use for our lives, jobs and pastimes; and

    16.3. The ways we connect – physically or otherwise – to the places where we live, work, play and get/give stuff.

17. This study focuses on just aspects of some of these domains, taking other relevant aspects as given. Specifically, it focuses on:

    17.1. How we heat spaces and water, and cook, in our homes;

    17.2. How we use heat in our jobs and businesses; and

    17.3. How we use powered vehicles – private, commercial and/or public, and in the air or on land or sea – to move ourselves and things.

18. This focus is for two reasons:

    18.1. First, New Zealand's electricity system is already largely renewables-based, and agricultural emissions account for the most of the country's GHG emissions (which are hard to abate) – so transport and heating are likely to be areas where New Zealand's greatest emissions reductions are to be made; and

    18.2. Second, the challenges in transitioning to net-zero emissions are especially pronounced in transport, and particularly so for the country's 3.5 million passenger cars and vans, making this a key area of focus.

19. As noted above, the study does not seek to determine whether any given low-emissions technology platform is to be preferred over any other. Indeed, it confines attention to only a subset of the possible clean technology platforms that might be anticipated, namely those involving:

19.1. Low-emissions technologies in transport – e.g. biofuels/e-fuels for ICEVs, BEVs, and H_2Vs (comprising technologies such as FCEVs and H_2ICEVs); and

19.2. The use of biofuels/biomass or hydrogen for cooking, space and water heating, and also in industrial processes (noting that electricity can already be used in some of such applications).

20. Much of this study is devoted to considering the challenges and questions associated with transitioning to net-zero emissions in private passenger vehicle transport:

20.1. This is not to suggest that other types of road or other transport are less relevant – in fact heavy road transport accounts for a significant share of transport-related emissions. Also, it is likely that transitioning to net-zero emissions in heavy transport and non-road transport will play a key role in assisting with the transition in other parts of the transport sector;

20.2. Rather, the study's focus on private passenger vehicle transport is because the coordination issues in transitioning to net-zero emissions are likely to be most pronounced in this area, so focusing on it showcases the key challenges and questions.

21. Relevant existing and potential technologies are taken as given. Instead, this study focuses on the strategic commercial, household, policy and regulatory decisions confronting firms, households and governments in the transition to net-zero emissions in these specific areas. Particular insights are drawn from scholarly economics literatures on:

21.1. How firms and households make decisions, and coordinate with the decisions taken by others;

21.2. How new technologies diffuse and are adopted; and

21.3. How the competitive process can be fundamentally affected by issues relevant to the net-zero transition, including economies of scale and network effects.

22. Insights are also drawn from major technology transitions that have occurred in the past, especially in transport systems (i.e. carts to canals, canals to rail, horses to automobiles).

1.4 Main Findings in Brief

23. The main findings of this study are:

23.1. Transitioning to net-zero emissions in transport, heating/cooking and process heat is best thought of as migrating a great number and variety of decision-makers from one energy technology platform (fossil fuels) to one or more low-emissions energy technology platforms (e.g. battery electric vehicles or hydrogen vehicles for transport):

23.1.1. This is because energy supply chains match and sustain hardware suppliers and servicers (of vehicles, heating/cooking appliances, and process heat technologies) on the one hand, and buyers and users of such hardware on the other (i.e. vehicle and appliance owners, and process heat users);

23.1.2. Moreover, there are substantial scale economies and network effects arising between users on any one side of energy platforms (i.e. between vehicle/appliance suppliers and servicers, or between vehicle/appliance users), meaning the benefits enjoyed by any one user of the platform is intrinsically related to how many other users there are on the platform.

23.2. Transitioning from the existing fossil fuel energy platform to a clean energy platform therefore raises incredibly challenging coordination issues. They arise between 1.7 million households, thousands of businesses, and perhaps hundreds of large industrial concerns, who each need to be convinced that sufficient other users will also migrate from the existing platform to a cleaner alternative, thereby unlocking the full benefits of such a migration (and avoiding individual "energy migrants" finding themselves isolated and stranded having made investments on a losing platform):

23.2.1. Those coordination issues are only significantly more pronounced if users face a choice between rival clean energy platforms rather than just one – so much so that this might delay or deter any migration at all (i.e. favour users remaining on the fossil fuel platform);

23.2.2. The migration is further deterred if clean energy alternatives are not clearly superior to existing fossil fuel technologies – even if they were superior, both history and research indicates that inferior incumbent technologies could still become locked in due to the difficulties in overcoming the problems of coordinating a migration to one or more alternative technologies;

23.3. However, the history of major technology transitions provides important lessons about how to kick start transitions to new technologies. In particular, large vested interests (e.g. large industrial concerns) who enjoy significant private benefits from investing in new technology infrastructures – and have the wherewithal to develop them – often spearhead the uptake of those technologies:

23.3.1. Once they do, this provides a credible signal that their chosen technology has a viable future, and that other users migrating to that technology can have good reason to expect that they will realise the benefits of making specific investments (e.g. in hardware like vehicles and appliances) tied to those new technologies;

23.3.2. This serves to resolve a critical "chicken and egg" problem commonly plaguing the adoption of new technologies – users hesitate to migrate until the technology platform is in place, but technology platform investors hesitate to invest unless sufficient users are in place;

23.4. There are many policy levers that can be used to engineer an orderly migration from fossil fuels to low-emissions energy platforms – once key strategic questions are resolved about whether to simply let rival low-emissions technologies vie for ascendancy, or to accelerate the transition by committing to a particular low-emissions platform. Using those levers to harness the incentives of large vested interests to spearhead the transition will be critical to success.

1.5 Structure of this Study

24. The balance of this study is structured as follows. Section 2 provides further context. It then explains how the transition to net-zero emissions is best framed as competition – or perhaps in some cases cooperation – between an existing energy "platform" or "ecosystem" on the one hand (i.e. fossil fuels), and one or more alternative, low-emissions (e.g. renewables-based electric or hydrogen) energy platforms/ecosystems on the other.

25. Section 3 highlights key lessons from major historical transport technology transitions that can inform the transition to net-zero emissions. These include the importance of path-dependency – i.e. how irreversible past choices affect current choices. They also include

lessons for how to resolve critical “chicken and egg” problems that arise when the uptake of new technologies by some parties hinge on decisions made by other parties (e.g. the decision to buy a BEV being affected by other parties’ investments in recharging infrastructure, or in suitable vehicles).

26. Section 4 sets out the key features of major technology transitions more generally, and the issues attaching to transitions involving network effects more specifically. It then focuses on some of the possible pitfalls and challenges presented by competition between energy platforms that feature network effects, and provides some illustrations highlighting key policy considerations in achieving a timely, efficient and equitable transition to net-zero.

27. Section 5 draws together the insights from Sections 2 through 4 for achieving a timely, efficient, equitable and orderly transition to low-emissions transport, household space/water heating and cooking, and process heat in New Zealand. It highlights the preconditions and path-dependencies constraining or facilitating the country’s net-zero transition. These include the legacy energy infrastructures that the country has to work with – or against – in the net-zero transition. It highlights the key policy challenges and questions the country faces in achieving its clean energy transition.

28. Section 6 discusses which policy levers are – or are not – available to New Zealand in achieving a timely, efficient and equitable – and orderly – transition to net-zero emissions. The suite of available levers reflects opportunities or constraints created by past choices and investments (i.e. path-dependencies), as well as choices being made by parties New Zealand is critically reliant upon (e.g. vehicle manufacturers). Both “push” and “pull” measures are discussed (i.e. those discouraging fossil fuel use and encouraging clean energy use, respectively), on both demand and supply sides. General policy levers are also summarised. Harnessing – or shaping – the incentives of large vested interests to spearhead the transition are emphasised.

29. Section 7 summarises and concludes.

2. Study Context, and Framing the Net-Zero Transition as Competition between Energy Platforms

Key points from this section:

1. Taking low-emissions transport as a motivating example, a key issue with existing alternatives to fossil fuel transport technologies is that they are currently not clearly superior (i.e. cheaper or better) than existing transport technologies. In fact they are more expensive, and currently inferior or no better in many key dimensions relevant for voluntary consumer uptake.
2. That said, low-emissions technologies like hydrogen have the potential to be transformative, in that they can lead to an entirely new energy ecosystem offering benefits for a wide range of low-emissions applications.
3. Energy technologies represent "platforms" linking suppliers and servicers of hardware with users of the services provided by that hardware. Even if low-emissions technology platforms are superior to existing, high-emissions platforms, this does not assure they will be adopted in a timely, efficient or equitable way due to economies of scale and network effects.

2.1 Overview

30. This section provides further context to the study. It explains how the transition to net-zero emissions is best framed as competition between an existing energy "platform" or "ecosystem" on the one hand (i.e. fossil fuels), and one or more alternative, low-emissions (e.g. renewables-based electric or hydrogen) energy platforms/ecosystems on the other.

31. The section begins, however, by setting out details of some key technologies to be considered in transitioning to net zero emissions, especially in private passenger transport. These provide important motivating examples of the types of issues and challenges arising in the transition.

32. Many of the issues introduced in this section are explored further in subsequent sections.

2.2 Some Leading Low-Emissions Technology Options

Hybrids and Battery Electric Vehicles

33. The fossil fuel energy platform that forms the backbone of the current fleet of petrol and diesel ICEVs has been established at great cost over many decades, and maintains key advantages relative to current rival technologies:

> "Fossil fuels are currently the most convenient on-board energy sources for vehicles in terms of energy density and refueling time."[4]

34. The current leading alternatives to ICEVs in actual use are:

    34.1. Battery electric vehicles (BEVs) – relying on grid-supplied electricity stored on on-board batteries to power electric motors for motion; and

    34.2. Internal combustion engine hybrid vehicles (ICEHVs) – which have internal combustion engines complemented by electric motors powered by batteries:

        34.2.1. Those batteries are charged by converting motion into electricity (e.g. through regenerative braking), and/or from grid-supplied electricity as in plug-in hybrid electric vehicles (PHEVs).

35. BEVs embed extra emissions relative to ICEVs due to the emissions required to make their batteries. However, if the electricity used to charge their batteries is produced from renewable sources, they produce no emissions when running, so their lifecycle emissions can be lower than for ICEVs if each vehicle type is driven sufficiently far:

    35.1. ICEHVs embed fewer emissions in their batteries than BEVs, but produce greater emissions from vehicle use due to burning fossil fuels. Compared with ICEVs, however, they can produce meaningful emissions reductions, without sacrificing driving range, or facing refuelling challenges.

36. It should be noted that although a large part of New Zealand's electricity production is renewable, gas or coal are often used during times of high/peak demand (and even geothermal generation causes produce some GHG emissions):

[4] Conway et al. (2021, p. 1).

36.1. Whether or not recharging BEV (or PHEV) uses renewable or polluting generation therefore depends on when charging occurs;

36.2. Hence recharging cannot be assumed to have the average emissions profile of New Zealand's electricity generation mix (i.e. is mostly renewable) – certainly BEV usage cannot be assumed to be emissions-free just because BEVs run on electricity.

37. Vehicle technologies are often compared in terms of their energy conversion efficiencies – i.e. the rate at which primary energy is ultimately realised, after allowing for various conversion, storage and other (e.g. transmission/distribution) losses. Comparing BEVs with ICEVs:[5]

37.1. BEVs have higher conversion efficiency provided they are supplied using renewable electricity;

37.2. However, their conversion efficiency is comparable to that of petrol ICEVs, and even inferior to that of diesel ICEVs, when supplied with electricity produced from coal or gas.

38. In any case, technical considerations such as energy conversion efficiency are less relevant to consumers than more practical attributes such as range and refuelling times (as below).

39. Finally, Figure 2.1 illustrates how BEVs are likely to form part of New Zealand's electricity ecosystem. This is not just because they will create demands for renewable electricity generation in order to run cleanly, and on electricity distribution networks to provide the private or public recharging infrastructure needed to enable convenient and timely recharging. It is also because:

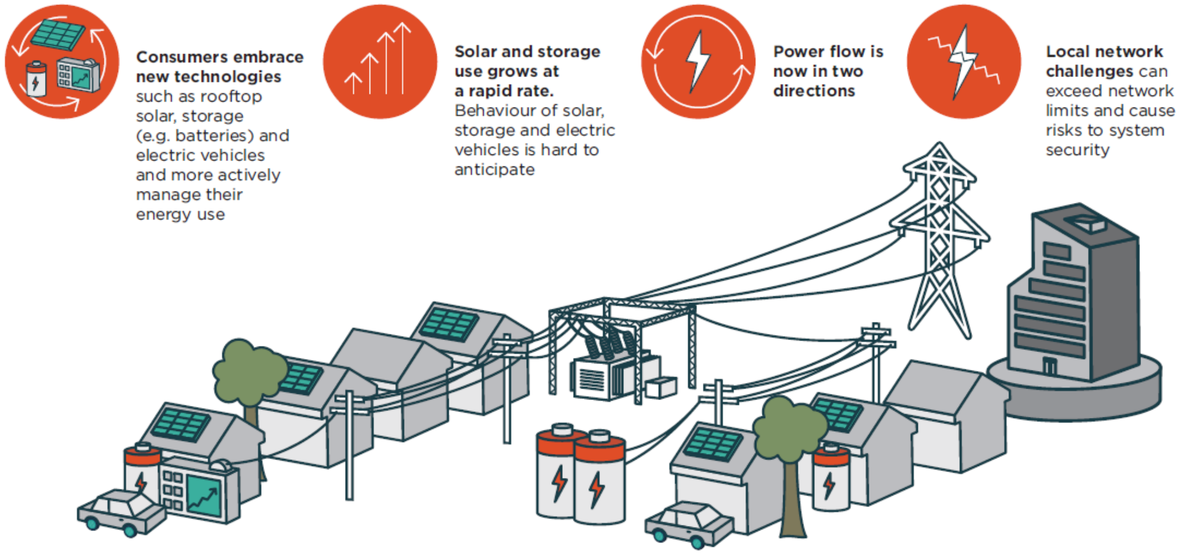
39.1. BEVs will likely form a natural complement to innovations like solar photovoltaics (PV, e.g. on rooftops), since using PV to recharge BEV batteries could improve the economics of owning PV; and

39.2. The batteries in BEVs – if equipped with vehicle-to-grid (V2G) technology – could be used to supply power when needed, either to provide support services to electricity distribution networks, or to trade electricity at a decentralised level (e.g. peer-to peer, P2P).[6]

[5] E.g. see Albatayneh et al. (2020), especially Figure 6.

[6] See Meade (2021a) for further discussion.

Figure 2.1 – Battery Electric Vehicles as Part of the Electricity Ecosystem



Source: Energy Networks Australia (2020), Figure 3.

Hydrogen

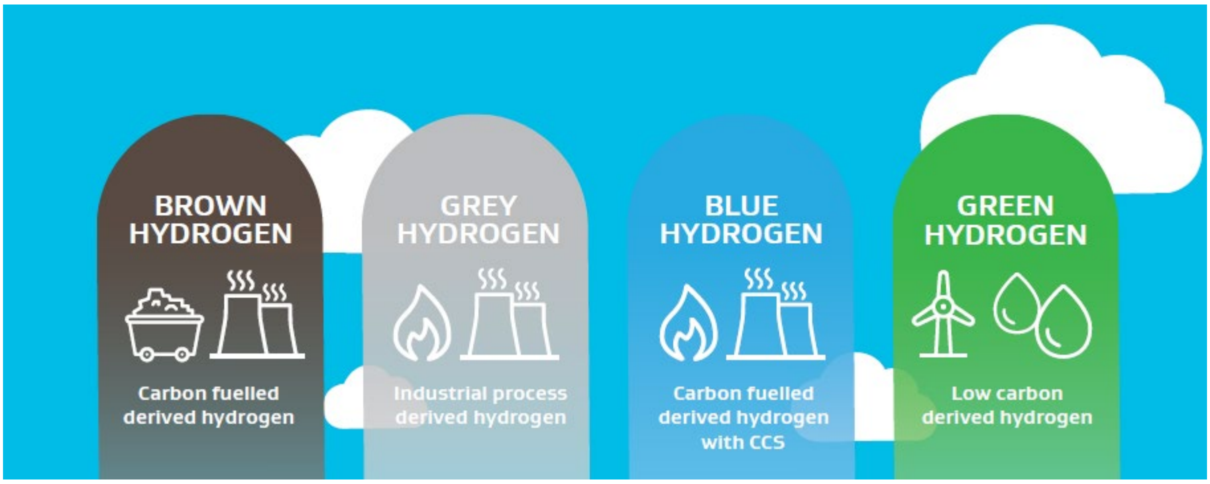
40. An emerging rival low-emissions technology uses hydrogen, whether to produce electricity to drive an electric motor (as in hydrogen fuel cell vehicles, FCEVs), or combusted like fossil fuels in hydrogen internal combustion engine vehicles (H_2ICEVs; together with FCEVs, Hydrogen Vehicles, H_2Vs):

40.1. An important possible advantage of H_2ICEVs is that it might prove viable to retrofit existing ICEVs with affordable technologies that enable them to run on hydrogen:

40.1.1. In much the same way ICEVs have in the past been converted to run on alternative fuels like CNG and LPG, which were also able to be supplied by relatively minor modifications to the existing fossil fuel supply chains (i.e. with distribution through petrol stations);

40.2. That could provide a relatively low-cost pathway to achieving a low-emissions vehicle fleet in a low-cost, timely and equitable way – provided hydrogen can be produced, transmitted, stored and distributed/retailed in a cost-competitive and convenient way.

Figure 2.2 – Different Types of Hydrogen



Source: MBIE (2019), Figure 15.

41. As illustrated in Figure 2.2, the main approaches to producing hydrogen are:

41.1. Brown hydrogen – using fossil fuels to make hydrogen, but producing CO_2 in the process;

41.2. Grey hydrogen – produced as part of industrial processes;

41.3. Blue hydrogen – producing hydrogen in a way that produces CO_2 but using technologies like carbon capture and storage (CCS) to trap the associated CO_2 emissions – for example, by pumping them into depleted gas fields, where they might be safely sequestered for millennia (just as the hydrocarbons previously extracted from them were); and

41.4. Green hydrogen – hydrogen produced by splitting water into its component parts using renewable electricity. This form of hydrogen is inherently emissions-free.

42. An important advantage of hydrogen is that it can be used in a wider range of applications than electricity stored in batteries, given current battery technologies:

42.1. For example, excess renewable energy production (i.e. wind, solar), which is highly intermittent, could be converted into hydrogen and stored. It could then later be converted back into electricity, or combusted, to produce clean energy, thus buffering renewables intermittency;

42.2. Hydrogen's storage and energy density can be improved by converting it into ammonia, which then also enables it to be transported more conveniently, and used in applications where greater energy density is required (e.g. shipping);

42.3. Hydrogen can also be used for heavy and/or long-distance transport, whereas the weight and size of batteries limits their applications to lighter and shorter-distance applications. It also finds applications in certain industrial processes (e.g. steelmaking, and other industrial processes for which significant heat is required, and alternatives like burning biomass or using electricity are costly or unavailable).

43. Hydrogen can be imported or exported, meaning that domestic production capacity for clean hydrogen need not be a constraint provided clean hydrogen can be imported – e.g. from Australia or Saudi Arabia where abundant solar and wind capacity might in future make them key exporters of clean hydrogen:

43.1. By converting renewable electricity into hydrogen, that electricity can not only be stored but also exported, whereas it is not possible to export that electricity from New Zealand via transmission connections (given Australia is so far away);

43.2. In contrast, while electricity could in principle be stored in batteries and then exported, it is currently uneconomic to do this at scale given current battery technologies.

44. The potential for hydrogen to form an entire low-emissions "energy ecosystem" is illustrated in Figure 2.3 (contrast the more modest role indicated for BEVs in Figure 2.1):

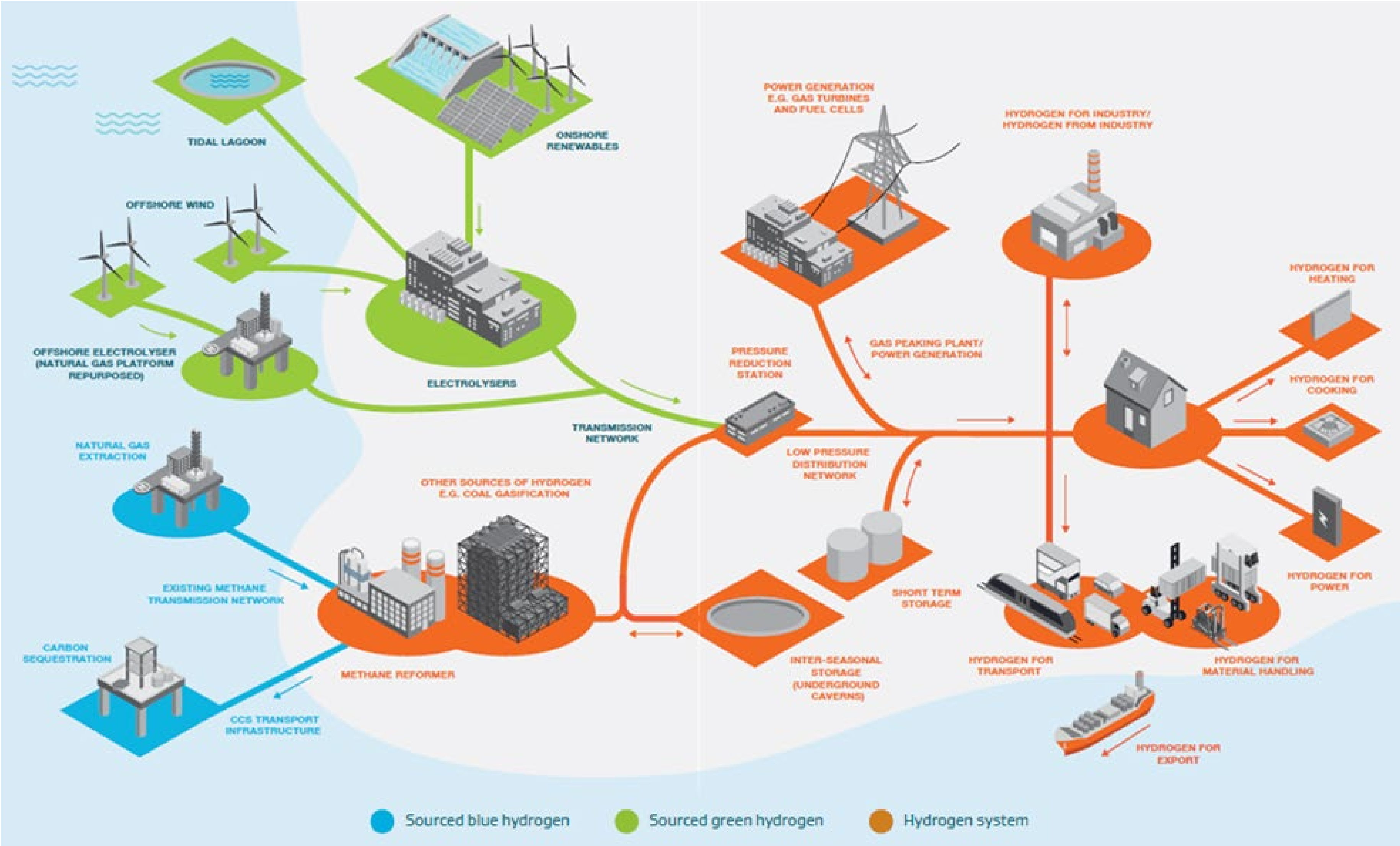
44.1. As highlighted by the figure, much of New Zealand's existing fossil fuels (i.e. natural gas related) infrastructure could play an important role in any such new ecosystem.

Biofuels and e-fuels

45. Mention should also be made of biofuels (such as ethanol made from sugar or cellulose), and biodiesel made from oils and fats. Many ICEVs are capable of running on fuel blends containing biofuels. With modifications, many might be able to run on 100% biofuels:

45.1. The main limitation of biofuels is that a great deal of land is required to produce the feeder stocks from which they are made, especially at large volume. This can result in the loss of other land uses such as natural forests, and competition for land that might be used for food production (raising food prices);

Figure 2.3 – A Possible Hydrogen Ecosystem for New Zealand



Source: Adapted from MBIE (2019), Figure 14.

45.2. Accordingly, while biofuels seem a natural substitute for fossil fuels, in practice this is limited to certain applications like aviation or shipping where other alternatives to fossil fuels are not currently viable.

46. Finally, e-fuels are another class of direct fossil fuel substitute to consider. They consume CO_2 to produce synthetic fossil fuels using energy. Provided that energy is produced from renewable sources, they represent a net-zero substitute to fossil fuels. Like biofuels, if they could be made economically at scale, they could easily be used in existing fossil fuel supply chains and ICEVs, reducing the costs of transitioning to a low-emissions economy.

47. Tables 2.1 and 2.2 compare these various fuel technologies. Table 2.1 highlights how the alternative technologies are, or are not, currently preferable from consumers' perspectives relative to ICEVs. Table 2.2 focuses more on how the different technologies compare in terms of their wider energy platform requirements, and emissions profiles.

48. Key points include:

48.1. BEVs are currently the leading alternative to ICEVs (apart from hybrid vehicles), but they suffer certain considerable disadvantages relative to ICEVs, meaning they are not clearly superior to ICEVs, and they also cost much more. This naturally limits their attractiveness as an alternative to ICEVs;

48.2. H_2Vs are not currently viable, but major investment is occurring worldwide to make them so, and major car manufacturers such as Toyota and Hyundai, and countries like Japan, are betting on hydrogen having a strong future despite BEVs' early lead:

48.2.1. In principle they are a much closer substitute to ICEVs than BEVs, but they are still much more expensive (though they are on a steeper segment of their technology development path than BEVs, so the same sort of cost improvements already experienced by BEVs might be expected for H_2Vs);[7]

48.3. Currently the closest alternative to ICEVs offering potentially net zero emissions are biofuels, but issues to do with their sustainability, amount of land required, and impact on food prices limit their desirability and widespread practicality.

[7] BEV battery costs in $/kWh fell 90% between 2010 and 2020 (Standage (2021, p. 164)).

Table 2.1 – Key Attributes of Clean Road Vehicle Technologies relative to ICEVs from the Vehicle User's Perspective

	BEVs	H_2Vs	Biofuels, e-fuels
Emissions	Lower if charged from renewables, but similar if charged from coal or gas	Depends on emissions content of electricity, but lacks embedded emissions of BEV batteries	Lower
Vehicle cost	Higher	Higher	Similar
Range	Less	Similar	Slightly less
Refuelling time	Longer	Similar	Same
Refuelling frequency	Greater	Similar	Slightly more
Refuelling infrastructure	Less	Less	Same
On-vehicle fuel storage	Less	Similar	Slightly less
Maintenance costs	Lower, except for battery replacement	Similar?	Similar
Acceleration	Greater	Similar/Greater	Slightly greater
Top speed	Limited by law	Limited by law	Limited by law
Towing capacity	Less	Similar?	Similar
Traffic congestion	Same	Same	Same
Travel times	Same	Same	Same

49. These rankings could significantly change with breakthroughs in technologies or business models, or changes in consumer preferences:

49.1. For example, BEV manufacturers might agree on standardised batteries, and co-invest or otherwise support the development of battery swapout networks (where batteries are effectively leased rather than owned, and discharged batteries are physically swapped for recharged ones in possibly just minutes);[8]

49.2. This could materially overcome the current range limitations and recharge time inconvenience suffered by BEVs relative to ICEVs, H_2Vs and biofuels/e-fuels.

[8] This approach was in fact adopted in the earliest days of BEVs at the turn of the 20th century (Standage (2021)). BEV manufacturers are reported to be developing this approach in China – https://energypost.eu/energy-conversion-for-hydrogen-cars-is-only-half-that-for-bevs/.

Table 2.2 – Comparing Fuel Technologies

	Fossil fuels	Grid electricity	Hydrogen	Biofuels, e-fuels
Suitable vehicle technologies	ICEVs, and ICEHVs	BEVs, and PHEVs	FCEVs, H_2ICEVs, H_2HVs	ICEVs, and ICEHVs
Maturity of vehicle technology	Mature (ICEVs), advancing (ICEHVs)	Advancing	Developing (H_2HVs), advancing (FCEVs, H_2ICEVs)	Mature (ICEVs, ICEHVs), though modifications required
Fuel production infrastructure	Mature, but facing regulatory and investor pressure. Could be repurposed to low or zero emissions fuels (e.g. brown hydrogen, or blue hydrogen using CCS)	Extra renewable generation required, supported by falling renewables costs (wind, solar)	Limited (e.g. mainly for industrial uses), but growing. Low-cost green hydrogen production supported by falling cost of renewables one possibility,[9] or blue hydrogen production using fossil fuels and CCS another.	Growing (biofuels), developing (e-fuels). Biofuels production constrained due to issues like sustainability and pressure on food prices.
Fuel storage and transmission/ distribution infrastructure	Mature, but facing regulatory and investor pressure. Could be repurposed to low or zero emissions fuels (e.g. hydrogen, biofuels)	Large-scale storage currently expensive, though could be coupled with hydrogen production	New storage infrastructure required, but existing fossil fuel transmission/ distribution infrastructure could be repurposed.	Mature – can repurpose existing fossil fuel infrastructure
Net-zero?	Fossil fuels and brown hydrogen no. Blue hydrogen maybe (depends on extent to which CCS captures all emissions from production)	Maybe – lower emissions if charging uses renewable electricity, to be weighed against extra emissions from battery production	Depends on emissions from hydrogen production (brown, grey, blue, green)	Depends on emissions from production (e.g. whether e-fuels are produced using renewable electricity)

[9] E.g. imported from countries with abundant sunshine and space – Australia and Saudi Arabia are strong candidates for exporting low-cost green hydrogen in bulk (e.g. as high energy density ammonia).

Table 2.3 – Likely Applications of Alternative Fuel Technologies

	Fossil fuels	Grid electricity	Hydrogen	Biofuels, e-fuels
Land transport:				
• Light/short	Y	Y	Y	Y
• Heavy/long	Y	-	Y	Y
Sea transport:				
• Light/short	Y	Y	Y	Y
• Heavy/long	Y	-	Y? (ammonia?)	Y
Air transport:				
• Light/short	Y	Y	Y	Y
• Heavy/long	Y	-	Y? (ammonia?)	Y
Domestic heating:				
• Cooking	Y	Y	Y	Y
• Space	Y	Y	Y	Y
• Water	Y	Y	Y	Y
Commercial heating:				
• Cooking	Y	-	Y	Y
• Space	Y	Y	Y	Y
• Water	Y	Y	Y	Y

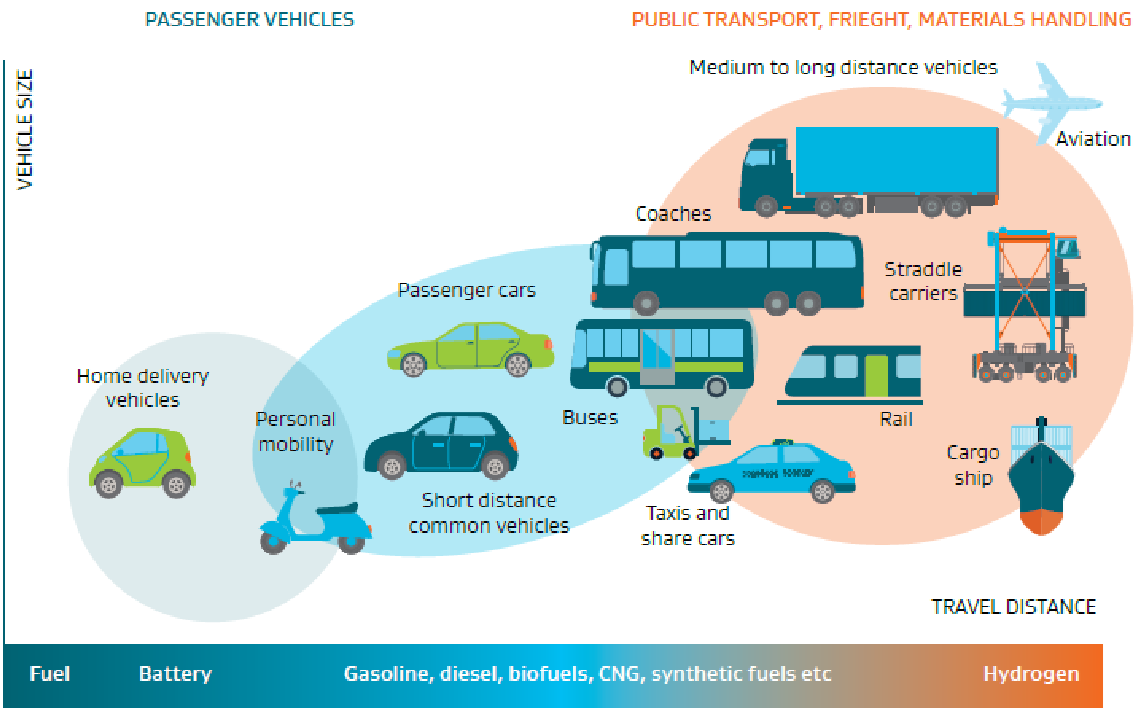
50. Having said that, ICEVs will also continue to improve (as will H_2Vs), and possibly radically so if ICEV manufacturers wish to remain competitive with alternative vehicle technologies:

50.1. This is particularly the case if the global second hand ICEV market balloons in response to clean vehicle regulations causing ICEV retirement, or simply as consumers increasingly adopt clean vehicle technologies.

51. Finally, Tables 2.3 and 2.4, and Figure 2.4, compare likely applications of non-fossil fuels with those of fossil fuels, for different types of transport, as well as domestic and commercial heating. As shown in Table 2.3, different types of fossil fuels – including coal and natural gas – find a wide range of applications:

51.1. In principle, biofuels and e-fuels could substitute for many of these applications, at least where petrol, diesel or natural gas are currently used. As above, however, feasibility and sustainability issues with biofuels production likely limit their effective range of applications.

Figure 2.4 – Suitability of Energy Platforms for Different Types of Transport



Source: MBIE (2019), Figure 16.

52. By contrast, hydrogen is likely to be suitable for the same range of applications as fossil fuels, even if this requires hydrogen to be converted to ammonia for higher-density storage in applications requiring greater energy density. Due to limitations in current battery technologies, however, grid electricity cannot be stored in batteries and used for certain applications, such as heavy or longer-distance transport by land, sea, or air.

53. Importantly, this points to hydrogen likely being a pivotal low-emissions alternative to fossil fuels for certain applications:

    53.1. That will either pave the way for hydrogen to become dominant in other applications as well, or result in different technologies dominating in different applications.

54. As shown in Table 2.3, hydrogen might be suitable for commercial cooking applications, but grid-supplied electricity is unlikely to. This is because commercial cooking often relies on high and instantly-available heat, which electricity does not provide. This points to a more general limitation for electricity in larger applications requiring significant amounts of heat, including for industrial processes such as steel and cement production, and dairy, meat and wood processing.

Table 2.4 – Deployment of Hydrogen Vehicles

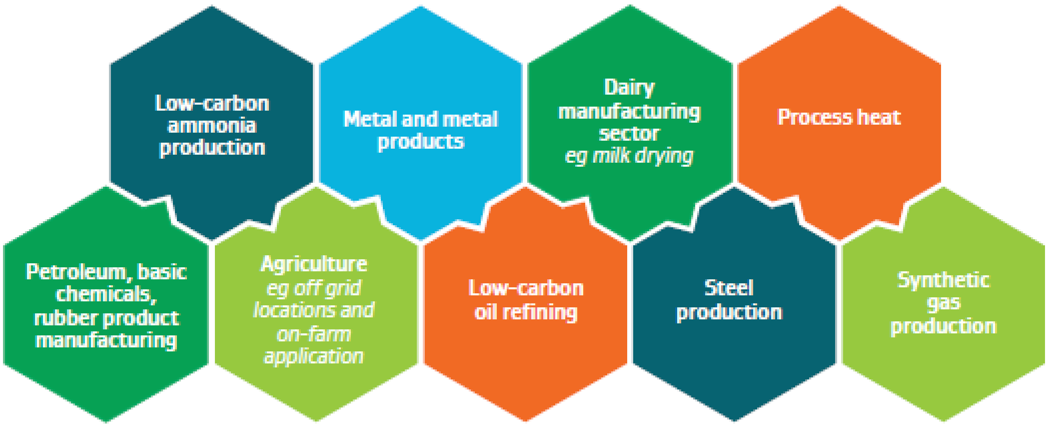
	Current role	Demand perspectives	Future deployment: OPPORTUNITIES	Future deployment: CHALLENGES
Cars and vans light-duty vehicles	11,200 vehicles in operation, mostly in California, Europe and Japan	The global car stock is expected to continue to grow; hydrogen could capture a part of this market	**Hydrogen**: Short refuelling time, less weight added for energy stored and zero tailpipe emissions. Fuel cells could have a lower material footprint than lithium batteries Return-to-home fleets can help overcome challenges of low utilisation of refuelling stations; long-distance and heavy-duty are attractive options	**Hydrogen**: Initial low utilisation of refuelling stations raises fuel cost; reductions in fuel cell and storage costs needed; efficiency losses on a well-to-wheels basis **Power-to-liquid**: Large electricity consumption and high production costs **Ammonia**: Caustic and hazardous substance close to end users mean that use is likely to remain limited to professional operators **Hydrogen**: Storage cost higher than other fuels **Hydrogen/ammonia**: Cargo volume lost due to storage (lower density than current liquid fuels)
Trucks and buses heavy-duty vehicles	Demonstration and niche markets: • 25,000 forklifts • 500 buses • 400 trucks • 100 vans. Several thousand buses and trucks expected in China* by end-2019	Strong growth segment; long-haul and heavy-duty applications are attractive for hydrogen		
Maritime	Limited to demonstration projects for small ships and on-board power supply in larger vessels	Maritime freight activity set to grow by around 45% to 2030. 2020 air pollution targets and 2050 greenhouse gas targets could promote hydrogen based fuels	**Hydrogen and ammonia** are candidates for both national action on domestic shipping decarbonisation, and the IMO Greenhouse Gas Reduction Strategy, given limitations on the use of other fuels	
Rail	Two hydrogen trains in Germany	Rail is a mainstay of transport in many countries	Hydrogen trains can be most competitive in rail freight (regional lines with low network utilisation and cross border freight)	Rail is the most electrified transport mode; hydrogen and battery electric trains with partial line electrification are both options to replace nonelectrified operations, which are substantial in many regions
Aviation	Limited to small demonstration projects and feasibility studies	Fastest-growing passenger transport mode. Large storage volume and redesign would be needed for pure hydrogen, making power-to-liquid and bio-fuels more attractive for this mode	**Power-to-liquid**: Limited changes to status quo in distribution, operations and facilities; also maximises biomass use by boosting yield Hydrogen: Together with batteries, can supply on-board energy supply at ports and during taxiing	**Power-to-liquid**: Currently 4 to 6 times more expensive than kerosene, decreasing to 1.5–2 times in the long-term, potentially increasing prices and decreasing demand

* China = People's Republic of China.

Source: MBIE (2019), Table 2.

55. The former depend on fossil fuels like coal for heat, but also for carbon as an integral part of the manufacturing process (e.g. for steel). The latter often depend on coal or natural gas to economically provide large amounts of heat (or biomass in the case of wood processing). If large amounts of new renewable generation result in reduced electricity prices, this might induce at least some of these process heat applications to switch from fossil fuels to electricity. Also, in parts of the country with access to biomass (e.g. wood chips/pellets from wood processing), this too might represent a cost-effective alternative to fossil fuels.

Figure 2.5 – Industrial Uses of Hydrogen



Source: MBIE (2019), Figure 17.

56. Given its higher energy density, however, especially if stored as ammonia, hydrogen might prove to be a viable alternative for many process heat applications. This could be the case even where existing gas transmission and storage infrastructure is not currently available, although this would require the creation of alternative networks for transporting and storing the required fuel (e.g. via trucks, as is the case for South Island petrol and diesel supplies, and bottled natural gas supplies).

57. Furthermore, with changes in processes, hydrogen might also be suitable for certain industrial applications in addition to providing process heat (e.g. in steel and cement manufacturing):

    57.1. For example, hydrogen can be reacted with CO_2 emitted during cement production to form methane which can then be combusted to provide the heat required for the production process. This reduces the associated GHG emissions if green hydrogen is used.[10] Figure 2.5 highlights some of these possibilities.

2.3 Low-Emissions Transition as Competition between Platforms

The Goal

58. New Zealand, like an increasing number of other developed countries, has committed itself to a pathway for achieving net-zero GHG emissions by 2050, as the country's contribution to averting damaging climate change. Although the task remains urgent, policies and policy

[10]– see: https://www.gasworld.com/deep-decarbonisation-of-cement-production/2020509.article.

settings to achieve this net-zero goal in a timely, efficient and equitable way are yet to be fully formed.[11]

59. Acknowledging there are key uncertainties to be grappled with, an important challenge is to transition to net-zero emissions in a way that is timely, efficient, equitable and orderly.

Changing Attitudes and Technologies Support Achievement of the Transition

60. There is cause for optimism in grappling with the challenge. Not only are social attitudes towards polluting technologies hardening, but consumers, producers, workers and suppliers (of capital and other inputs) are increasingly giving priority to solutions with lower environmental footprints. This is both leading and responding to regulatory moves in this direction (e.g. emissions trading schemes that effectively put a price on GHG emissions).

61. Likewise, technology breakthroughs are enabling consumers to access solutions with much improved environmental footprints. These include advances in lithium ion battery technologies making battery electric vehicles (BEVs) a more attractive and viable option for transport, especially for lighter vehicles and shorter journeys. As battery technologies continue to mature and evolve, BEVs will become increasingly cost- and quality-competitive with existing internal combustion engine vehicle (ICEV) technologies based around fossil fuels.

62. At the same time, novel technologies for low-emissions transport and other applications are becoming increasingly realistic and attractive. These include transport, heating and industrial solutions fuelled by hydrogen, such as hydrogen vehicles (H_2Vs), whether they be fuel cell electric vehicles (FCEVs) or hydrogen internal combustion engines vehicles (H_2ICEVs). As for BEVs, if the energy used to operate these vehicles is derived in low-emitting ways, then this opens the door on low-emissions transport. Innovations in vehicle sharing services and public transport might also reduce transport-related emissions.

63. And this is just what we already know. Current breakthroughs in technologies, business models and consumer preferences will doubtless spawn further breakthroughs. This means the transition to net zero emissions does not depend just on reducing our use of current emitting technologies using the best available alternative technologies. We have to anticipate that even better technologies will emerge, possibly enabling a cheaper, faster and/or more appealing transition to a low-emissions world. Technology revolutions have

[11] For example, Ministry for the Environment (2021).

occurred in the past, when the technology platforms and pace of technological change were less than what they are now. They will happen again, especially if urgency is applied to making the necessary transitions.

Experience of Complications with Previous Transitions

64. However history teaches us that technology revolutions like the shift from canals to rail in the 19th century, and from horse- and steam-based transport to ICEVs around the turn of the 20th century, can take decades to occur, and often are the preserve of the wealthy (who can afford new technologies before they become affordable to the mass market). To achieve widespread net-zero emissions with urgency, there may not be the luxury of waiting for required technology revolutions to simply take their own course.

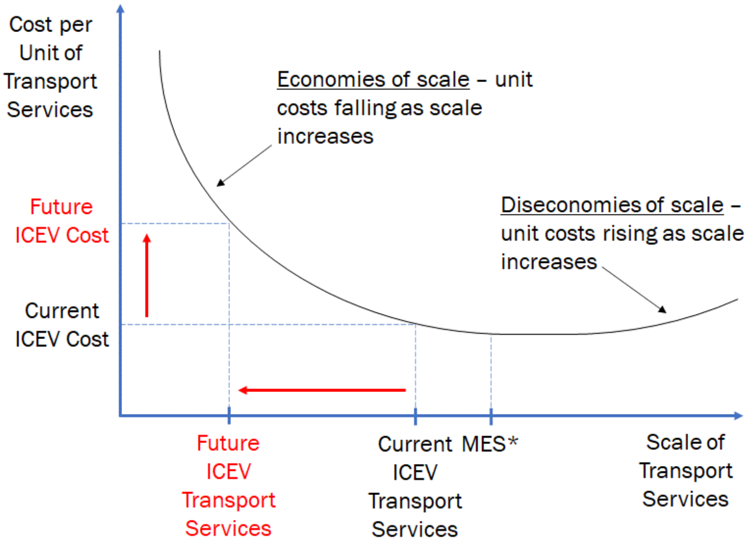
65. Likewise, we have numerous examples of how new technologies have had to vie not just for their place relative to existing technologies. They have often had to also vie against rival alternatives to existing technologies, with periods – sometimes measured in decades, but sometimes much shorter – in which consumers, hardware suppliers, and network providers have gravitated towards particular alternatives, only for another alternative to become the de facto standard at the expense of all others. These historical lessons are explored further in Section 3.

Platform Competition Complications – Path Dependence, and Scale Economies/Network Effects

66. While such battles for technological ascendancy – i.e. "competition for the market" – might be expected to result in socially efficient outcomes, this is far from assured. This results from two sets of key complicating factors. The first is path dependence – in which the best course ahead is often constrained by past choices:

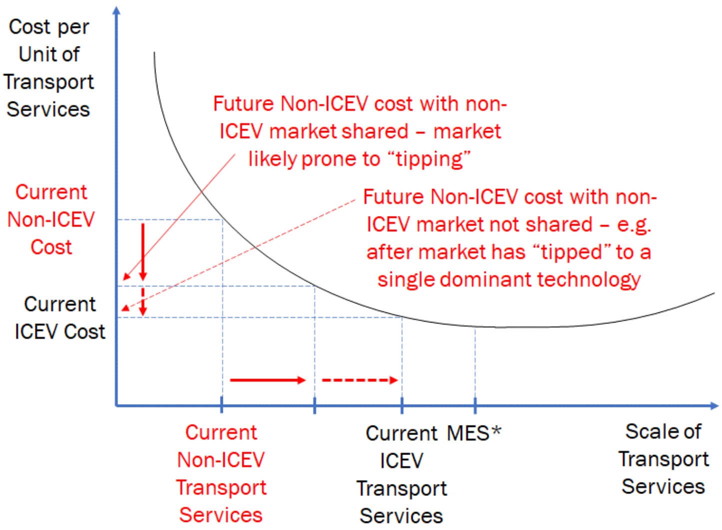
    66.1. This is especially so if existing technology providers respond to the threat of new technologies by improving their own offerings, or simply using their incumbency to secure advantage (e.g. lobbying for regulation to deter entry by new technologies). It can also reflect the fact that new technologies rarely start with a clean slate, and instead coexist with existing alternatives which might either complement or compete with them.

Figure 2.3 – Scale Economies for Incumbent and Entrant Transport Technologies



As new vehicle technologies gain market share from ICEVs, ICEVs must operate at a less-efficient level, increasing the unit costs of ICEV transport services:

- This supports the transition by closing any cost gap between new and old technologies;
- Ultimately this can lead to an ICEV "death spiral" because suppliers can no longer profitably operate, and users defect to new technologies.



Supposing (illustratively) that scale economies for new transport technologies are comparable to those for ICEVs – i.e. same cost curves and MESs:

- If any one new technology could wholly displace ICEVs, then it could achieve the same sorts of unit costs as ICEVs, helping to accelerate the transition as ICEV transport services share falls and ICEV unit costs rise;
- But if competing new technologies share the transport market, neither achieves full scale, and each will have unit costs that are higher than for ICEVs. This maintains a cost gap in favour of ICEVs, and could delay the transition to new technologies.

If unit costs are falling sufficiently with greater scale, this inclines markets to "tip" towards a single dominant technology, in which case the shared market scenario would likely be unsustainable.

* Minimum efficient scale – affects number of profitable competing providers/technologies that market can sustain.

67. Another reason why competition for technology ascendancy is no guarantee of socially preferred outcomes is that certain technologies enjoy both scale economies and network effects. The first means that production at scale is required to achieve low unit costs, and in smaller markets this often leaves room for one or only few technology (e.g. network)

providers.[12] This also arises when greater production of a given technology helps to improve how that technology is produced (learning by doing):

67.1. This means incumbent technologies can enjoy significant cost advantages relative to rivals that have not yet achieved full scale, making it harder for such rivals to gain a toehold in the market, as illustrated in Figure 2.3 for the case of rival transport technologies.

68. The second reason why competition for technology ascendancy is no guarantee of socially preferred outcomes – network effects – refers to the situation where the benefits enjoyed by users of a new technology hinge very much on how many other users or suppliers also use that technology – so-called “network effects”. Such effects can be:

68.1. Direct network effects (DNEs) – meaning that the benefits of one type of platform user (e.g. consumers, or hardware suppliers) are affected by how many other such users are also on the same platform; and

68.2. Indirect network effects (INEs) – meaning that the benefits of one type of platform user are affected by the nature and number of other types of platform users.

69. An example of DNEs is mobile phone networks – mobile phone users benefit when there are more other mobile phone users they can call. An example of INEs is ride hailing platforms – riders benefit when there are more drivers available, and vice versa:

69.1. Network effects are often positive, but can also be negative – for example, some network users enjoy their network being exclusive, so dislike it when there are too many other users (or the wrong type of users).

70. Direct and indirect network effects are illustrated in Figure 2.4.

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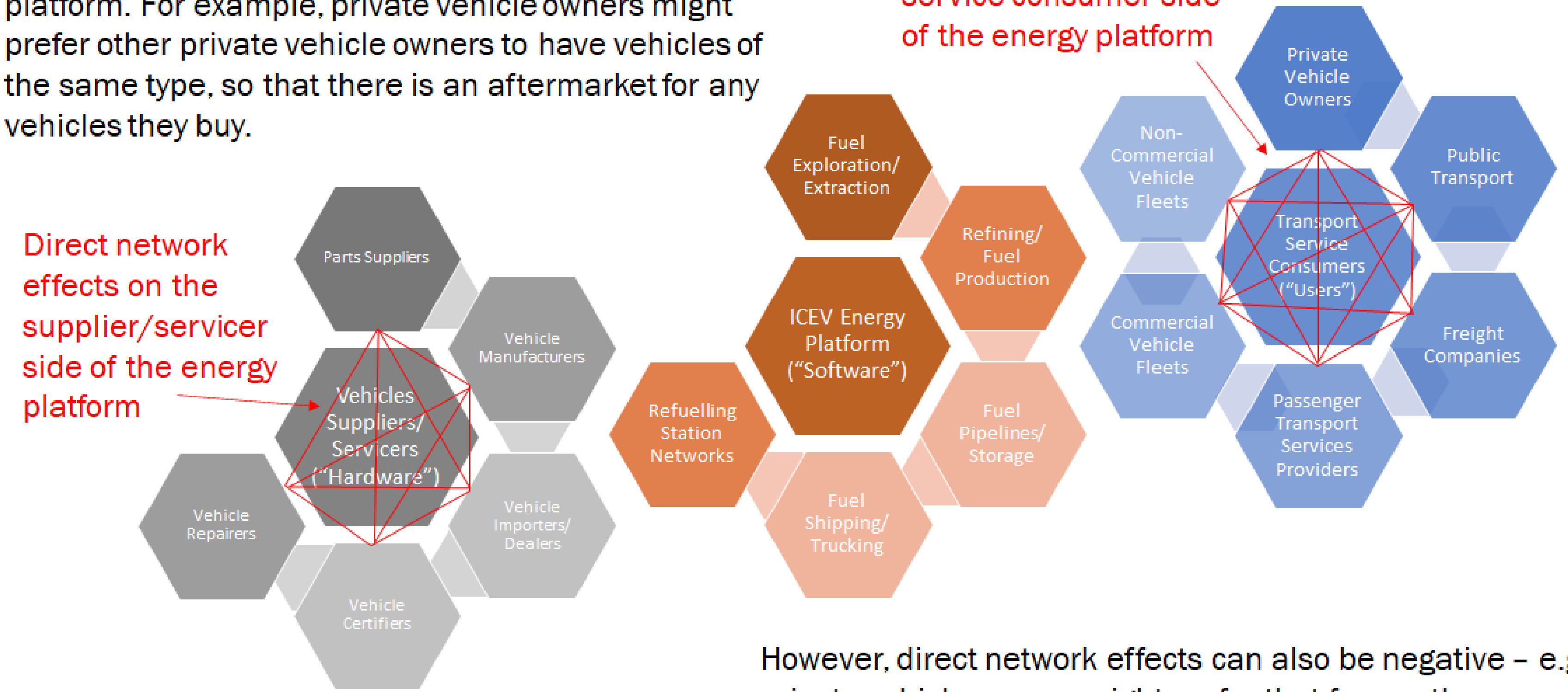
[12] This is particularly the case if the minimum efficient scale of production – i.e. the scale of production at which unit production cost are minimised – is large relative to the total market size to be served (as is often the case for New Zealand).

Figure 2.4 – Direct and Indirect Network Effects for Fossil Fuels Based Transport

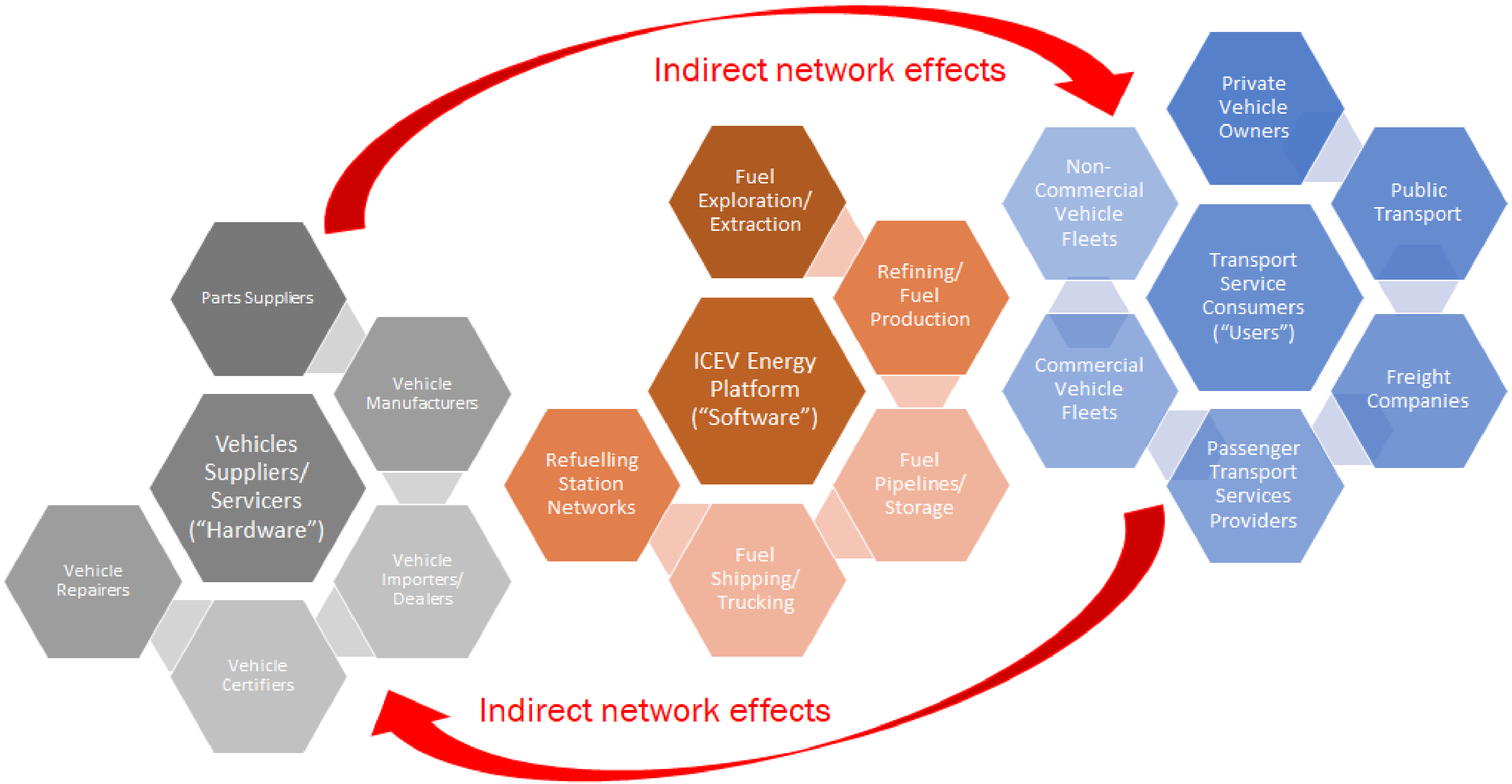
Direct network effects (DNEs) arise when decisions of parties on one side of a platform affect outcomes experienced by other parties on the same side of the platform. For example, private vehicle owners might prefer other private vehicle owners to have vehicles of the same type, so that there is an aftermarket for any vehicles they buy.



However, direct network effects can also be negative – e.g. private vehicle owners might prefer that fewer other people also own private vehicles, in order that they can enjoy reduced traffic congestion.

Figure 2.4 (cont'd) – Direct and Indirect Network Effects for Fossil Fuels Based Transport

Indirect network effects (INEs) arise when decisions by parties on one side of the energy platform affect outcomes for parties on the other side. For example, vehicle purchase choices by private vehicle owners affect sales made by car manufacturers. Conversely, vehicle technology and product range choices by vehicle manufacturers affect vehicle buyers.



Excess Inertia/Lock-In and Excess Momentum

71. Competition between existing and new technologies, or between existing and multiple new technologies – when such network effects are present – creates particular challenges. Specifically, consumers, producers and network providers need to form expectations about the choices made by other parties and which platforms will be successful, and coordinate their decisions, if they want to maximise the benefits they individually and collectively enjoy by being on the same technology "platform":

    71.1. Experience shows that this can lead to issues like "lock-in" and "excess inertia" (new technologies being adopted less or more slowly than they should, to the benefit of inferior existing technologies);

    71.2. They can also result in "excess momentum", for example in which existing technologies might offer better solutions if only more consumers and suppliers stuck with them, instead of migrating to fundamentally inferior solutions in large numbers.

72. A well-established finding in the literature on competition in the presence of network effects is that competition for the market does not assure that the best technology necessarily wins:

    72.1. Inferior technologies can become locked in when superior technologies exist – at the expense of consumers and society. This is discussed further in Section 4.4.

Transition to Net-Zero Emissions Shares such Complications

73. Transitioning away from existing polluting technologies like ICEVs for transport, and the use of coal, gas or other fossil fuels for residential/commercial heating and cooking, and for process heat in industrial applications, shares some of these complicating features. Existing energy and technology platforms such as fossil fuel supply chains enjoy significant incumbency advantages. These include having had many decades to achieve scale economies and to establish highly developed networks (such as for the transmission, distribution, storage, and retailing of fossil fuels).

74. Sometimes vast ancillary supply chains have developed around existing energy and technology platforms (e.g. vehicle manufacturing, retailing and servicing). Large customer bases have also chosen how and where they live, work and play based on the possibilities offered by those platforms (e.g. the possibility of commuting using private vehicles).

Disrupting such well-entrenched platforms is relatively easy to achieve – they can be destroyed by edict. Convincing existing or new players to develop a low-emissions platform to replace existing ones – especially when large, irreversible investments are required – also requires convincing them that hardware suppliers and consumers will follow. Making sure there is something new to replace the old as it is retired – in a timely way, and avoiding massive service disruptions – cannot be achieved simply by decree, and is not something that necessarily happens by itself.

75. The pathway to net zero emissions is therefore potentially fraught. Numerous parties have to make big decisions and investments to get there, under considerable uncertainty. The transition isn't as simple as asking people to all buy green apples instead of red ones.[13] Energy platform suppliers – from fuel producers through to transmission, storage and distribution/retailing network suppliers – need to decide which technologies to make long-term investments in. At the same time, hardware suppliers such as vehicle and appliance manufacturers, and ancillary suppliers such as retailers and servicers, need to tool up to produce products and services based on given technologies.

76. In turn, platform users need to decide which expensive pieces of hardware to purchase or invest in (e.g. vehicles and appliances for residential and commercial consumers, specialised machinery and production processes for industrial consumers). And the outcomes enjoyed by each of these key groups of parties will hinge on the decisions made by members of the other key groups. This is hard to achieve when incumbent technologies face just one alternative, even supposing that alternative is superior to existing technologies. It is an order of magnitude even more complicated when there are multiple alternatives to the incumbent technology (or those alternatives are inferior to existing technologies).

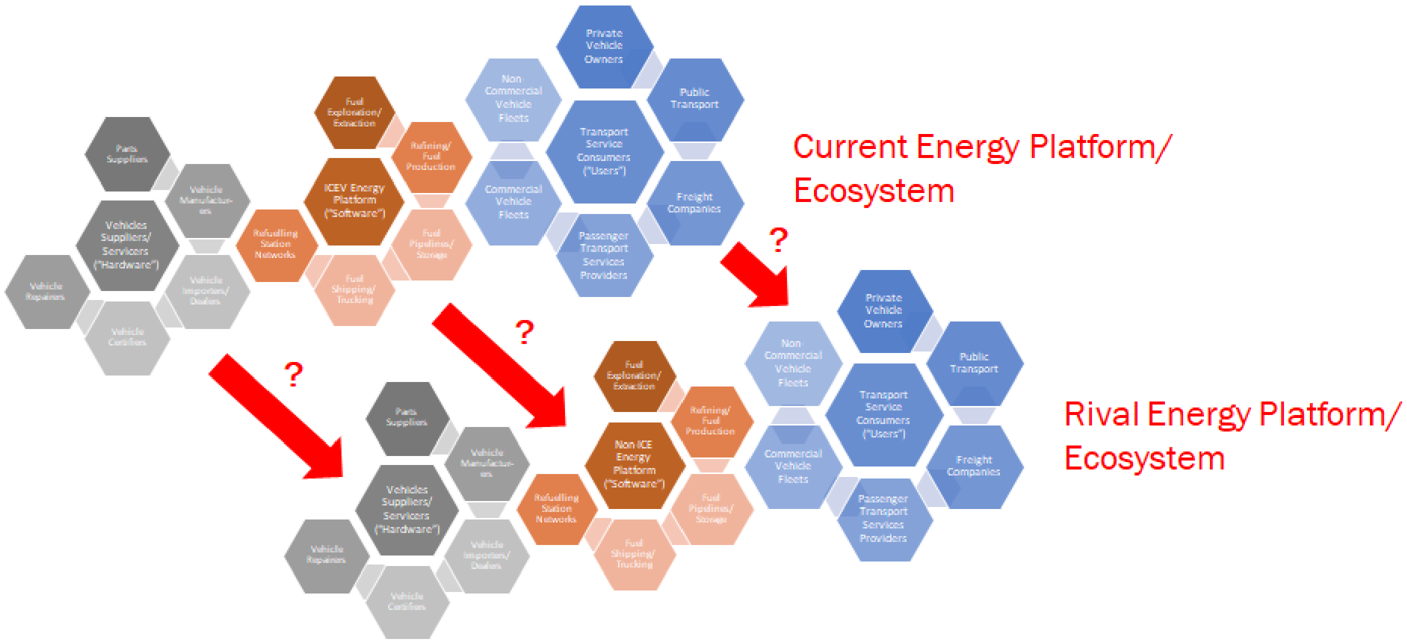
77. These challenges are depicted in Figure 2.5.

[13] Even then, apple suppliers and retailers would need to be able to ensure they could meet the change in demand for apples of different colours – network effects can arise even in this very simple context.

Figure 2.5 – The Challenges of Transitioning from the ICEV Energy Platform to One or More Low-Emissions Alternative Platforms

Transitioning to a low-emissions transport system requires transport service users to choose if and when to migrate to using a new energy platform. Emphasising just how great a coordination challenge this is, this simultaneously requires:

- Current vehicle suppliers/servicers and energy platform providers to migrate to the same energy platform in a timely way; or
- New suppliers/servicers and energy platform providers to arise in a timely way – and to successfully compete against current suppliers/servicers and providers based on the existing ICEV energy platform.

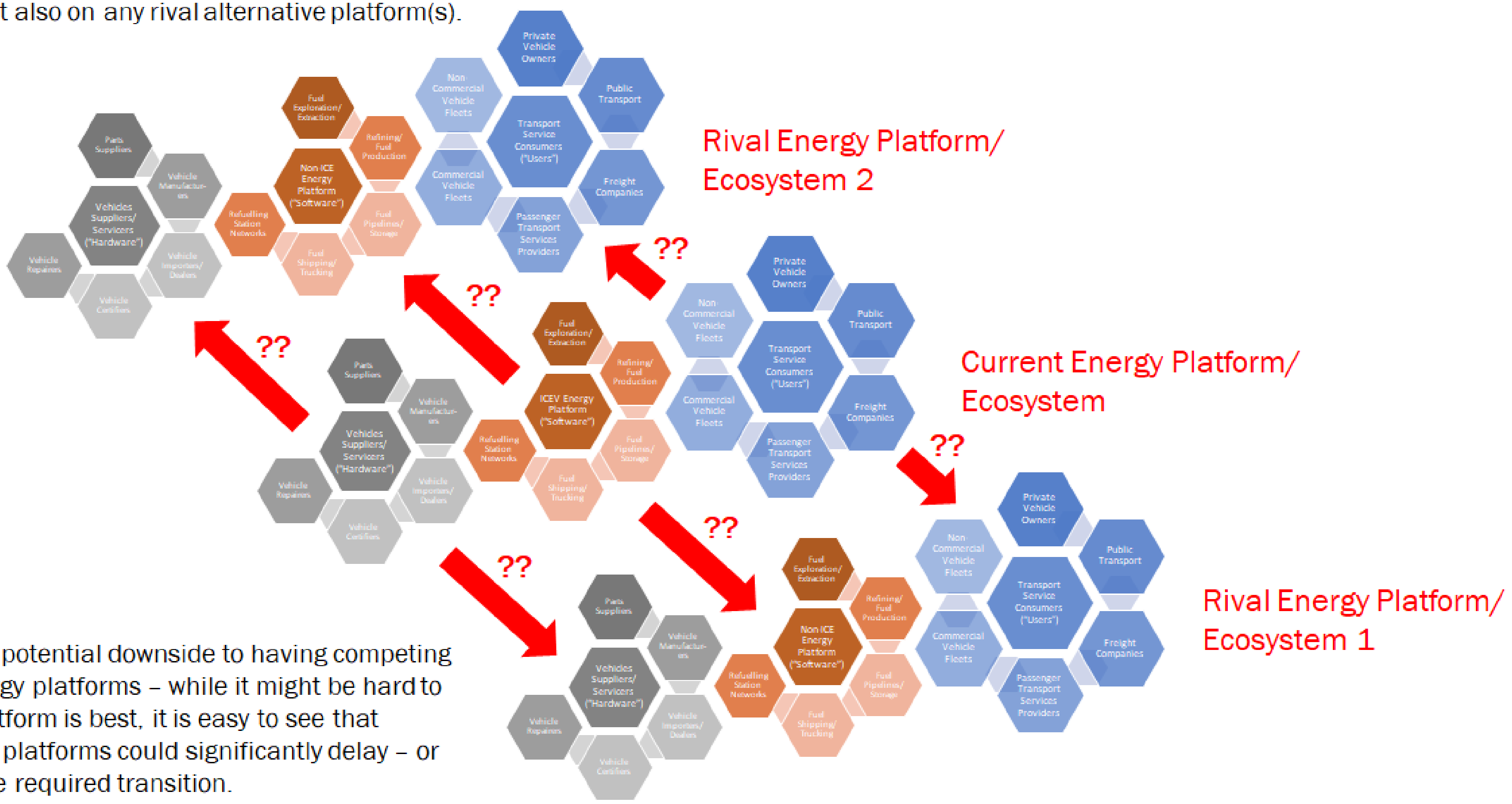


This points to a potential linchpin role for current vehicle suppliers/ servicers and energy platform providers, if repurposing existing supply chains and infrastructures is more efficient than producing new, competing ones.

Figure 2.5 (cont'd) – The Challenges of Transitioning from the ICEV Energy Platform to One or More Low-Emissions Alternative Platforms

If the transition to a low-emissions transport system involves competing alternatives to the ICEV energy platform:

- Consumers, suppliers/servicers, and energy platform providers face an even greater coordination challenge – needing to choose not just if and when to migrate, but also to which alternative energy platform; and
- New suppliers/servicers and energy platform providers need to successfully compete not just against rivals on the existing ICEV energy platform, but also on any rival alternative platform(s).



This points to a potential downside to having competing alternative energy platforms – while it might be hard to know which platform is best, it is easy to see that competing rival platforms could significantly delay – or even deter – the required transition.

78. Recognising the transition to net-zero emissions to be a transition from an existing energy platform to one or more alternative energy platforms highlights the significant complications this entails. There are therefore important questions to be addressed in ensuring the transition to a low emissions economy progresses in a timely, efficient and equitable way:

   78.1. If these were not relevant considerations, the messy process of “competition for the market” could be left to be played out as it will, potentially over decades;

   78.2. If they are relevant, however, policymakers and other key decision-makers have potentially critical roles to play in facilitating a timely, efficient, equitable and orderly transition.

3. Key Lessons from Major Historical Transport Technology Transitions

Key points from this section (apologies in advance for any unintentional puns):

1. Major transport revolutions were driven by new technologies offering clear cost, time, speed, quality and convenience advantages over existing alternatives.
2. The revolutions were heavily path-dependent, including pushbacks and wrong turns, but also leg-ups and breakthroughs.
3. Large industrial concerns with vested interests in securing better transport services were often instrumental in making the substantial and risky investments needed to kick start transport revolutions.

3.1 Overview

79. This section highlights some key lessons from major historical transport technology transitions that can inform the transition to net-zero emissions.[14] These include the importance of path-dependencies – i.e. how irreversible past choices affect current choices. They also include lessons on how to resolve critical “chicken and egg” problems that arise when the uptake of new technologies by some parties hinges on decisions made by other parties, and highlight the importance of standardisation.

80. Key historical transport revolutions are considered, especially in the UK. In particular this section considers the transitions:

80.1. From poor roads and animal-drawn vehicles to canals and barges at the time of the Industrial Revolution;

80.2. From canals to railways in the 19th century; and

80.3. From improved roads and horse-drawn carriages to motor vehicles around the turn of the 20th century.

[14] E.g. see sources like Standage (2021), Evans (1981), James (1890).

3.2 Summary of Selected Key Transport Transitions

From Roads to Canals

81. At the turn of the Industrial Revolution, roads were very poor due to lack of knowledge about road engineering. This made them unreliable (e.g. in poor weather) and of limited use in moving bulk materials or items. They also had uneven surfaces, making the unsuitable for moving fragile items such as china.

82. Many industrial concerns were located next to rivers, enabling them to use water wheels for power. With the advent of steam, factories could now be located near coal mines for fuel, away from rivers. This created a need for better transport options between factories and markets, not tied to natural water ways. Artificial canals were a solution, with locks to lift barges over rising terrain, though still requiring water access to operate the locks.

83. Bulk items could now be shipped not only quickly, but more cheaply. Since movement on canals was smooth, fragile items could be moved with fewer breakages. While canals freezing in winter or lacking water in summer reduced their reliability, they were not as vulnerable to bad weather as primitive roads (which could be rendered impassable when they became wet and muddy). Between 1750 and around 1820 canals were both spurred by the Industrial Revolution, and in turn boosted the revolution.

From Canals to Trains

84. Horse-drawn trains on wooden tracks soon became part of the canal ecosystem on privately-owned feeder lines – e.g. taking loads to and from sites that were not located directly on canals, where it was cheaper to use this solution than extending feeder canals. With the advent of steam power (initially for static, industrial purposes), and a transition to iron tracks, railways became a viable rival to canals. They not only offered lower costs and greater speeds, but also greater freedom to route lines in areas where canals were less feasible (e.g. due to steep terrain and/or lack of reliable water supply).

85. From the 1820s railways began to displace canals for all but the most bulky freight movements. While initially focused on moving raw materials and finished goods for industry, they quickly showed their value for mass public transport – offering affordable, comfortable, rapid, convenient and reliable transport options. This enabled rapid inter-city passenger transport, quickly displacing stage coaches.

86. Markets that had previously been regional were now national, or by being conveniently linked to ports with long-distance shipping, even global. Fresh produce or other time-sensitive goods (including the post, and newspapers) could be reliably transported nationwide. National sporting competitions could now be sustained due to improved passenger transport. Leisure activities such as cross-country day-trips were possible for the very first time.

87. Cities and towns on train routes boomed, and new towns were able to develop and flourish. For the first time in history, people no longer needed to live near where they worked. While inter-city rail caused the rapid decline of stage coaches, it caused a boom in intra-city horse and buggy (or horse-drawn tram and bus) travel services, servicing commuters from out of town. Ironically, this caused horse numbers in major cities to boom, leading to massive problems with traffic congestion and noise, as well as pollution and public health issues (due to horse manure, and the flies it attracted).

88. As for canals, the early commercial success of rail attracted large amounts of investment from investors wanting to take advantage of expected growth in services. This resulted in booms in railway construction, followed by busts.

From Horse Drawn Vehicles to Motor Vehicles

89. Early attempts at steam-driven road vehicles proved unsuccessful, due to issues such as noise, smoke, damage to roads, and the risk of boiler explosions. Not long afterwards, modern bicycles were developed. This allowed mass-market private vehicle ownership for the first time, since private ownership of horses and of horse-drawn carriages was typically only available to the affluent. Bicycles also offered speed and freedom to roam (not tied to train or tram/bus timetables or routes) at an affordable cost.

90. However, many roads were not smooth enough for comfortable bicycle rides, or were reserved for horses and carriages. Cyclists lobbied for better roading, and access to previously reserved roads, perhaps inadvertently helping to pave the way (literally and figuratively) for the advent of motor vehicles.

91. Technological breakthroughs in ICEV technology in the 1880s clearly played a pivotal role in the rise of the ICEV. But so too did key events demonstrating the superiority of ICEVs over alternative powered road transport. Ironically, just as BEVs are currently being touted as an alternative to ICEVs, they were a very real rival to ICEVs in the 1890s – even outselling ICEVs in America for a time. Steam-powered road vehicles were also making a come-back.

92. However, highly-publicised road transport competitions in France in the 1890s – seeking to determine which of these three technologies represented the successor to horses – anointed ICEVs as the winner. These competitions gained international attention, and helped to cement ICEVs as the leading technology platform for road transport:

92.1. Bertha Benz, the wife of the inventor of practical ICEVs, also played a key role, popularising Karl Benz's car by taking it on a long road-trip to demonstrate its practicality and benefits.

93. Just as trains were faster than canals, ICEVs were faster than trains, or simply offered unrivalled independence, and freedom to drive when and where their owners wanted. Likewise, early ICEVs were cheaper, faster, more reliable and/or more convenient than contemporary BEVs and steam-powered vehicle. For example, as now, early BEVs had more limited range and took longer to refuel than ICEVs. Consumers were quickly won over to ICEVs, just as they had earlier been to bicycles.

94. Initially motor vehicles were the preserve of the affluent. However, Henry Ford's strategy of mass producing standardised vehicles – the Model T – radically lowered vehicle costs, and powered private vehicle ownership was suddenly available to the masses. This transformed cities and landscapes, with unprecedented freedom for the masses to live, work and play with the assistance of affordable, fast and convenient private transport.

95. Table 3.1 summarises key features of these transitions. As an example of how successful new technologies were convincingly better than existing ones, consider:

> "In 1822 William James wrote: 'In comparison with navigable canals, generally speaking, articles may be moved by this improved [steam] engine system three times as fast, at one third the expense, and with the advance of only one-seventh the capital in the construction.'"[15]

96. Naturally none of these revolutions was without side-effects. Just as the explosion of horse populations spurred by inter-city rail led to problems like traffic congestion, noise and pollution, so too has the rise of private ICEV ownership over the 20th and early 21st centuries. This creates an imperative to transition yet again, to resolve the issues presented by current transport technologies – not least their contribution to GHG emissions. With foresight, it might be possible to moderate any adverse consequences of the next transition, as well as to maximise its benefits.

[15] Evans (1981, pp 16-17).

Table 3.1 – Comparing Features of Major Historical Transport Revolutions

	Initial Sponsors	Travel Costs, Times, Reliability and Comfort	Viable Routes	Mass Market Opportunities	Fuel Requirements
From primitive roads and animal-drawn wagons to canals	Industrialists needing to move bulk raw materials (coal, iron) or manufactures (china, etc). Investors subsequently.	Much improved, though affected by seasonal variation (e.g. canals freezing in winter, and lack of water in summer).	Limited by topography due to need for locks and access to reliable water supplies to use them (meaning competition with mills using water for power).	Shared passenger transport developed after initial industrial and commercial applications supported canal development.	Feed for horses and crews. Water to operate locks. Later, coal for steam-hauled or steam-driven barges.
From canals to railways	Industrialists needing to move bulk raw materials (coal, iron) or manufactures (china, etc). Investors subsequently.	Much improved, and less affected by seasonal variation. Improved further with advances in steam locomotion technology.	Much less restricted by topography and access to water. Development linked to coal supply meant fuel access was less a limitation.	Shared passenger transport developed after initial industrial and commercial applications supported railways development.	Coal and water for locomotives. Coal access assisted by railways developing near coal mines. Water requirements less than for canals.
From horse-drawn carriages on improved roads to automobiles: • Steam • Battery electric • Petrol	Enthusiasts, tinkerers, and would-be vehicle manufacturers.	All types of powered vehicle offered possible speed and travel time advantages. Steam suffered from less reliability and comfort, and petrol was initially less reliable than electric.	Limited by fuel access, and to roads with suitable surfaces (and which were not reserved to horses and carriages). Otherwise unlimited (i.e. by topography, or train timetables and rail routes).	Initially motor vehicles were the preserve of the wealthy, so mass market linked to motor buses and taxis (competing with trams). Private vehicle ownership enabled by mass production.	Steam vehicles limited by regular access to water. Electric vehicles limited by recharge times and access to electricity. Petrol vehicles able to exploit general availability as common solvent.

3.3 Path Dependencies

Transport Revolutions Never Occurred in a Vacuum

97. Transport revolutions never occurred in a vacuum. For example, the advent of rail in the UK – spurred by improvements in processes and materials that enabled viable steam power – occurred against the backdrop of existing transport alternatives:

> "Between 1760 and 1840 Britain passed from a state of local economies, with poor to middling transport, into a nation with the promise of a national railway system superimposed on a network of good canals and roads."[16]

98. Likewise, canals had to compete with existing roads and animal-powered vehicles, and both reflected and contributed to the industrial revolution.

99. In the same way, ICEVs competed with both shared transport platforms (buses, trams) and rival motor vehicle technologies (steam, and battery-electric). Furthermore, ICEVs benefitted from roading improvements and access achieved by predecessors, e.g. by:

    99.1. Napoleon, who had improved France's road network for military purposes – perhaps explaining why pivotal competitions in the 1890s to reveal the best technology for motor vehicles (steam, electric or petrol) occurred in France; and

    99.2. Cyclist lobby groups who campaigned for smoother roads and better road access.

Leapfrogging

100. The latter is also perhaps an example of "leapfrogging". By improving roads and road access, cyclists paved the way for being eclipsed by motor vehicles.

101. Ironically, if BEV or H_2V technologies are successful in providing lightweight, energy dense, and easily-refuelled vehicles, it is not hard to imagine that the associated breakthroughs might spur a truly revolutionary transition in transport – to affordable and reliable, personalised flight (e.g. electric vertical take-off and landing vehicles, or eVTOLVs):[17]

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[16] Evans (1981, p. 1).

[17] E.g. see https://www.theguardian.com/environment/2021/oct/25/could-flying-electric-air-taxis-help-fix-urban-transportation. Such a revolution would likely hinge on breakthroughs in associated technologies such as autonomous navigation and collision avoidance.

101.1. Whereas BEVs and H_2Vs do not inherently revolutionise land-based transport except in relation to emissions (they face the same congestion, travel times, regulated top speeds, etc), affordable personalised flight would truly represent a transport revolution – though a revolution likely to complement rather than completely displace land-based transport.

102. Hence, breakthroughs in powering clean land-based transport might pave the way for the initial application of those technologies (BEVs and H_2Vs) to be leapfrogged by more radical applications.

Pushbacks

103. Because transport revolutions always occurred against the backdrop of existing alternatives, it is no surprise that the owners and operators of existing technologies were sometimes active – at other times insufficiently so – to protect their own investments in the face of disruption.

104. For example, steam wagons were banned from London roads in the 1840s, and the UK's 1865 red flag law was similarly a way for railway and stage coach companies to prevent competition from steam vehicles on the road. It required any locomotive working on a highway to have a crew of three, with one walking at least 60 yards ahead to warn other road users that the vehicle was approaching:

104.1. This perhaps helps to explain why ICEVs were instead invented in Germany (by Daimler and Benz), and popularised in France (with its good roads dating back to Napoleon);

104.2. It points to a possible hazard of "swimming against the tide" – namely, being late to adopt welfare-enhancing innovations.

105. Similarly, 19th century canal owners in the U.S. attempted to have taxes levied on railways to help fund their own networks, while impeding the development of railways. Bus operators in 1920s New Zealand had to charge fares that were required by regulation to be higher than for trams, as a way to protect tramlines:

> "Competition by motor-buses is a problem that is troubling tramway authorities the world over at the present time. … In 1926 relief came in the Motor-omnibus Traffic Act, 1926, which prohibited

the competition of buses with trams, except where the fare charged per section by buses is 2d. more than the tram fare."[18]

106. Conversely, rail operators sometimes bought up canals in order to reduce their service levels, thus making rail operations more competitive. Sometimes such rail operators simply repurposed canals by emptying them and using them as a route to lay tracks.

Wrong Turns

107. The path-dependent route to new transport technologies also includes various wrong turns, even if judged with the benefit of hindsight. For example, New Zealand – like other former British colonies – inherited the UK's system of driving on the left of the road. This continues to limit the pool of new and used right-hand drive vehicles that can be purchased – causing the country to be heavily reliant on imports of used Japanese vehicles to update its fleet:

107.1. By contrast, countries like the U.S. opted early on to drive on the right of the road, as is also the case in much of Europe, as a consequence of Napoleon exporting this rule in the early 19th century.

108. A more telling example was the development of canals in the UK. Each canal was privately owned and operated, and although canals might link up with others, this occurred without standardisation of depths and widths, or systems for organising and pricing conveyance along sequences of canals:

108.1. Additionally, UK canals are typically narrow, limiting their ability to use larger barges enjoying economies of scale which could have improved their economics when confronted with competition by rail.

109. An example of a turn that had both virtues as well as costs was the UK's decision to standardise rail gauges in the mid-19th century. While this had the clear advantage of meaning that rail lines operated by different owners could inter-connect (unlike the case for canals), the particular gauge chosen is arguably inferior:

109.1. The famous engineer Brunel had constructed a line with a much wider gauge than that mandated, resulting in extremely comfortable and stable rides, but his gauge was not able to be used when the lower standard had been adopted.

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[18] *New Zealand Official Yearbook 1933*, available at www.stats.govt.nz.

110. An inadvertent wrong turn involved the introduction of alcohol taxes in the U.S. to finance the country's civil war. At the time ethanol made from plant materials was used for clean-burning lighting. The alcohol tax caused a switch to burning kerosene refined from fossil fuel oil:

110.1. Bioethanol as a biofuel is unlikely to be viable at scale for all ICEV applications, due to the pressure it puts on land use, with associated issues of sustainability and pressure on food prices;

110.2. Rather, the issue is that petrol was a by-product of using oil to make kerosene, and was widely available as a low-cost solvent in U.S. general stores:

110.2.1. This meant ICEVs enjoyed the head start of a ready-made refuelling network at a time when the technology was vying for ascendancy against early BEVs (which did not enjoy as established a refuelling network);

110.2.2. The history of motor transport may have been quite different had ICEVs not enjoyed range and refuelling time advantages over BEVs at a critical juncture in the technology's development.

111. The evolution of ICEVs has raised the bar for any new transport technology that wishes to displace it. As well as offering range and refuelling time advantages over rival technologies, consumer preferences have shifted towards both safer and larger private motor vehicles (e.g. SUVs and utes):

111.1. Cleaner technologies like BEVs are most cost-effective for smaller and lighter applications – such as for powered bicycles, and smaller vehicles;

111.2. However, unless they have dedicated lanes, such smaller vehicles have to coexist with an existing stock of larger and heavier ICEVs, placing them at a safety disadvantage needing to be weighed against their other benefits when consumers consider adopting them.

112. If consumer preferences for smaller vehicles had persisted, that might have assisted with transitioning to smaller and lighter BEVs.

113. Finally, and perhaps ironically, it is not necessarily socially-undesirable for wrong turns to have been taken, at least for current generations.[19] For example, when railroads were built in the 19th century, they were effectively overbuilt due to future competition from motor vehicles not being anticipated:

113.1. This means that when motor vehicles became viable in the early 20th century, they had to vie with an already strong – arguably over-strong – railway competitor;

113.2. As a consequence, motor vehicles had to be sufficiently more efficient than trains in order to secure market share.

114. Current members of society enjoy higher welfare than they would have had the earlier rail investors had perfect foresight and anticipated road-based competition (at the expense of forbears who overinvested in rail due to their myopia).[20]

Leg-Ups and Breakthroughs

115. It has already been mentioned that ICEVs have enjoyed certain leg-ups:

115.1. They enjoyed access to better quality roads partly as a result of early lobbying by cyclists (and Napoleon's desire to have good roads for moving his army);

115.2. They also enjoyed access to a ready-made refuelling network in countries like the U.S. and Germany, where the fuel they needed was readily available at low cost from general stores and pharmacies respectively;[21] and

115.3. Being declared the winner of prominent competitions against steam-powered vehicles and BEVs helped to cement ICEVs in the minds of consumers and

[19] Meade and Grimes (2017).

[20] A similar example arises in relation to cinema. Marble-clad theatres built in the heyday of cinema would not likely have been built had VHS and DVD players – let alone streaming – been anticipated. While many such theatres no longer function as cinemas, they are often high-quality structures suitable for alternative contemporary uses. Current generations would not have the benefit of those uses had previous generations realised how much they were over-investing at the time they were built.

[21] The latter was relied upon by Bertha Benz when she took her husband's invention on a long road-trip to demonstrate its practicality and benefits. She planned her route to ensure she had access to pharmacies at which she could refuel.

suppliers as the leading option for those wishing to move on from horse-drawn road transport.

116. Major technology breakthroughs also clearly played a role, such as the development of practical ICEVs by Benz in 1886. But the rise of ICEVs owned by the mass market also depended on breakthroughs in both production techniques and business models:

116.1. Ford established the mass-market for privately-owned ICEVs through standardisation, mass production, and learning by doing, all of which meant quality vehicles could be produced affordably;[22]

116.2. General Motors built on Ford's breakthrough by using business innovations like financing to assist car buyers with vehicle purchases, differentiating cars through styling and quality ladders, and constantly updating vehicle ranges to entice consumers with changing offerings.

117. In terms of reducing the environmental impacts of ICEVs, and creating a pathway for them to be replaced by BEVs:

117.1. The oil price shocks of the 1970s increased demand for smaller, more efficient vehicles – especially in the U.S. where large V8s had long been the norm – and resulted in the introduction of fuel efficiency standards; and

117.2. Breakthroughs in lithium ion battery technologies paved the way for a renewed interest in BEVs, aided by the fact that a certain tech entrepreneur with considerable resources chose to champion BEVs as a desirable, low-emissions, mass market alternative to ICEVs.

3.4 Importance of Standardisation

118. It was mentioned above that UK canal owners had failed to standardise their canals, and to provide canal users with end-to-end solutions such as timetables and fares for inter-canal transport. Conversely, UK rail track gauges were standardised in the mid-19th century, paving the way for interoperability between separately owned rail lines:

[22] Standage (2021) notes that each doubling of Ford's Model T cumulative production was reported to have resulted in a 16% fall in manufacturing costs.

118.1. In fact, interoperability was further assisted through ownership consolidations and interoperability agreements – including timetable coordination and fare sharing for tickets sold across multiple lines – allowing consumers to be sold end-to-end solutions;

118.2. As well as track gauge standardisation, the UK also standardised national time keeping. This further assisted with the development of train timetables.

119. These are but a few examples of how failing to standardise can leave a transport platform at peril of being disrupted by a superior alternative. This is especially the case if that alternative enjoys the benefits of standardisation.

3.5 Roles of Vested Interests

120. It was mentioned above that the owners of existing transport technologies often sought to head off competition from rival technologies:

120.1. One way was to improve their own offerings – an example of the so-called "sailing ship effect", referencing how sailing ship manufacturers improved their ships to defend their position against the advent of steamships;[23]

120.2. Another was to use regulation, taxation or other means to disadvantage rivals.[24]

121. However, vested interests also played a significant positive role in the advent of new transport technologies. One of the important themes highlighted in Section 3.2 was that major new transport technologies were initially developed by parties – mainly industrialists – that had no inherent interest in building or owning transport infrastructures. Instead, they needed such infrastructures to support and develop their existing interests in things like coal mining and manufacturing:[25]

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[23] Evans (1981) reports similar responses by canal owners to the threat of rail. They reacted to impending rail disruption by increasing barge speeds, using steam for hauling canal boats (rail/canal hybrids) and also for propulsion.

[24] It is also worth mentioning that while New Zealand tram operators in the 1920s sought to impede the migration from trams to buses through regulation that forced buses to set fares uncompetitively, they also began investing in their own bus fleets (perhaps seeing the writing on the wall for trams).

[25] Another example is Thomas Edison investing in electricity generation capacity and distribution networks in order to sell more lightbulbs.

121.1. The value they secured from developing and owning new transport technologies was primarily related to how those technologies lowered their production costs (including through better access to labour), and created new product markets;

121.2. Passenger services often developed as an adjunct to freight services, and only when these new technologies proved profitable in their own right did investors choose to also build networks based around the new technologies (often in crazes, resulting in booms and then busts).

122. Such major vested interests not only secured major benefits from new transport technologies. They also had considerable resources – including technical expertise as well as capital (not to mention useful political connections) – which enabled them to spearhead new technologies by undertaking the major investments needed to give them momentum:

122.1. We can see this afresh with major BEV manufacturers like Tesla and Ford in the U.S. rolling out recharging networks for their vehicle owners,[26] and Chinese BEV manufacturers offering battery swapout networks.[27]

123. We also see it in New Zealand's own hydrogen pioneers (see Figure 3.1 for examples), which include parties that have existing interests in:[28]

123.1. Energy production (Meridian/Contact, Tuaropaki Trust, Refining NZ) or chemicals production (Ballance Agri-Nutrients/Hiringa joint venture) – benefitting by expanding their businesses through offering clean hydrogen production;

123.2. Major transport service users (Ports of Auckland) – benefitting by accessing better transport services; and

123.3. Existing fossil fuel transmission/storage and/or distribution networks (e.g. Waitomo, First Gas – as partners to the Balance Agri-Nutrients/Hiringa joint venture) – benefitting by finding new opportunities to use their networks, especially when facing declines in the use of their networks for fossil fuels.

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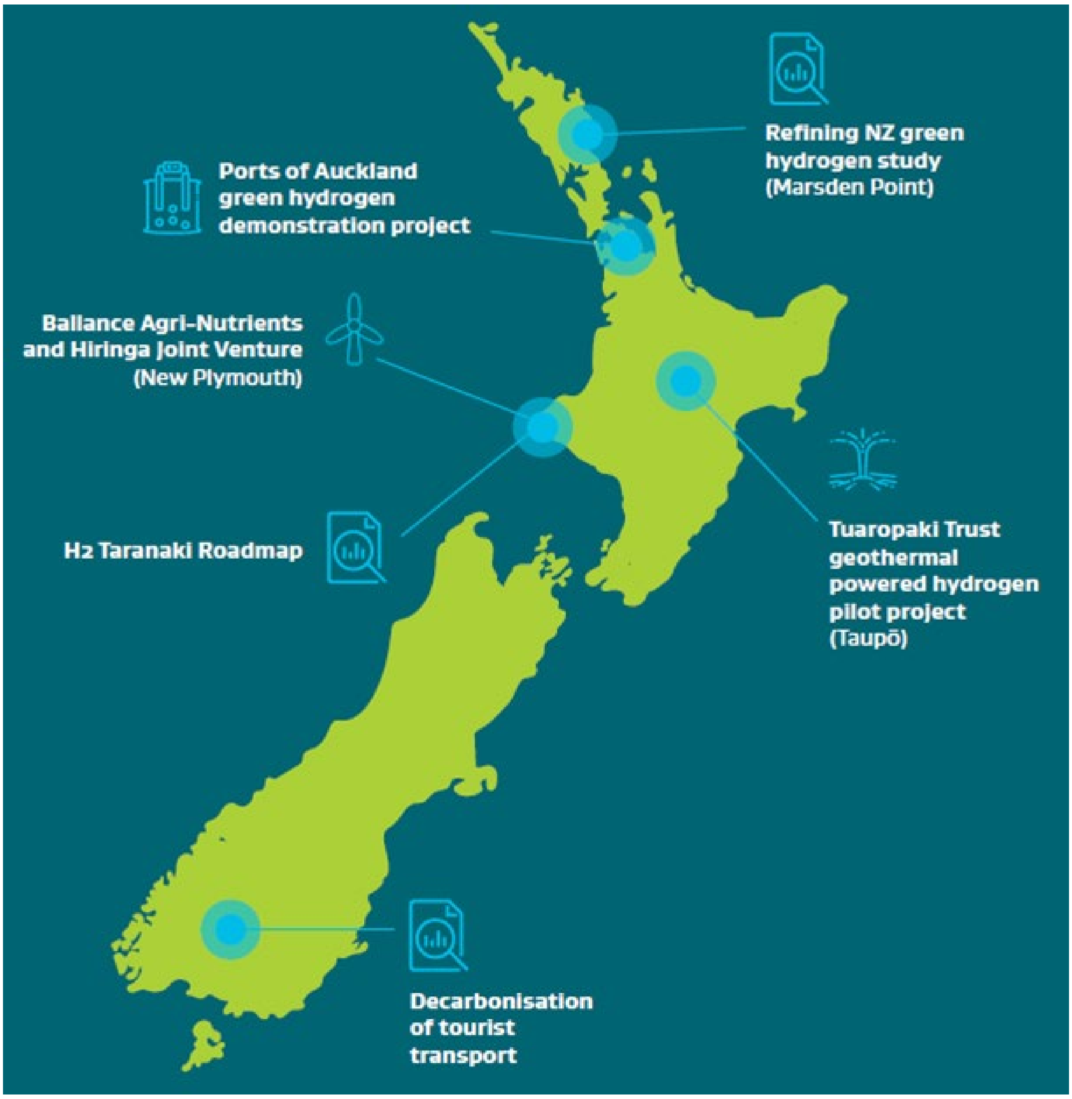
[26] Ford is offering its all-electric vehicle customers North America's largest electric vehicle public charging network, with more than 12,000 places to charge, including fast charging, and more than 35,000 charge plugs – more than any other automotive manufacturer, addressing a big concern for those switching to all-electric cars (https://corporate.ford.com/articles/sustainability/north-americas-largest-electric-vehicle-charging-network.html).

[27] https://energypost.eu/energy-conversion-for-hydrogen-cars-is-only-half-that-for-bevs/.

[28] E.g. see MBIE (2019) Figure 1, or https://www.southerngreenhydrogen.co.nz/.

Figure 3.1 – Some Hydrogen Initiatives in New Zealand



Source: Adapted from MBIE (2021), Figure 1.

124. Companies like these can potentially secure sufficient private benefit from developing new technology platforms that they find it profitable to invest in them, even if initially for their private benefit only:

124.1. Because such networks feature potentially substantial scale economies and network effects, these investments represent foundations for much greater network expansion should their initial investments prove successful, and additional use cases be developed (economies of scope).

125. Importantly, investments by such vested interests can help to resolve the "chicken and egg" problem that often plagues the development of new technology infrastructures:

125.1. Where "merchant" investors are being relied upon to invest in such infrastructures, they are naturally reluctant to do so without a clear expectation that enough customers will be prepared to pay to use their infrastructures that they can make a commercial return on their investment;[29]

125.2. However, in turn, potential users of new infrastructures will be reluctant to make the large investments they might need to use them (e.g. making costly investments in hardware that might only work on the new infrastructure) unless they know that infrastructure will materialise, in part hinging on other users also making the same commitments.

126. By vested interests finding it in their own self-interest to make the necessary investments, this makes it clear that the infrastructure will be provided, the only question then being to what degree:

126.1. This pre-commitment then provides the surety needed for other parties to make the investments required to accelerate the networks' uptake.

127. Relatedly, municipalities have also been instrumental in adopting key new technologies. For example, U.S. municipalities with large industrial bases were significant adopters of steam fire engines in the 19th century, since this helped to protect an important source of municipal funding (industrial ratepayers, and their ratepaying, high-income employees).[30]

128. Cooperative organisations are a similar example – with potential users of a new technology clubbing together to jointly fund and develop it, not so much on the basis that it provides commercial returns as a standalone investment, but because it enables them to secure benefits as consumers of the new technology in situations where commercial providers find it unprofitable to invest:[31]

128.1. The development of electricity, telecommunications and water infrastructures in less-densely populated (e.g. rural) areas are important historical examples;

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[29] Exceptions clearly arise. Major industrial concerns in Australia have announced plans to invest in large-scale green and blue hydrogen production, building on the country's existing platform as a global supplier of natural gas. E.g. see https://www.smh.com.au/business/companies/fortescue-s-forrest-takes-one-small-step-in-a-nine-year-hydrogen-moonshot-20211008-p58ykb.html.

[30] Falaris et al. (2018).

[31] Meade (2021a) discusses the role of consumer cooperatives in accelerating the uptake of distributed renewable energy.

128.2. The development of infrastructures by iwi organisations on behalf of their members is another – e.g. wireless broadband developed by Tuhoe for its tribal members in remote areas.

129. As above, vested interests such as these can play a critical role in accelerating the development of new infrastructures, since they benefit from the infrastructures in ways beyond simply charging others for using them:

129.1. Depending on the objectives of those vested interests, they can also develop new infrastructures for reasons beyond just monetary motives, recognising they need to be financially viable though to survive (e.g. as is the case for cooperatives and municipalities).

130. Where the self-interest (possibly altruistic) of vested interests is insufficient to induce them to develop new infrastructures, other support measures such as government subsidies and other incentives (e.g. BEV access to transit lanes for faster travel) can also play a key role in resolving the chicken and egg problem and inducing development:[32]

130.1. In the case of BEVs, subsidising vehicles can have direct and indirect benefits – making BEVs cheaper induces greater BEV uptake, which improves the profitability of investing in recharging networks, in turn leading to better recharging networks and hence further BEV uptake.[33]

3.6 Conclusions from Selected Historical Transitions

131. New technologies do not necessarily have to be better than existing ones to induce their adoption. It can be sufficient that they simply offer a better price-quality point – e.g. are sufficiently cheaper, despite having even lower quality. Alternatively, it can be sufficient that they simply meet the preferences of certain users better than existing alternatives:[34]

131.1. This is important for the current state of low-emissions transport alternatives to ICEVs, since they are currently more expensive, and not clearly superior in other key dimensions (except potentially for emissions, depending on how clean their fuel is).

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[32] Hu and Green (2011) examine the uptake of alternative fuel (e.g. CNG, LPG) ICEVs in a range of countries, and discuss the importance of support measures in inducing uptake.

[33] Yu et al. (2016).

[34] Stoneman (2018). A possible example is digital photography in its early days. Image quality was not superior to that of mature optical film technology, but it was much more convenient, and had a much lower cost per image.

132. That said, uptake drivers include very compelling benefits to users, not just marginal benefits, relative to existing options – e.g.:

132.1. Manufacturers – cost and shipping time savings, greater locational flexibility, greater reliability and quality, and increased access to input/output markets (including totally new markets); and

132.2. Travellers – travel cost and travel time savings for passengers, greater convenience and reliability, greater freedom/autonomy, and possibility of private vehicle ownership (previously the preserve of the affluent).

133. A key enabler of such user benefits being realised is access to the underlying technology platforms – often literal networks – requiring large investments:

133.1. Vested interests with the resources, capabilities and self-interest needed to develop new infrastructures have often been instrumental in spearheading this critical aspect of transitioning to new technologies;

133.2. Conversely, the owners of existing infrastructures can have incentives to frustrate transitions to new ones, at least until they win by making the transition themselves.

4. Quirks of Platform Competition and Technology Transitions

Key points from this section:

1. Technology transitions are inherently dynamic, which makes them hard to predict and often messy.
2. Platform competition – or competition "for the market" (i.e. to be the dominant technology) in the presence of network effects – can be particularly intense, and often leads to markets "tipping" so that only one/few platforms remain. Despite the usual presumption that competition is better for consumers, such tipping can in fact be best for both consumer and social welfare.
3. However, there is no guarantee that platform competition – of itself – will deliver socially-preferred outcomes. "Excess inertia" can mean inferior platforms become locked in despite better platforms being available.

4.1 Overview

134. This section builds on the contextualising and framing of the net-zero transition provided in Section 2, and the review of key historical transport revolutions in Section 3. It does so by setting out the key features of major technology transitions more generally, and the issues attaching to transitions involving network effects more specifically.

135. It then focuses on some of the possible pitfalls and challenges presented by competition between energy platforms that feature network effects, and provides some illustrations highlighting key policy considerations in achieving a timely, efficient and equitable transition to net-zero (as in earlier sections, using passenger transport as a motivating example). This then provides a foundation for the application of these ideas to New Zealand's net-zero transition, in transport, heating/cooking and process heat.

4.2 Features of Technology Transitions

Dynamics, and the Familiar S-Shaped Uptake Curve

136. Technology diffusion – or transition from one technology to another – is an inherently dynamic process. We never start from one state of affairs, and then magically find ourself in another. Diffusion only makes sense when we introduce a time dimension:

136.1. Over some period of time – sometimes very quickly, other times over years or even decades – changes occur. New things happen, and old things die away.

137. It is common to think of technology diffusion in terms of the familiar S-shaped uptake curve, in which diffusion starts slowly, suddenly accelerates, and then ultimately peters out. However, as intuitive as that curve seems, it glosses over a great many mechanics, and the multiple factors that can contribute to whether a technology diffuses slowly or quickly, or even at all.

138. As emphasised in Section 2, transitions involve "very complex dynamics between consumers, vehicle manufacturers, and infrastructure providers …".[35] Indeed, diffusion dynamics reflect a combination of both technological and market forces:

> "[T]he composition of the industry's technology, the quality of the supporting technical infrastructure, and the industry's competitive dynamics combine to determine both the shape of the expansion path and the rate of expansion, and also affect the ability of competing platforms to replace it."[36]

139. However, diffusion also reflects regulatory factors, such as a regulator's explicit or unwitting attitude towards a new technology, as illustrated in Figure 4.1:

139.1. While a favourable regulatory attitude might enable rapid uptake, a less favourable attitude might delay it – shifting the position, and possibly the shape of the curve.

140. In fact regulation might affect uptake in other ways, for example by enabling regulated investors to socialise the costs and risks of their investment in new technologies across their entire customer base via regulated prices:[37]

140.1. Whether or not regulation intends this, it could accelerate investments in contexts where other investors would be unable to do this, and therefore invest later, less, or not at all;

140.2. An important insight is that even status quo regulation can be a choice about the nature and extent of new technology diffusion – the real question is whether it is a conscious choice, or the best choice.

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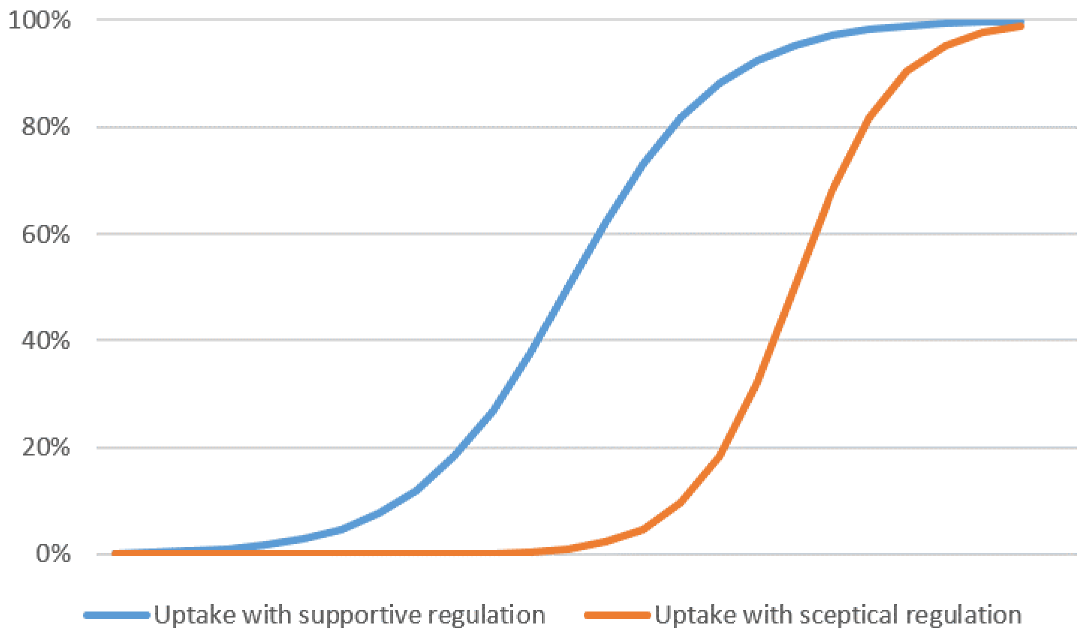
[35] Hu and Green (2011, p. 6399).

[36] Tassey (2016, p. 603).

[37] Some pros and cons of this are discussed in Meade (2018).

Figure 4.1 – Illustration of How Technology Diffusion Can be Affected by Regulation (Market Share Terms)



Source: Meade (2018), Figure 1.

141. User preferences towards existing and new technologies are clearly also fundamental to if, how and when new technologies are adopted (either without migrating from existing technologies, or displacing such technologies – as is likely in transitioning transport to net-zero emissions). Common explanations for S-shaped uptake curves include:[38]

141.1. Users adopting new technologies when they learn about them and their benefits (e.g. by word of mouth – peer effects – or from other sources);

141.2. Different users adopting new technologies at different stages reflecting when new technologies are sufficiently desirable based on users' differing preferences (and circumstances – e.g. ability to afford the new technologies, or their existing vehicles/appliances reaching the end of their useful lives); and

141.3. Users' adoption decisions depending on the adoption decisions of others – either positively ("bandwagon effects") or negatively ("snob effects") – see Table 4.1 below.

[38] Camerani et al. (2016).

Diffusion with Multiple Technologies

142. One of the many things that S-shaped diffusion curves can mask is the interaction between a new technology and either existing or other new technologies. Multiple technologies can interact in markedly different ways, and in ways that change over time, or as a function of how each other technology is progressing. This means diffusion is not necessarily S-shaped.

143. Three important categories of interaction arise where technologies are:[39]

143.1. Substitutes/competitors – increasing diffusion of one technology undermines the other (potentially causing it to go into a "death spiral" – see Table 4.1 below):

143.1.1. As in Section 3, examples include rail and canals, and trains and inter-city stage coaches;[40]

143.2. Complements/symbiotic – increasing diffusion of one technology causes another technology to prosper, driving the simultaneous and earlier adoption of both (a "virtuous circle"):[41]

143.2.1. As in Section 3, this occurred when inter-city travel spurred by rail caused increased demand for intra-city horse-drawn buggy/tram/bus travel;

143.3. "Predator-prey" dynamics – where diffusion of one technology benefits the other, but diffusion of the other technology harms the former:[42]

143.3.1. As in Section 3, this occurred when the development of canals spurred demand for short-haul rail on canal feeder lines – ultimately leading to rail reaching the scale and maturity that made it a substitute for canals.

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[39] Pistorius and Utterback (1996), Stoneman (2018).

[40] Other examples include the decline of postal services and fax machines with the advent of email, and increasingly of fixed line telephony with the rise of ubiquitous mobile telephony.

[41] Stoneman and Kwon (1994).

[42] Predator-prey dynamics arise in nature – e.g. rising populations of rabbits cause an increase in the number of foxes, but as the fox population grows this can cause the rabbit population to collapse. This shrinks the fox population to the point where the rabbit population can once again take off …

From S-Shaped Curves to Switches Along Multiple Technology Trajectories

144. Recognising that transitions often involve multiple technologies, it can be helpful to think of technology transitions in terms of switches along different technology trajectories. Each trajectory shows how the cost and performance of any given technology evolves over time – as summarised by trajectories in cost-performance ratios:[43]

144.1. A declining cost-performance ratio means that a technology is improving – either its cost is falling, or its performance is rising.

145. In simple terms, we should expect users to migrate from inferior technologies to superior ones – i.e. to technologies with better cost-performance ratios:

145.1. This clearly sets aside the very real and significant coordination issues and other switching costs usually involved in switching from one technology to another (e.g. in the presence of scale economies or network effects), to which we return below.

146. Consider the example of transitioning from ICEVs to BEVs (an existing and relatively advanced low-emissions alternative), and then to H_2Vs (an emerging and relatively immature low-emissions alternative). Figure 4.2 illustrates this simple approach to characterising the transition across these transport technologies:

146.1. ICEVs are depicted as a mature technology which initially offers better cost-performance (i.e. a lower cost-performance ratio) than BEVs and H_2Vs;

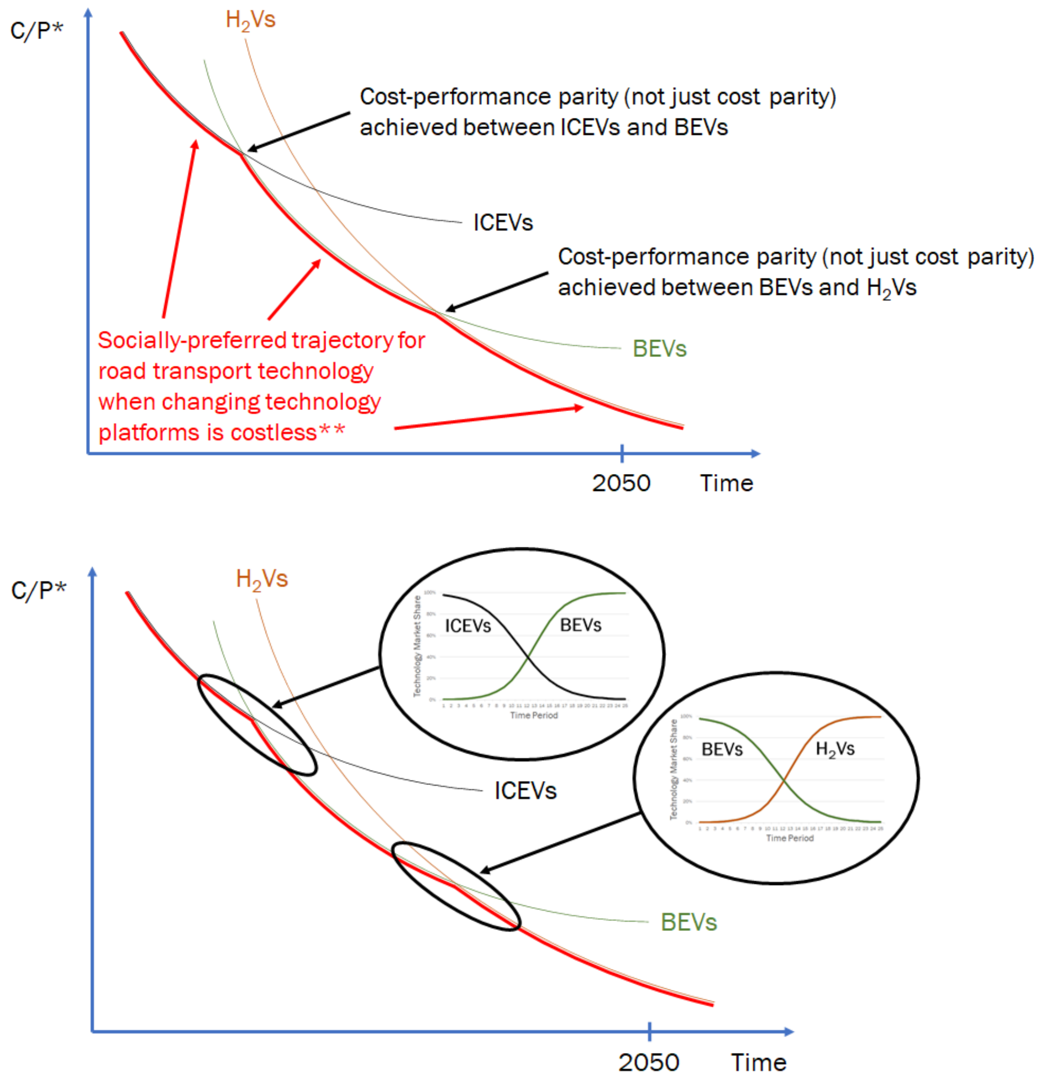
146.2. The illustration assumes that BEVs, as the next most mature technology, will over time be the technology that will have better cost-performance than ICEVs, and that H_2Vs will eventually offer better cost-performance than BEVs.

147. As above, ignoring the challenges in migrating from one technology platform to another, in simple terms the socially preferred technology trajectory is represented by the "envelope" along the lower side of each of these technology trajectory curves (as shown in red):

147.1. In other words, the socially-preferred trajectory changes from one technology to another once cost-performance parity – not just cost parity – is reached between an existing technology and its next best alternative;

[43] This discussion adapts Kalthaus (2019), which in turn adapts Durand (1992).

Figure 4.2 – Simple Representation of Transition Along ICEV, BEV and H_2V Technology Trajectories



* C/P = cost to performance ratio, accounting for transport technologies' non-environmental as well as environmental performance. ** Socially-optimal trajectory may differ from socially-preferred, depending on weights to be given to environmental and non-environmental performance.

147.2. As noted in the figure, the socially-preferred trajectory (i.e. that preferred by decision-makers pursuing their own interests) may or may not coincide with the socially-optimal trajectory (which may involve different weightings on cost of performance components to those attached by individual decision-makers).

148. Even in this simplistic case we should not expect immediate and total migration from any one energy platform to its next best alternative when that alternative becomes superior in cost-performance terms:

148.1. More likely we would observe some sort of uptake curve like the familiar S-shaped curve arising for the superior technology either side of the cost-performance parity points (and an inverted S-shaped curve in relation to the defunct technology, as users migrate away from it) – as also depicted in Figure 2.2;

148.2. This is because early adopters might face lower transition costs than others, and so begin migrating earlier. Conversely, some users might face particularly high transition costs, and so migrate later.[44]

149. More realistically, the costs of transitioning from one technology to another should also be taken into account. These include:

149.1. Direct switching costs – e.g. the costs of buying new hardware, or losing the benefits of existing investments; and

149.2. Network effects (indirect switching costs) – e.g. the costs and risks of coordinating transition decisions with other parties, such as the costs of transitioning to a new platform when others don't, with the benefits expected of that new platform then failing to materialise (e.g. due to unrealised scale economies or network effects).[45]

150. Figure 4.3 extends Figure 4.2 by including such transition costs. As above, the socially-preferred transition is the envelope showed in red. In this case, however:

150.1. Transitions do not occur as soon as cost-performance parity is reached between any given technology and its next best alternative;

150.2. Instead, the benefits of the new technology have to be at least as great as the costs incurred in making the transition from the current technology to the new one.

151. This means transitions occur later than they would if there were no transition costs. It also sheds light on the challenge of transitioning from ICEVs to either BEVs or H_2Vs:

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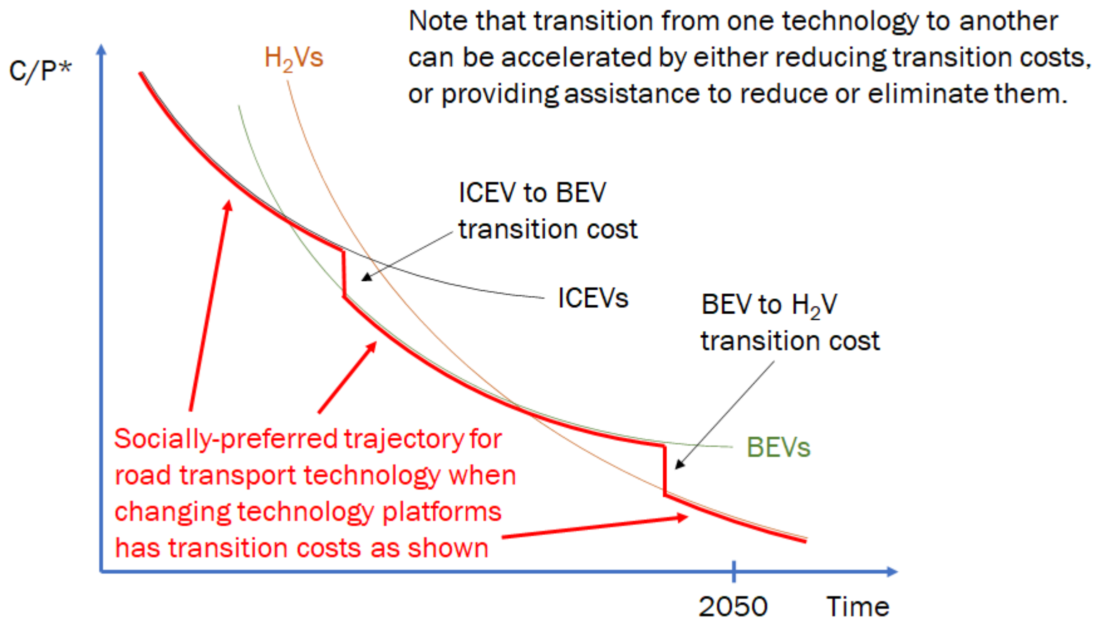
[44] More generally, different adopters should be expected to each have their own cost-performance curve, reflecting their specific preferences and circumstances when comparing technologies. This provides a more satisfactory explanation for why S-shaped diffusion curves – rather than immediate transition – can be imagined to arise at technology junctures (e.g. points of cost-performance parity). The framework presented in this section is a deliberate simplification to highlight key points without being overly complex.

[45] Switching costs and network effects are conceptually different, since only the latter involve users forming beliefs about other users' actions (Halaburda et al. (2020)).

Figure 4.3 – Transition Along ICEV, BEV and H_2V Technology Trajectories with Transition Costs



* C/P = cost to performance ratio, accounting for transport technologies' non-environmental as well as environmental performance

151.1. The new technologies cannot rely on simply achieving cost-performance parity to induce migration from existing technologies – they need to be materially better than existing technologies for this to occur (as was highlighted in Section 3) given the costs of making transitions from one platform to another.

152. This also points to areas of focus for accelerating uptake, or overcoming obstacles to transitioning from one technology to another, such as:

152.1. Reducing direct transition costs – e.g. through subsidies for buying new hardware or investing in new networks, or imposing emissions taxes;

152.2. Reducing indirect transition costs – e.g. de-risking users' decision to change technologies, such as by underwriting hardware purchases (e.g. buyback schemes), or improving coordination (e.g. mandating new technologies, or banning old ones); and

152.3. Directly changing the relative performance of technologies.

153. The latter might be achieved by:

153.1. Allowing BEVs to drive in bus/transit lanes – synthetically increasing their effective travel speed, and reducing travel time and congestion (at least until enough BEV users travel in the same lane); or

153.2. Banning ICEVs from multiple-passenger transit lanes – reducing their effective travel speed, and increasing their travel time and congestion (at least until enough ICEV users migrate to BEVs or H_2Vs).

154. These themes are returned to in Section 4.5 and Section 6.

155. Table 4.1 provides a quick snapshot of some of the features often arising in technology transitions. These features further explain why transitioning from one technology to another can be messy and hard to predict.

Visualising Technology Transition Pathways

156. To close out this sub-section, Figure 4.4 illustrates two different types of possible technology pathway:

156.1. The first – diffusion, adoption, or uptake – illustrates how new technologies often take hold over time. While not necessarily the case, the familiar S-shaped uptake curve depicts how adoption is often slow to take hold, then hits a phase of rapid adoption, and then ultimately takes a while to achieve full market penetration;

156.2. The second – representing the death spiral, anti-diffusion, or retrenchment – depicts how an existing technology might only slowly give ground to a new rival technology, but that this eventually can cause a runaway decline in that technology, though with a lingering tail of die-hards only eventually also abandoning it. An inverted S-shaped curve can be a convenient way to represent this transition.

157. The figure simplifies by representing diffusion or anti-diffusion in terms of market shares for a market of a given size:

157.1. In reality, the market size for a new technology might be either greater or smaller than the size of the market that the new technology is displacing, and there is no guarantee that new technologies will be adopted at the same rate that old technologies retrench.

Table 4.1 – Common Features of Technology Transitions

Feature	Description
Osborne effect	Consumers defer purchasing existing products in expectation that superior ones will soon be available (named after a computer manufacturer whose sales slumped after it prematurely announced an upcoming model)
Penguin effect[46]	Firms or consumers wait for others to be first to enter into a new area for fear of making a choice they then regret (like penguins not wanting to be first to dive into a sea in which predators might be lurking)
Sailing Ship effect[47]	Incumbent firms strategically improve their offerings when confronted with a potentially superior alternative, to delay or deter the alternative
Tipping[48]	The inclination for a market characterised by large economies of scale and/or strong network effects to end up with only one/few dominant alternative(s) despite starting with multiple competing alternatives
Matthew effect[49]	Related to tipping – larger or more successful alternatives prosper and dominate while smaller or less successful ones wither and die ("to every one who has will more be given, and he will have abundance; but from him who has not, even what he has will be taken away")[50]
Bandwagon and snob effects	Bandwagon effects refer to situations where consumers prefer to adopt a new technology when other users do (i.e. following the crowd). Snob effects refer to the opposite – some adopters may value prestige and exclusivity (e.g. adoption of high-cost new technologies as a signal of wealth, or only wanting to associate with an exclusive peer group). In this case mass adoption of a technology can cause such users to abandon it.
Vapourware	A product that is announced before it is available or even possible, often with the intention of convincing consumers to wait for the product rather than purchasing some rival product in the meanwhile and giving that rival product critical mass.

[46] E.g. see Weitzel et al. (2006).

[47] E.g. see Filatrella et al. (2021), Filatrella and De Liso (2020), Evans (1981).

[48] Discussed further in Section 4.3.

[49] E.g. see Pereira and Suárez (2018).

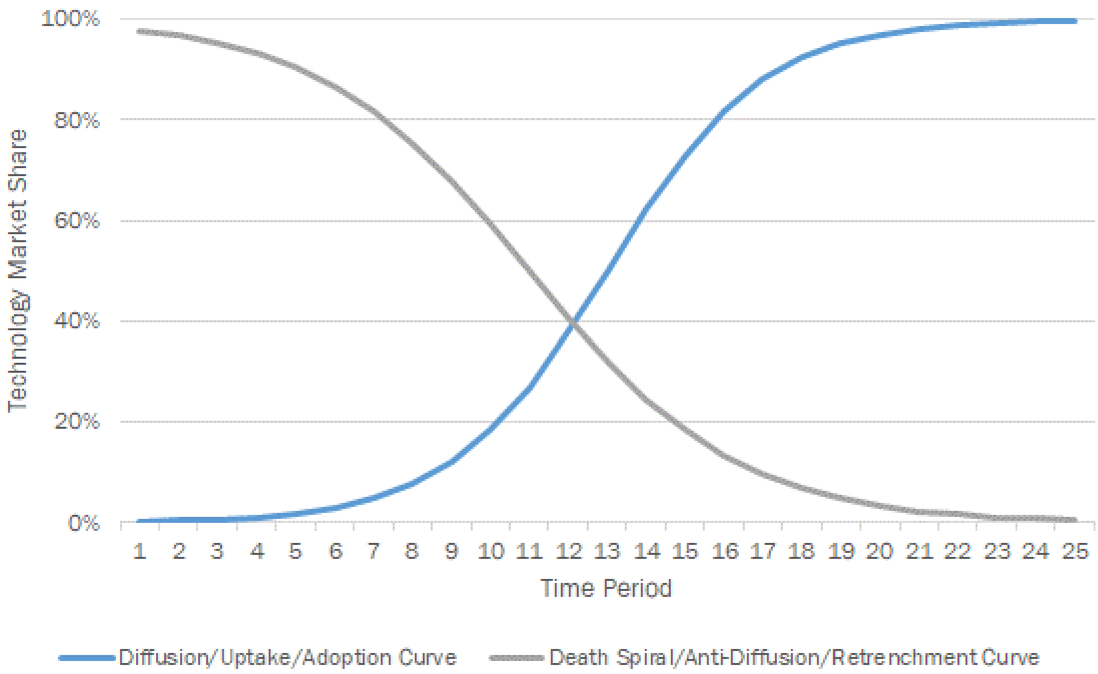
[50] Matthew 25:29, Revised Standard Version of the English translation of the Bible.

Table 4.1 (cont'd) – Common Features of Technology Transitions

Feature	Description
Network paradoxes	E.g. in transport networks, adding road capacity or new roads can result in persistent congestion and/or longer travel times (Downs-Thomson paradox, Pigou-Knight-Downs paradox, Braess paradox).[51] In electricity systems, adding additional transmission capacity can reduce overall capacity due to how electricity flows through different constrained network paths (Kirchoff's laws)
First-mover advantage	Being first mover in a new area can create an incumbency advantage not available to later movers (e.g. a dominant market share – a.k.a. Stackelberg leadership in markets featuring imperfect competition among few firms)
Path-dependence	Related to first-mover advantage – the best decisions that can be made now are constrained by hard-to-reverse choices that were made in the past
Second-mover advantage	Sometimes a first mover helps to establish a new area only for a later mover to then dominate that area
Death spiral	A scenario in which an existing technology platform experiences user losses when a rival technology becomes sufficiently attractive. As users defect, the costs of sustaining the existing technology (e.g. if it is a network with large fixed costs) are passed on to a shrinking user base, and those costs also rise due to diseconomies of scale being introduced. Service quality can also suffer (e.g. due to the network being unprofitable to maintain). If the technology features network effects, user defections further reduce the benefits of the existing technology to other users. Such rising costs and prices, and declining service quality and network benefits, accelerate defections, with the process becoming irreversible if a tipping point is reached. The existing platform then dies.
Chicken and egg problem	Before investors in new technology platforms commit to making large and irreversible (e.g. network) investments, they want to know that there will be sufficient users of their platform (i.e. consumers, or suppliers) to make the investment profitable. However, users are reluctant to commit to using a new platform (e.g. buying specialised hardware that is not valuable unless the platform attracts sufficient other users) before they know platform investments will be made. This kind of "mutual penguin effect" can forestall platform take-off.

[51] E.g. see Arnott and Small (1994).

Figure 4.4 – Illustrative Diffusion and Anti-Diffusion/Death Spiral Pathways



158. This is explored further in Section 4.5, in discussing how the transition to net-zero emissions in transport may or may not preserve the overall vehicle fleet size, and hence level of transport services.

4.3 Nature of Platform Competition

Complications Caused by Network Effects

159. Section 4.2 highlighted the various ways in which technology transitions can be messy and hard to predict. This can be the case even when technologies do not involve significant direct or indirect network effects (as described in Section 2.3) – i.e. decisions of platform users (suppliers or consumers) creating benefits or costs for other platform users. However, this section focuses on how network effects, in particular, affect competition between two or more platforms.[52]

160. One key theme is that network effects can be thought of as causing "dynamic increasing returns to scale". This represents a kind of "whiplash" effect in which platforms gaining sufficiently rapid uptake can find themselves rapidly able to offer increasingly better

[52] Katz and Shapiro (1994) remains a very useful summary.

services at falling cost. Conversely, those on the decline can experience the reverse. This is an expression of the Matthew effect described in Table 4.1.

161. Another theme is that a key driver of successful network take-off or decline is influencing platform user expectations about which platform or platforms are likely to succeed (and attract the most other users), as well as overcoming the "chicken and egg problems" and "penguin effects" described in Table 4.1.

Resolving Complications Caused by Network Effects

162. De-risking users' decisions to join a given platform is also important, such as:

162.1. Enabling them to lease new hardware instead of buying it; or

162.2. Through discounted initial platform pricing ("penetration pricing") to reward early adopters – this is more feasible where platforms are "proprietary" (i.e. jointly owned) rather than "open", since the platform owner can expect to better reap the future rewards of penetration pricing, making such pricing more worth their while.[53]

163. Resolving chicken and egg problems is also a key driver of uptake:

163.1. One way is through merchant platform investors (or vested interests who stand to gain from accessing platform services) making large, long-term and irreversible investments in platform-related infrastructures – i.e. in the platform technology itself (e.g. BEV recharging networks):

163.1.1. This can strongly influence uptake decisions by others, since it involves commitment to provide the infrastructure required to make those others' own investments safer bets;

163.2. Large investments in capacity for manufacturing any required hardware can also achieve this – e.g. investments in large, specialised BEV battery supplies.

164. Such investment commitment also serves to de-risk users' decisions to join a given platform (since they can have greater confidence that other users will join if there is greater certainty the platform will be there for them to join):

[53] Greaker and Midttømme (2016).

164.1. It can also serve to deter investments in rival platforms, which likewise supports uptake of the investor's platform.[54]

"Tipping" to Dominance by One or Only Few Platforms

165. Finally, another key theme is that platform competition often results in one or only few platforms dominating and all others withering – i.e. competition is subject to "tipping", to either monopoly, or to duopoly (two dominant firms) or other forms of oligopoly (i.e. a limited number of firms):[55]

> "It is not unusual for several competing technology platforms to emerge in the early phases of the technology life cycle. In these cases, multiple sets of potential market applications (innovations) are created and two or more platforms may reach commercialization and compete for a period of time. However, in most cases, a dominant platform eventually emerges and becomes the de facto standard."[56]

166. Platform competition – or "competition for the market", a.k.a. "standards wars" – can be particularly intense:

166.1. This is because rival platforms are effectively vying to become future monopolists, meaning the stakes to winning are especially high (which incentivises them to offer inducements to potential users in order to increase the odds of their platform ultimately dominating).[57]

167. Such tipping is more likely to occur when network effects are sufficiently strong.[58]

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[54] Markovich (2008), Lin et al. (2020).

[55] E.g. see Katz and Shapiro (1994), Economides et al. (2005), Weitzel et al. (2006), Dubé et al. (2010), Cabral (2011), Tassey (2016), Fatas-Villafranca et al. (2019), Halaburda et al. (2020), Amir et al. (2021), Ko and Shen (2021). Weitzel et al. (2006) and Fatas-Villafranca et al. (2019) also show when tipping does not occur. Tucker (2018) stresses that network effects do not guarantee tipping, but can lead to rapid instability (especially in digital platforms).

[56] Tassey (2016, p. 599).

[57] Katz and Shapiro (1994).

[58] E.g. see Economides et al. (2005), Dubé et al. (2010), Cabral (2011), Ko and Shen (2021). Weitzel et al. (2006) also point to network topology (e.g. density) as playing a role in whether tipping is to monopoly or oligopoly.

"Tipping" Can be Beneficial

168. However, despite the usual presumption that competition benefits consumers, some degree of tipping is often regarded as benefitting both consumers and social welfare:[59]

> "Although more than one technology platform can exist in the same industry, … achieving maximum economic efficiency usually requires that one come to dominate fairly early in the underlying technology life cycle. …
>
> Whichever technology platform becomes the 'standard', a set of assets (technology, capital, labor), and technical infrastructure will evolve based on it. As the technology's life cycle proceeds, more products based on the platform are created (economies of scope are realized) [i.e. a technology "ecosystem" evolves]."[60]

169. Likewise, the history and evolution of many network industries indicates that standards wars delay industry development, harming consumers and firms, and:

> "[A] single network is always preferable from a welfare perspective and often also from the firms' standpoint, in particular, when the viability of the industry itself is at stake."[61]

170. This means that while network effects incline platform competition towards tipping to having only one or few dominant platforms, this can in fact be welfare-enhancing:

    170.1. Conversely, prolonged standards wars, in which firms vie for dominance, can be harmful for welfare.

171. These considerations are relevant when thinking about the transition from the ICEV energy platform to either the BEV and/or H_2V (or some other) low-emissions energy platforms. Research on platform competition in the presence of network effects points to protracted standards wars potentially harming welfare. At the very least they should be expected to delay the transition to net-zero emissions.

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[59] Ko and Shen (2021) suggest that consumer welfare is highest when network effects are only moderate, in which case a single firm becomes dominant, but one or more smaller rivals remain (Android smartphones vs iPhones is a possible example of where this arises). This is relative to consumer welfare arising with weak network effects (in which many similar networks compete with each other), and with strong network effects (which result in outright monopoly).

[60] Tassey (2016, p. 601).

[61] Amir et al. (2021, p. 1205).

4.4 How Platform Competition Can Deliver Poor Results – Excess Inertia and "Lock-In"

Causes of Excess Inertia and Lock-In

172. While platform competition tipping to monopoly or oligopoly can be socially beneficial (e.g. compared to protracted standards wars), there is another way in which platform competition is not guaranteed to result in socially-desirable outcomes. Specifically, a common prediction of platform competition research is that such competition can result in "excess inertia" – i.e. "lock-in" to inferior technologies:[62]

> "A traditional concern in markets with network externalities is that the 'wrong' platform may dominate due to consumers' miscoordination."[63]

173. In particular, while new platforms may offer users higher quality than incumbent platforms, the latter benefit from consumers more easily believing that they will remain dominant in the future. Consumers might prefer the quality of the rival platform, but dislike the risk that if they migrate to the new platform, possibly incurring switching costs in doing so (e.g. incurring the costs of new hardware), insufficient other users will also migrate, meaning the rival platform does not achieve the scale required for it to fully offer its benefits:

> "[platform competition] models do indeed exhibit excess inertia; that is, users tend to stick with an established technology even when total surplus would be greater were they to adopt a new but incompatible technology. Today's consumers may be reluctant to adopt a new technology if they must bear the cost of the transition from one technology to the next, and if most of the benefits of switching will accrue to future users ..."[64]

174. Network effects being sufficiently strong also explains excess inertia. In that case simply having a strong initial market position can be sufficient to lead to monopoly.[65] Conversely, when network effects are moderate, inherent quality can play a greater role in determining which platform secures a monopoly.

175. Other explanations for lock-in include:

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[62] E.g. see Katz and Shapiro (1994), Economides et al. (2005), Weitzel et al. (2006), Brécard (2013), Onufrey and Bergek (2015), Greaker and Midttømme (2016), Krauthaus (2019), Filatrella and De Liso (2020), Halaburda et al. (2020), Amir et al. (2021).

[63] Halaburda et al. (2020, p. 3).

[64] Katz and Shapiro (1994, p. 108).

[65] Economides et al. (2005).

175.1. Randomness in technology breakthroughs – e.g. platforms with higher expected quality are more likely to be able to defend their market position, even if their realised quality turns out to be lower than that of their rivals;[66] and

175.2. Financing costs – if they are high, this can lead to underinvestment in superior technologies by potential disruptors.[67]

Lock-In to Polluting Technologies

176. It might be expected that a clean technology platform enjoying strong network effects might easily displace a polluting technology platform with weaker network effects. However, perhaps paradoxically, when a clean (polluting) technology has stronger network effects than a polluting (clean) one, this results in lower (higher) environmental quality for both technologies:[68]

176.1. Moreover, the clean technology can have less than the socially preferred quality and uptake, although this can be corrected with a tax comprising an ad valorem component, a pollution tax, and a subsidy for purchase of the clean technology.

177. Furthermore, taxing emissions should be expected to encourage the uptake of cleaner technologies, albeit they may need to be very high to overcome transition costs. However, mis-specified environmental taxes can also lead to excess inertia, locking in higher-polluting technologies:

177.1. This can arise, for example, when emissions charges are set to reflect just the cost of emissions' environmental damage, but fail to also account for network effects, and the effects of technology platforms being proprietary (i.e. owned by their sponsors);

177.2. Indeed, failure to implement the optimal tax can result in excess inertia, and if the clean network lacks a sponsor then the clean technology might never take hold (and even with a clean technology sponsor, the clean technology can end up with too low a market share).[69]

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[66] Halaburda et al. (2020), Filatrella et al. (2021).

[67] Filatrella and De Liso (2020).

[68] Brécard (2013).

[69] Greaker and Midttømme (2016).

178. Moreover, the optimal environmental tax in the presence of network effects should also reflect how competitively or otherwise the clean technology is provided. If the clean (polluting) technology is monopolistic and hence high pricing (competitive and hence low pricing), then a higher tax on the polluting technology is required to support the optimal transition to the clean technology, and vice versa:

> "Since the dirty durable has the entire market initially, a fully competitive dirty sector is a more fierce opponent to the clean sponsor than a monopolist trying to earn positive profits. The dirty car sponsor sets a positive price on the dirty good, and thus the dirty good tax can be lower."[70]

179. These are especially important considerations in thinking about how to transition from the ICEV energy platform to the BEV, H_2V or other lower-emissions platforms. If emissions prices fail to account for network effects and the relative competitiveness of different parts of the relevant energy platforms, then this could impede the transition to net-zero emissions in transport.

Platform Competition can also Feature Excess Momentum

180. Excess inertia locking in incumbent platforms is not always predicted, and clearly older platforms are often surpassed by newer, better ones. Also, some studies also point to the opposite possibility of "excess momentum":[71]

    180.1. In that case platform users too easily migrate to rival platforms. Anticipating this can make platform sponsors reluctant to make the investments or offer the uptake inducements (e.g. penetration pricing) required to achieve platform take-off, even if their platform technology is inherently superior.

181. More particularly:

> "The … argument for standardization processes [i.e. adopting a single technology/approach] is that the discrepancy between private (individual) and collective (network wide) gains leads to coordination problems … With incomplete information about other actors' preferences, *excess inertia* can occur, as no actor is willing to bear the disproportionate risk of being the first adopter of a standard and then becoming stranded in a small network if all others eventually decide in favor of another standard [i.e. the penguin effect]. This startup problem can prevent the adoption of any standard at all, even if it is preferred by everyone.

[70] Greaker and Midttømme (2016, p. 33).

[71] Katz and Shapiro (1994), Brocas (2003), Weitzel et al. (2006).

> "Conversely, *excess momentum* is a possible outcome, for example, if a sponsoring firm uses low prices during early periods of diffusion [i.e. penetration pricing] … In sponsored networks [i.e. networks owned by one or a group of its suppliers or users], the problem is attenuated since, for example, there is the possibility of internalizing the potential network gains by strategic inter-temporal pricing … There are private incentives to providing networks that can overcome inertia problems; however, they do not guarantee social optimality *per se*."[72]

When Excess Inertia Does Not Arise – Possible Policy Prescriptions

182. As above, excess momentum can arise when switching costs are low, or due to penetration pricing. Other situations in which excess inertia might not be expected to arise include:[73]

182.1. When all actors have complete information about each other's payoffs, and there is no installed base of users for an existing, inferior technology;

182.2. The most eager consumers adopt first, and entry decisions are irreversible (even if players have private information about their payoffs, and there is an incumbent technology with an installed base of consumers) – although uncoordinated adoption is only optimal as a limiting case; and

182.3. If network technologies are proprietary (i.e. owed by a technology sponsor).

183. The first of these three scenarios is implausible, and the second is not generally applicable. The third, however, points to a possible policy prescription – namely ensuring that platforms are proprietary (owned). In that case a wider range of uptake inducements is viable (e.g. penetration pricing):

183.1. Even in that case, however, the sponsor of a clean energy platform has incentives to skim the market (i.e. target high-value users);

183.2. The socially-preferable solution involves the clean technology dominating (i.e. being adopted by the mass-market), and an emissions tax that properly accounts for network effects and platform ownership, not just the environmental costs of emissions.

184. This possible policy prescription is explored further in Section 6.

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[72] Weitzel et al. (2006, p. 491).

[73] Greaker and Midttømme (2016).

4.5 Some Possibilities for the Transition to Net-Zero Emissions in Transport

185. This section is rounded out with some illustrations of the types of pathways we might observe in the transition to net-zero emissions in New Zealand motor transport. These are not predictions, but rather just illustrations of some of the possible pathways:

185.1. This helps to identify scenarios that are either to be preferred or avoided;

185.2. That in turn informs the sorts of policy levers New Zealand might care to deploy to achieve its preferred trajectory.

Excess Inertia Scenarios

186. Figures 4.5. and 4.6 illustrate two plausible scenarios involving excess inertia:

186.1. The first supposes that once BEVs have been adopted, the transition costs to H_2Vs are sufficiently great as to cause BEVs to be locked in even if H_2Vs offer better cost-performance;

186.2. The second supposes that the transition costs from ICEVs to either BEVs or H_2Vs is sufficient to cause lock-in to the ICEV energy platform, even when the alternative technologies are inherently superior in terms of cost-performance.

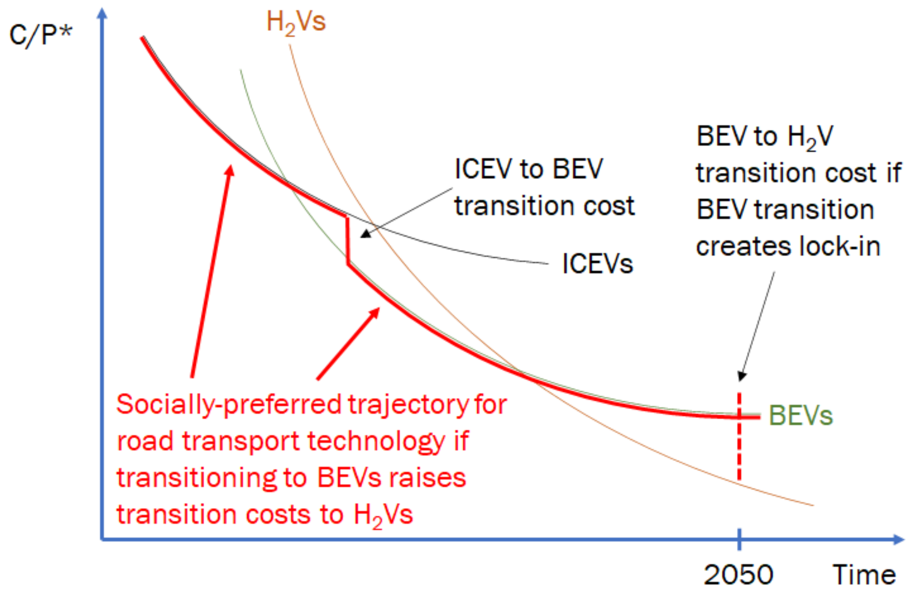
Leapfrogging and Bypass Scenarios

187. Figures 4.7 and 4.8 illustrate two other plausible scenarios in which certain technologies prove to have sufficiently good cost-performance that they cause one or more of BEVs and H_2Vs to never be socially-preferred:

187.1. The first involves BEVs being leapfrogged by H_2Vs;

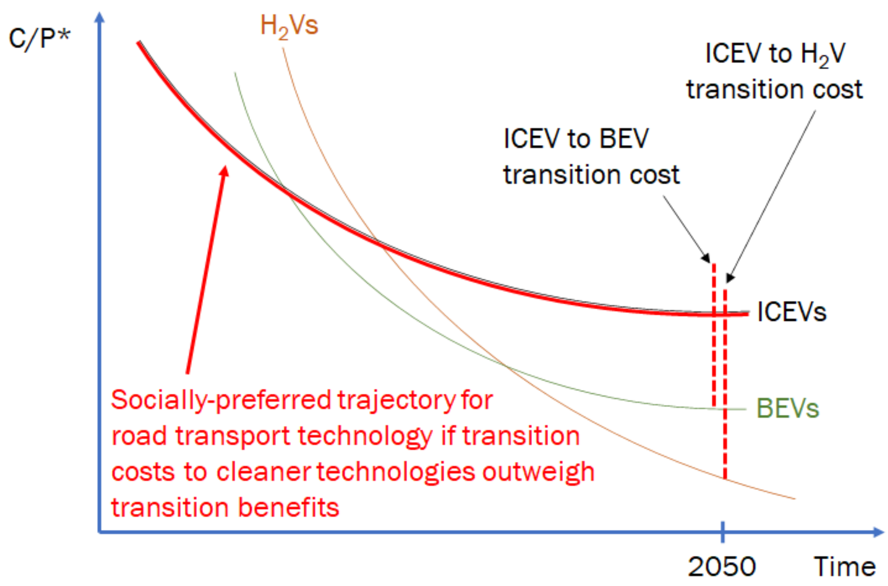
187.2. The second supposes hybrid vehicles are a “dark horse” that causes both BEVs and H_2Vs to be bypassed in the transition away from ICEVs.

Figure 4.5 – Lock-In to BEVs when H_2Vs Superior



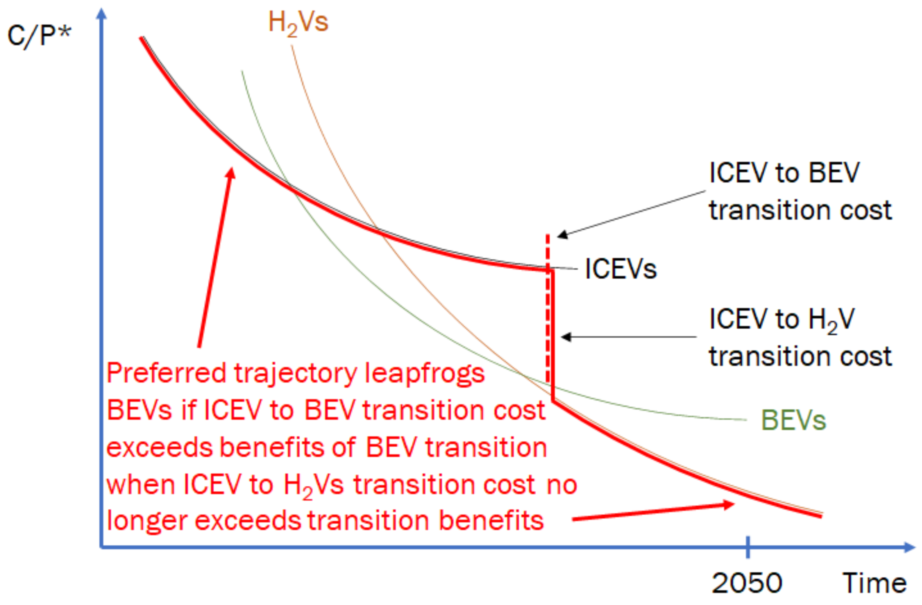
* C/P = cost to performance ratio, accounting for transport technologies' non-environmental as well as environmental performance

Figure 4.6 – Lock-In to ICEVs when BEVs and H_2Vs Both Superior



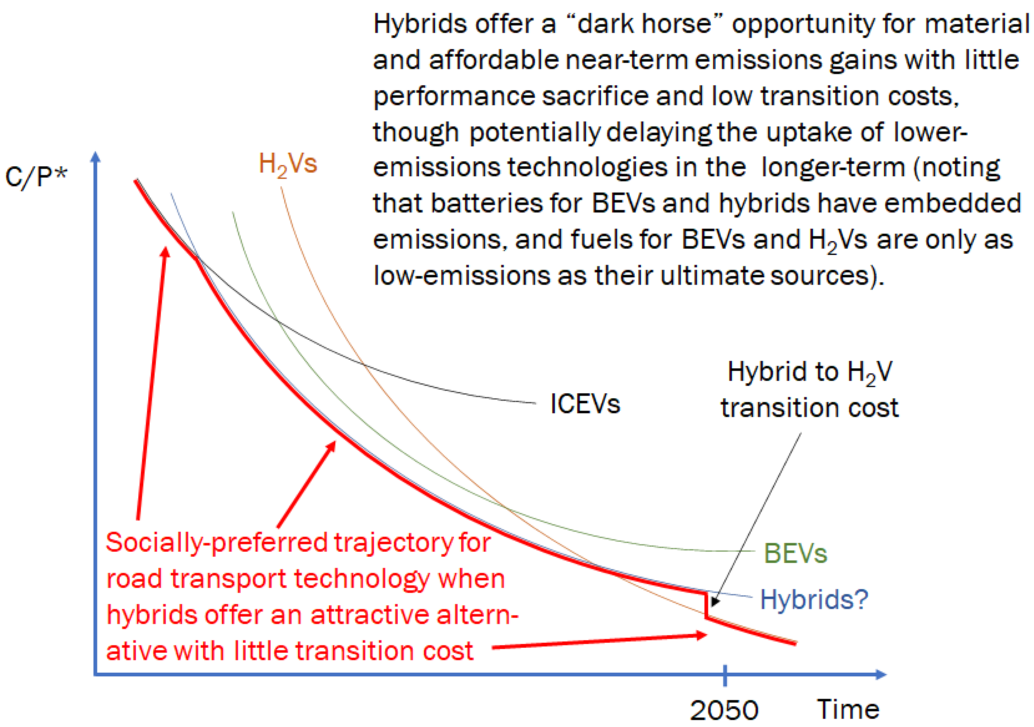
* C/P = cost to performance ratio, accounting for transport technologies' non-environmental as well as environmental performance

Figure 4.7 – BEVs Leapfrogged by H_2Vs



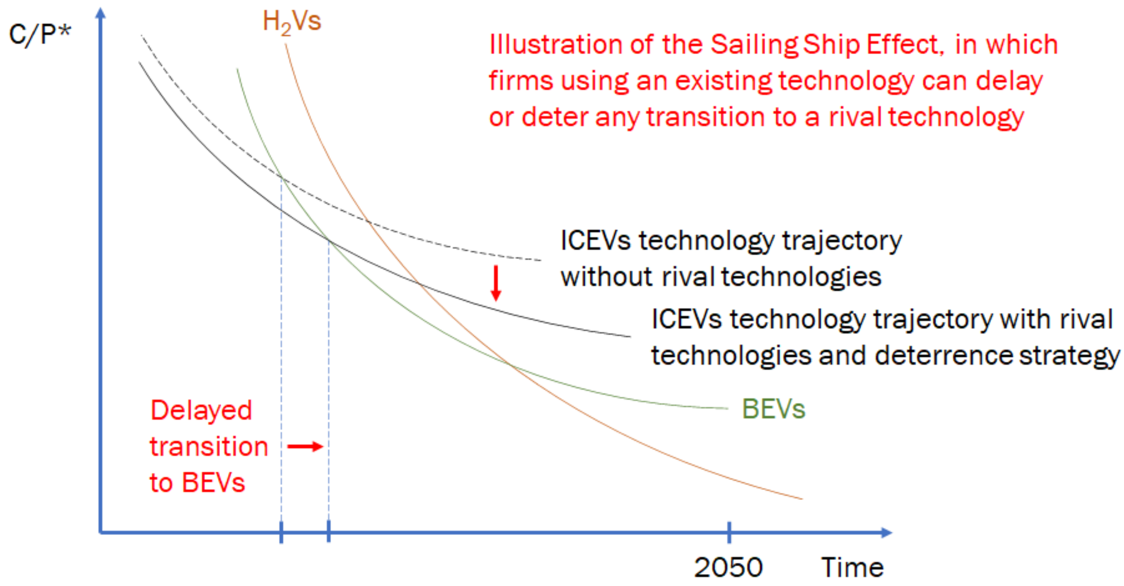
* C/P = cost to performance ratio, accounting for transport technologies' non-environmental as well as environmental performance

Figure 4.8 – Hybrid Vehicles Bypassing Both BEVs and H_2Vs



* C/P = cost to performance ratio, accounting for transport technologies' non-environmental as well as environmental performance

Figure 4.9 – Sailing Ship Effect: Strategic Improvements to ICEVs



* C/P = cost to performance ratio, accounting for transport technologies' non-environmental as well as environmental performance.

Sailing Ship Effect – Deterrence Strategy Adopted by ICEV Energy Platform or Suppliers

188. Figure 4.9 uses cost-performance technology trajectory graphs to illustrate the sailing ship effect referred to in Section 4.2:

    188.1. In this case it is supposed that the cost-performance of ICEVs is materially improved so as to deter uptake of BEVs and H_2Vs – for example by vehicle manufacturers dropping their prices, or offering much higher quality vehicles than they would absent the threat of disruption by cleaner technologies.

Combining ICEV Death Spiral with Uptake of BEVs and/or H_2Vs

189. Finally, to more clearly bring together what migration from ICEVs to alternative transport technologies looks like at an aggregate level, the following figures trace uptake curves for new technologies, death spiral curves for ICEVs, and what this could mean for the availability of transport services over time.

190. Clearly migration from one technology to another means these uptake and death spiral curves are intrinsically related. This does not, however, mean they are synchronised or coordinated, especially if regulation or policies deliberately seek to specifically affect each in different ways:

190.1. For example, policies designed to make ICEVs unattractive might succeed in reducing ICEV numbers at a rate that differs to the rate at which BEV and/or H_2V numbers grow in response to subsidies or other policies designed to encourage their uptake;

190.2. The reality is that dismantling an existing infrastructure (e.g. ICEVs) is inherently simpler than inducing multiple, independent parties to build a replacement – the former can be achieved by legislative fiat (e.g. prohibiting ICEVs altogether), whereas no amount of legislation can make BEV or H2V transport platforms simply materialise given the multiple parties (including those overseas, like car manufacturers) whose combined compliance would be required.

191. Figure 4.10 illustrates a scenario in which BEVs and H_2Vs (passenger vehicles and vans) are adopted at a sufficient pace that they maintain and even grow overall fleet numbers over time (from the current base of 3.5 million vehicles), despite declining ICEV numbers.

192. Figure 4.11, by contrast, supposes that ICEV numbers go into a death spiral faster than BEVs and/or H_2Vs materialise to fill the gap that this leaves:

192.1. As can be seen, total vehicles numbers dip substantially along the transition.

193. This potentially creates opportunities for substituting shared and public transport for vehicle ownership:

193.1. Supposing this could be engineered/synchronised, especially in New Zealand's many small, remote, low-density towns for which public transport can be costly to supply at any level, and shared transport might not be profitable.

194. Conversely, it points to possibly glaring equity of access issues in the transition to net-zero emissions in transport – especially for those:

194.1. Who cannot afford new technologies;

194.2. For whom building new technology infrastructure is prohibitively costly; and/or

194.3. Who cannot access adequate or affordable public or shared transport.

Figure 4.10 – Total Vehicle Numbers Maintained by New Technology Vehicles Replacing Old Ones in a Timely Way

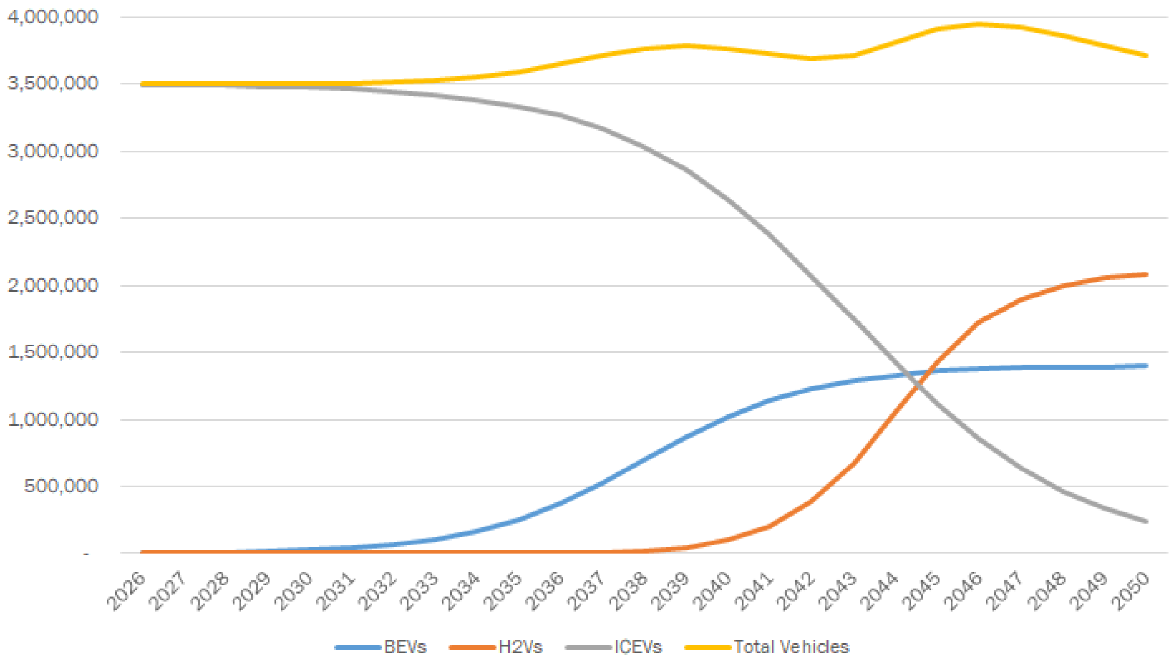
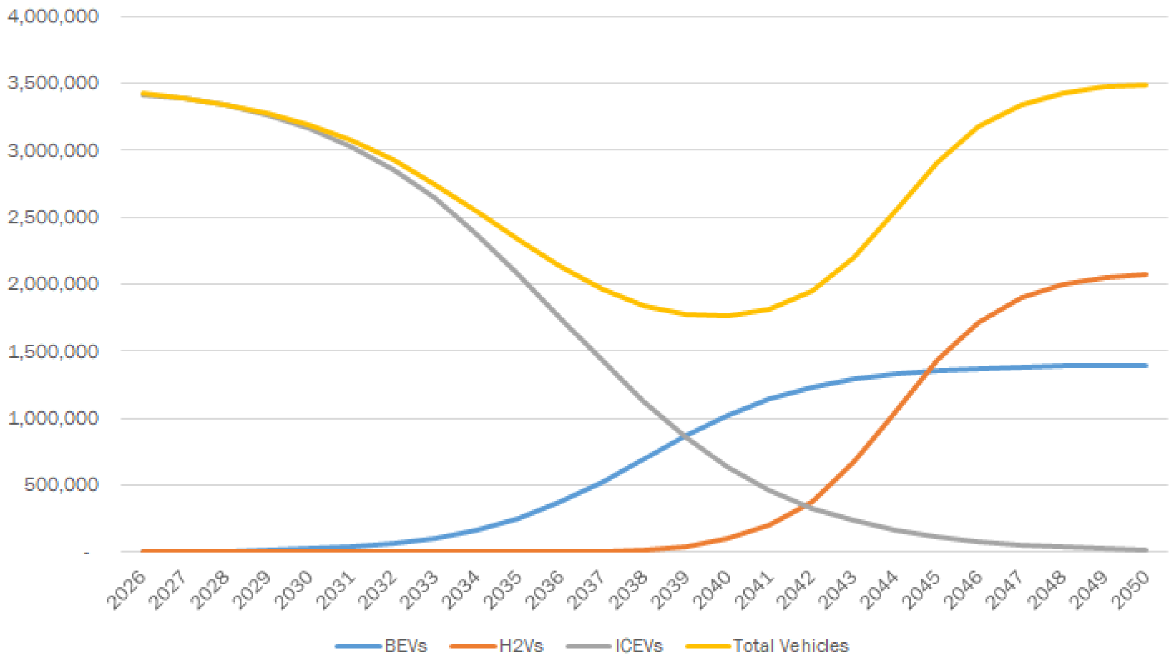


Figure 4.11 – Total Vehicle Numbers Crashing due to New Technology Vehicles Materialising More Slowly than Old Technology Vehicles are Disappearing



195. An important policy consideration is that the road to net-zero emissions in the transport sector could be littered with the bodies of unusable or unaffordable ICEVs, while BEVs, H2Vs or alternatives (e.g. public or shared transport) are too slow to materialise:

195.1. Implementing a suite of policies that not only retires ICEVs, but also ensures a timely, efficient and equitable uptake of clean alternatives – and does so in the context of network effects and scale economies, and a need for major changes in both the vehicle fleet, and the energy platform or platforms that support it.

196. Finally, Figures 4.12-4.14 illustrate the possible impact on the total fleet trajectory of having multiple possible clean technologies instead of just one:

196.1. The first figure repeats Figure 4.11, allowing BEVs and H_2Vs to compete against each other as well as ICEVs in order to gain uptake;

196.2. The second supposes that just H_2Vs compete against ICEVs, and face no rival clean technology; and

196.3. The third supposes that just BEVs compete against ICEVs, without a clean technology rival

197. For the particular illustrative scenarios chosen, collapses in total vehicle numbers occur in either scenario, while it is shorter and sharper, with faster recovery, in the case that only H_2Vs vie with ICEVs (on the assumption this leads to a more fierce contest with ICEVs, quickening their demise, and hastening the rise of H_2Vs since they do not also have to contend with BEVs), and likewise for only BEVs competing with ICEVs:

197.1. This highlights a key policy consideration – the pros and cons of waiting to see which if any new vehicle technology will ultimately win any standards war – versus influencing that process – and how either approach affects the ability of a winning clean technology to then win the standards war against ICEVs;

198. If having only one clean technology to ICEVs results in a more rapid uptake of low-emissions vehicles, this may or may not avoid a collapse in total vehicle numbers (i.e. of the sort shown in Figures 4.13 and 4.14), depending on how much this affects the rate of decline in ICEVs, but is likely to avoid a prolonged collapse by virtue of the more rapid uptake.

Figure 4.12 – Total Vehicle Numbers with BEVs and H_2Vs Competing with Each Other as well as ICEVs for Market Share

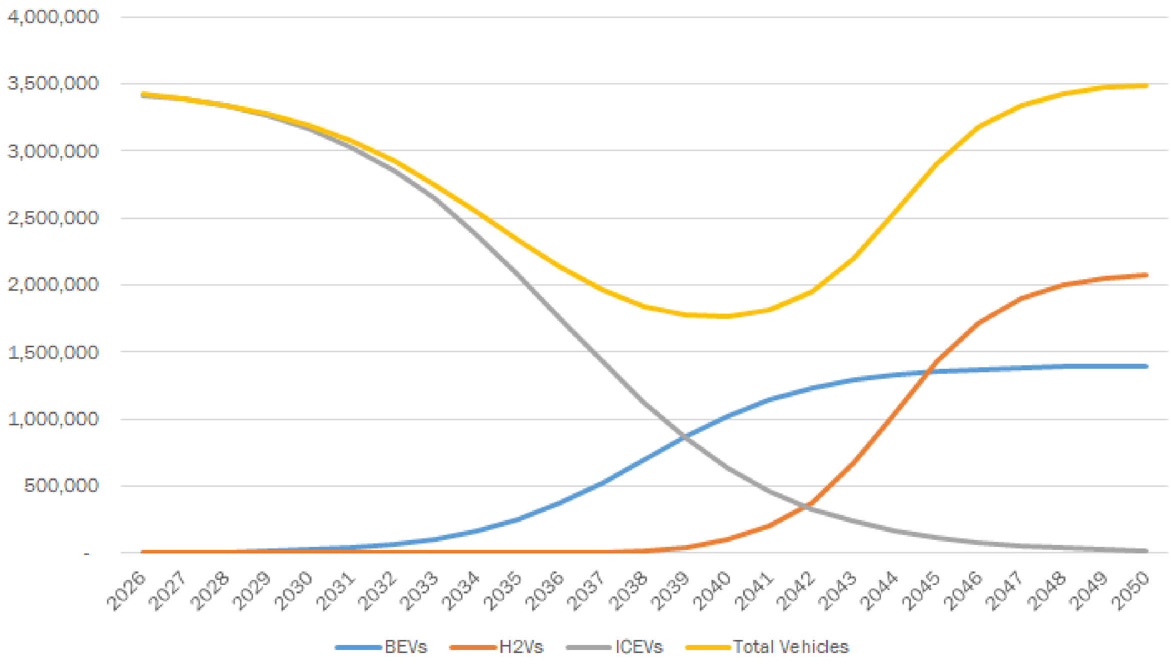


Figure 4.13 – Total Vehicle Numbers with Only H_2Vs Competing with ICEVs for Market Share

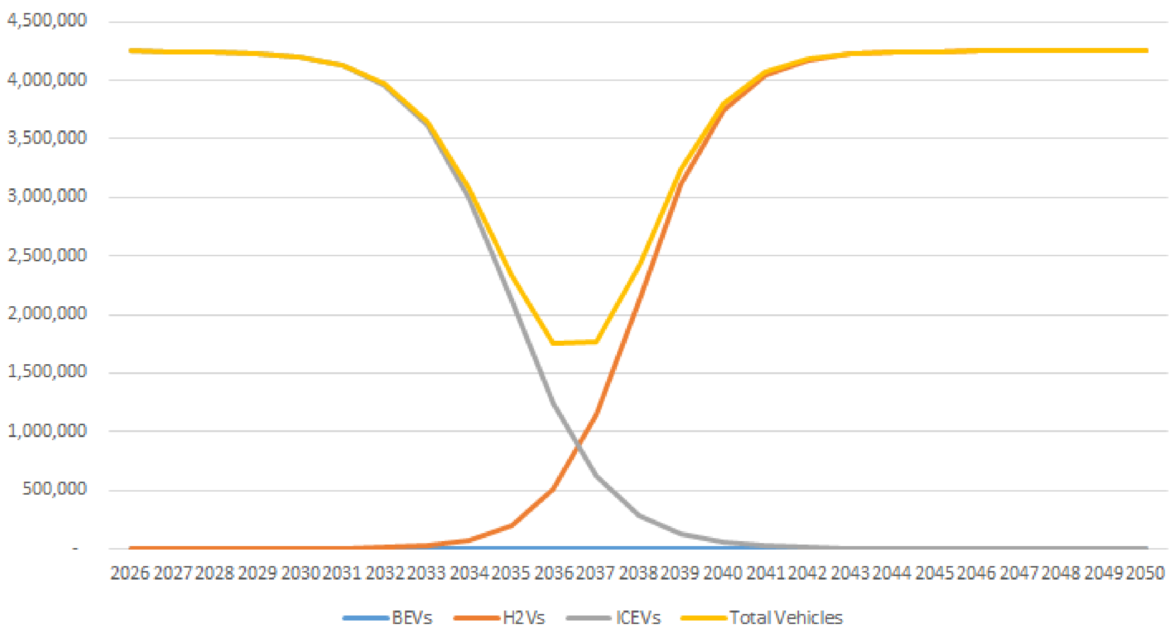
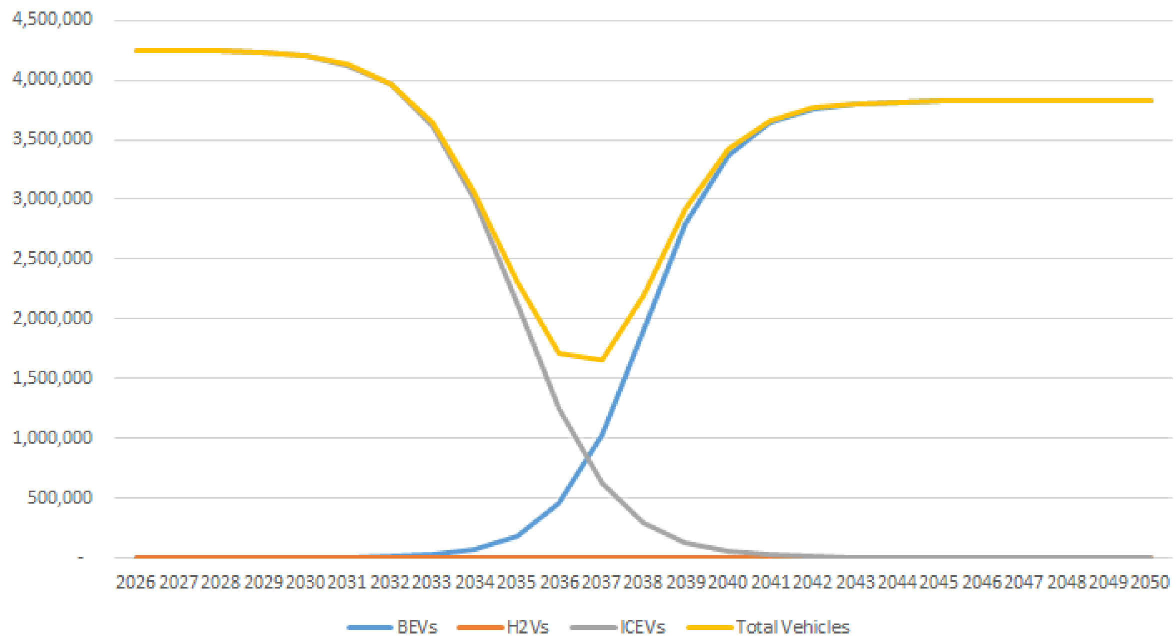


Figure 4.14 – Total Vehicle Numbers with Only BEVs Competing with ICEVs for Market Share



5. Implications for New Zealand’s Net-Zero Transition

Key points from this section:

1. New Zealand starts with certain preconditions and path dependencies complicating its transition to net-zero emissions (particularly in transport).
2. The country also has certain legacy infrastructure that could either impede or accelerate the transition.
3. A number of key policy-relevant questions are posed for how to achieve net-zero emissions in transport, heating/cooking and process heat in a timely, efficient, equitable and orderly way.

5.1 Overview

199. As highlighted in earlier sections, technology transitions can be highly path-dependent, and highly unpredictable as a consequence.[74] This means New Zealand’s transition to net-zero emissions in transport, heating/cooking and process heat must be considered in light of the context (preconditions and path-dependencies) in which that transition begins. These include the legacy energy infrastructures that the country has to work with – or against – in the net-zero transition. It also means that the policy questions the country faces in achieving its clean energy transition need to be tailored to the particular circumstances, challenges and opportunities at hand. This section explores these questions in turn.

5.2 Relevant Preconditions and Path-Dependencies

200. Some important pre-conditions affecting New Zealand’s transition to net-zero emissions include:

200.1. A small population, with few major centres, and many remote, low-density towns, spread over a relatively long land area (and separated by Cook Strait);

200.2. Relatively under-developed public transport, even in the larger urban areas, meaning a correspondingly greater reliance on private motor vehicle ownership

[74] Weitzel et al. (2006).

than in many other countries (with refuelling infrastructure adequate to service the vehicle fleet);

200.3. A relatively low-income population, especially outside of major urban areas and in more remote areas, and a particular reliance on imports of used Japanese vehicles to update the country's passenger transport fleet;

200.4. No significant vehicle manufacturing capacity, and limited heavy industry;

200.5. Aside from energy sector operators (both electricity and fossil fuels), few local organisations have the substantial balance sheets and expertise required for major infrastructure investments, or sufficient vested interest to undertake them; and

200.6. An electricity system that is already largely renewable, but with limited storage capacity.

201. The relevance of each of these is now discussed in turn.

Small and Low-Density Population

202. Due to economies of scale, network infrastructures are more viable to develop when networks are dense, rather than long and sparse. This is because more customers can be served for a given network size when they are more closely packed around that network.

203. By developed world standards even Auckland, the country's largest city, has a low population and low population density. Overall the country has low population density, spread out over a relatively long country. This makes it costly to establish new network infrastructures, such as BEV public rechargers outside of main urban areas (and possibly even then):

203.1. This is particularly important because the existing fossil fuel refuelling network is capable of delivering hundreds of kilometres of vehicle range per vehicle in just a few minutes of refuelling;

203.2. Achieving the equivalent travelling range through recharging takes hours on slow chargers, and much more than just a few minutes even on fast chargers (given current battery technologies).

204. This means a significantly greater public recharging network would need to be developed than the existing 1,350 service stations in operation[75] – even allowing for home-based charging – if a fleet of 3.5 million BEVs is to have any prospect of being a viable alternative to the existing ICEV fleet of passenger vehicles and vans:

204.1. With a small, low-density population, the size of the prize for rolling out such a network is modest, and the cost of doing so substantial;

204.2. This is an important limitation that would need to be overcome for an adequate BEV recharging network to be rolled out in a timely way – and certainly if any party chose to pre-commit to over-building a comprehensive national network to accelerate BEV uptake.

205. More generally, New Zealand's low population means its entire market is possibly too small for economically rolling out even just one new energy technology platform – given the existing technology platforms already in place – let alone two or more:

205.1. This could fundamentally impede the development and uptake of any one alternative technology platform that is not reliant on existing technology platforms, and certainly impede the uptake of multiple, competing such platforms.

Under-Developed Public Transport and Reliance on Private Motor Vehicles

206. Just as network infrastructures are more viable in dense networks, so too are public transport networks. For the same reasons that New Zealand's low population and low population density affect the viability of developing physical networks, they also constrain the development of public transport networks. This partly explains why the country's public transport networks are relatively underdeveloped, compared with other developed nations (acknowledging that past policy decisions, urban planning, and other considerations are also highly relevant).

207. This too partly explains why New Zealand has one of the highest per-capita private vehicle ownership rates in the world. In non-urban and more remote areas it is simply impossible to rely on public transport, and even in urban centres private vehicle ownership can be essential where public transport services are inadequate or unreliable.

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[75] Commerce Commission (2019), p. 60.

208. There is clearly a chicken and egg issue in this regard – public transport is less viable when so many people have access to private motor vehicles, but people rely on private motor vehicles when public transport is inadequate. As highlighted in Section 4.5, a transition to a low-emission vehicle fleet might in fact involve ICEV numbers declining faster than they are replaced by BEVs, H_2Vs or other technologies:

208.1. That could create an opportunity for improving the country's public transport options, at least in urban areas;

208.2. Failing to do so could create very real inequities in transport services access.

209. In any case, it is unlikely that private vehicle ownership will become unnecessary or uncommon in New Zealand's transition to net-zero emissions, certainly in low-population density areas.[76] This means policies for ensuring a timely, efficient and equitable transition will necessarily need to provide for a transition to a significant number of low-emissions private vehicles.

Relatively Low-Income Population

210. Allied to the issue of New Zealand having a small, low-density population is the issue that the country's population is also relatively low-income for a developed country. This has two immediate implications for the transition to net-zero emissions:

210.1. Many New Zealanders will lack the financial resources to purchase expensive new low-emissions vehicles or appliances (space/water heating, and cooking) to replace their current stocks – they will necessarily be relying on purchasing vehicles in particular on second hand markets;

210.2. This means that until those markets include a suitable range of affordable low-emissions vehicles, a great many New Zealanders will simply be holding onto, or buying, other ICEVs when it comes time to replace their existing ICEV – especially if a global glut of ICEVs is created due to their retirement in other countries, which would make such vehicles even more affordable.

[76] This would likely remain true even if breakthroughs in autonomous vehicle technologies made shared transport much more affordable and widespread, given better capacity utilisation available only in denser urban areas with shorter travelling distances.

211. This will be even more the case for those who rent rather than own their own home:

211.1. They will be particularly reliant on landlords' choices regarding the installation of low-emissions appliances, and infrastructure required for low-emissions vehicles (e.g. BEV rechargers).

212. These considerations point not just to likely equity issues arising in the net-zero transition, but also a probable source of considerable inertia in that transition:

212.1. Higher-income and home-owning households can be expected to take advantage of new technologies, which will become more attractive and viable as more and more people adopt them (due to network effects and scale economies) – though they are currently more expensive and generally offer lower performance than ICEVs (as discussed in Section 2.2);

212.2. By contrast, lower-income and renting households are more likely to be locked into old vehicle and appliance technologies, and hence facing a greater impact from rising emissions charges, and declining network effects and rising costs due to declining usage and possible death spirals on fossil fuel energy platforms.

213. What could fundamentally alter this situation is the advent of low-cost ways to retrofit the existing vehicle fleet to run on low-emissions fossil fuel substitutes:

213.1. In principle biofuels is one option (and e-fuels another), subject to the sustainability and land-use issues that this entails (e.g. destruction of habitats for feeder crop production, or pressure on food prices due to increased competition for arable land);

213.2. H_2ICEV technology is another (whether based on stored hydrogen, or ammonia as a more energy-dense alternative) – Japanese and Korean vehicle manufacturers are already successfully trialling H_2ICEVs, which could lead to breakthroughs enabling affordable retrofits;

213.3. Blending hydrogen into existing gas networks, as a prelude to converting all gas infrastructure and connected equipment/appliances to running on 100% of the gas, is another possibility.

214. Converting the existing ICEV fleet to low-emissions fuels could prove a vastly more affordable and hence timely way to achieve a low-emissions vehicle fleet, and reduce

equity issues arising when only expensive new or used low-emissions vehicles must be purchased otherwise:

214.1. That could buy time for other clean technologies to become more affordable and attractive, and thereby reduce equity of access issues.

Reliance on Imported Used Vehicles from Japan

215. New Zealand has no significant vehicle manufacturing capacity. Coupling this with a relatively low-income population means that the country is not just dependent on importing vehicles from overseas, but on importing used vehicles – mainly from Japan. This too has important implications for how rapidly and equitably the New Zealand vehicle fleet might be updated to low-emissions technologies:

215.1. Until used imported vehicles from Japan are BEVs, H_2Vs or other low-emissions vehicle technologies, very few ICEVs in New Zealand will be replaced with low-emissions vehicles in any given year;

215.2. Banning the importation of ICEVs could conceivably lead to worsening fleet emissions, by impeding access to later-model vehicles (with greater fuel efficiency) and locking in use of existing ICEVs at a time when low-emissions vehicles are either unavailable or unaffordable.

216. The challenge in adopting BEVs in any great numbers is only made worse by the fact that the world's current leaders in BEV production are U.S., Chinese or European manufacturers:

216.1. While second-hand markets for vehicles from these manufacturers might eventually become available to substitute for imports from Japan, this is impeded by New Zealand's historical accident of being a country that drives on the left (unless the country swaps to the right, like Sweden and other countries have done – a not-insignificant one-off transition cost, but one potentially worth considering if this provides greater access to used low-emissions vehicles).

217. This means that, for the foreseeable future, New Zealand's vehicle fleet strategy will need to be closely aligned with that of the current major Asian (i.e. Japanese and Korean) vehicle manufacturers that provide access to affordable right-hand drive vehicles:

217.1. Notably, most major Japanese and Korean vehicle manufacturers are more committed to the production of hybrids and H_2Vs – notably, not BEVs – as is consistent with wider hydrogen strategies in Japan and Korea.

No Significant Vehicle Manufacturing Capacity, and Limited Heavy Industry

218. The above considerations are relevant demand-side factors that could significantly affect the viability of low-emissions energy infrastructures being developed in New Zealand, in general, let alone in a timely way.

219. Turning to supply-side drivers, in Sections 3 and 4 the role of large vested interests in developing new infrastructures was highlighted. Historically they have played a key role in rolling out new infrastructures, drawing not just on their substantial financial resources and technical expertise, but also on the benefits their existing activities derived through access to better infrastructures.

220. This explains why owners of coal mines and large manufacturing interests in Industrial Revolution era Britain led the rollout of canals, the development of steam power, and the rollout of railway lines feeding canals, leading to the later displacement of canals by privately-owned railways:

220.1. Importantly, such large vested interests help to resolve the chicken and egg problem that can plague the diffusion of new technologies requiring large investments in infrastructure;

220.2. This is because they expect to derive sufficient private benefit from the infrastructure that they do not need to rely on others also using it in order to make their adoption of the new technology worthwhile.

221. Major BEV manufacturers like Tesla and Ford are already active in rolling out BEV recharging networks in the U.S., including public chargers, and home-based charging solutions. They have sufficient vested interest in doing so because it helps them to sell more BEVs:[77]

221.1. The issue for New Zealand is that the entire New Zealand market is unlikely to offer enough BEV sales to induce either BEV manufacturer, let alone both, to roll out

[77] Just as Edison invested in electricity generation and distribution to help him sell more light bulbs.

recharging infrastructure in New Zealand. This is only more the case given the cost of rolling out such an infrastructure in such a spread-out, low-density country;

221.2. For similar reasons, if major H_2V manufacturers decide to invest in hydrogen refuelling production, transmission and distribution as a means of boosting their H_2V sales, they will most likely find it unprofitable to do so in New Zealand.

222. Likewise, New Zealand has limited heavy industrial concerns that might find it profitable to invest in new energy technology infrastructure for their own benefit (see Section 3.5 for examples of instances where existing vested interests are exploring the viability of hydrogen investments):[78]

222.1. Instead of such "vertical" investment in new energy infrastructures, this could leave a much greater role for "horizontal" investments – e.g. in BEV recharging infrastructure by national retail chains, or other parties who can maintain suitable nationwide networks on the strength of returns generated from other activities, with transport infrastructures offering modest additional returns but also requiring relatively modest outlays.

223. These factors point to there being few natural champions of new energy infrastructures in New Zealand, at least those in vehicle manufacturing, or heavy industry:

223.1. However, their possible role in championing new infrastructure developments should not be understated – having few, larger parties coordinating such investments can play a critical role in seeding new infrastructures, especially if relying on coordinating the choices of numerous small parties (e.g. of the owners of New Zealand's 3.5 million passenger vehicles and vans) is the alternative.

224. Ironically, unlike many other countries, New Zealand enjoys a degree of freedom in its vehicle technology choices. This is because the country shares no land borders with other countries, so it has a freer hand than countries whose vehicles must be capable of being driven cross-border:

224.1. This somewhat mitigates the risk of the country pursuing any given technology path, should other countries take alternative paths;

[78] NZ Steel for green steel production, and pulp and paper mills using biomass for process heat, are examples of parties who could potentially make such infrastructure investments alone.

224.2. It does not entirely insulate the country though, given ongoing reliance on imported vehicles, and the wider benefits of coordinating technology choices with fuel (e.g. imported hydrogen) and equipment suppliers.

Few Local Organisations with Large Balance Sheets and Infrastructure Development Expertise

225. Possibly the most natural large concerns that might have sufficient self-interest to sponsor new low-emissions infrastructure investments in New Zealand are the country's existing energy sector players.

226. Electricity generators have a natural interest in selling more electricity for BEVs or hydrogen production (and accessing low-cost storage to manage renewables intermittency, such as through hydrogen production):

226.1. However, their vertical separation from transmission and distribution makes it harder for them to capture the full benefits of inducing uptake of BEVs or H2Vs (since any extra transmission and distribution returns are captured by the grid operator, Transpower, and local lines companies, respectively).

227. Fossil fuel concerns have a natural interest in protecting the value of their existing assets against the uptake of low-emissions alternatives (the sailing ship effect referred to in Section 4.2, and illustrated in Section 4.5). Where this is untenable – e.g. due to changing consumer preferences and/or political or regulatory pressure – they also have a vested interest in capturing as much value as they can from their existing investments in any transition to net-zero emissions:

227.1. That might be achieved, for example, by repurposing their existing fossil fuel production, refining, transmission and distribution infrastructures to be used with low-emissions alternatives (hydrogen being an obvious example – especially if blue hydrogen is produced using natural gas as an input, and depleted gas fields as natural reservoirs for CO_2 storage – but possibly also biofuels or e-fuels);

227.2. It would clearly be assisted by the fact that they have substantial balance sheets and financing capacity, as well as significant technical expertise and trained workforces capable of repurposing or developing the required infrastructures.

228. There are other organisations in New Zealand with large balance sheets. However, aside from energy sector operators, few in the country have the expertise or vested interest

required for them to wish to champion the development of low-emissions energy infrastructures, as is often instrumental in accelerating the uptake of new technologies.

Electricity System Largely Renewable, but with Limited Storage

229. New Zealand is both blessed and cursed by having an electricity system that is already mostly renewables-based:

229.1. On the one hand this means the country enjoys access to relatively low-cost, low-emissions electricity – unlike most other developed countries, which rely on coal and gas to a substantial degree;

229.2. On the other, it means the country's electricity system is vulnerable to climate-related variability, and it also means there are few easy wins in terms of decarbonising electricity production (especially since the country's limited fossil fuel generation provides back-up for when natural fuel supplies are limited).

230. Exacerbating this situation is the country's lack of energy storage. With the existing renewables share, the electricity system is prone to periodic dry years in which wholesale electricity prices climb dramatically to maintain supply-demand balance when hydro storage lake levels are low:

230.1. If the country increases its share of intermittent renewables to meet future transport energy requirements (i.e. electricity for BEVs) or to decommission coal and gas generation, then the need for additional storage will become even more pronounced.

231. The government is currently investigating how best to produce additional storage for the electricity system as part of its NZ Battery initiative.[79] Options include building pumped-storage hydro capacity (Lake Onslow), and possibly other approaches for achieving large-scale storage:

231.1. This could have a critical impact on the business case for developing hydrogen production capacity in New Zealand, such as by replacing the aluminium smelter at Tiwai Point if it is decommissioned and frees up significant electricity capacity for alternative uses;[80]

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[79] For details, see: https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/low-emissions-economy/nz-battery/.

[80] For details, see: https://www.southerngreenhydrogen.co.nz/.

231.2. In particular, producing hydrogen using electrolysis and storing it (e.g. as higher-energy density ammonia), is a form of large-scale electricity storage – since the stored hydrogen can later be used to produce electricity (in fuel cells, or by combusting it in a gas turbine), or to substitute for electricity-using uses and thereby freeing up existing electricity supply for other purposes.

232. This points to decisions regarding NZ Battery potentially having large impacts – either positively or negatively – on the feasibility of developing green hydrogen production at scale in New Zealand:

232.1. In turn, this could affect the viability – also positively or negatively – of developing blue hydrogen production capacity.

233. In the short term at least, both green and blue hydrogen production are likely to be complementary/symbiotic, in that they assist with the uptake of the hydrogen energy platform:

233.1. This means that policies or other decisions affecting the joint development of green and blue hydrogen could prove critical in either accelerating or delaying any transition to hydrogen as a low-emissions alternative to fossil fuels;

233.2. Indirectly, this could also affect the viability of BEVs fuelled using intermittent renewable energy, given battery technologies are currently inadequate for the large-scale energy storage needed to buffer intermittency, whereas large-scale hydrogen production could be a suitable storage alternative.[81]

5.3 Possible Importance of Legacy Infrastructures

234. Section 4.2 has already highlighted the lack of natural sponsors in New Zealand for new energy infrastructures, with existing energy concerns being key candidates for taking a leading role (acknowledging the possible role of other parties, as discussed in Section 3.5).

235. Relevant considerations include the extent to which existing, legacy infrastructures can be repurposed or augmented to enable a transition to low-emissions transport, space/water heating, and process heat (Section 2.2 discussed the suitability of different energy platforms for relevant end uses):

[81] APERC (2020).

235.1. This is especially the case if current planning and environmental management rules might impede or preclude the development of required new infrastructures;

235.2. Legacy infrastructures have an additional head start over any new ones in terms of having been created and consented at a time when rules were potentially far more accommodating than now – e.g. repurposing the existing network of retail refuelling sites in urban areas is likely to be easier to achieve than building potentially hazardous new refuelling sites in such areas.

236. Table 5.1 compares the requirements of creating BEV and H_2V energy ecosystems, highlighting where existing energy infrastructures play a role, and how those infrastructures might need augmenting or repurposing to do so. As can be seen:

236.1. A BEV energy ecosystem requires extra renewable electricity generation, augmented distribution network capacity (and/or smart charging technologies to manage peak loads from BEV charging), additional storage to buffer intermittent renewable electricity supplies, and the rollout of public and private rechargers;

236.2. Conversely, an H_2V ecosystem requires hydrogen production or import capacity (with production potentially from renewable generation, but also using natural gas with CCS), and could potentially take advantage of repurposed gas transmission, storage and distribution capacity.

237. Importantly, an H_2V ecosystem could also enjoy significant economies of scale and scope due to other emerging hydrogen uses (e.g. large/heavy transport, including aviation and shipping, as well as process heat applications):

237.1. Also, hydrogen production and storage would provide energy storage, rather than necessitate extra storage to buffer renewable electricity intermittency;

237.2. As noted above, major Japanese and Korean vehicle manufacturers that New Zealand relies upon for right-hand drive vehicles are pursing H_2Vs (both FCEVs and H_2ICEVs) as part of wider hydrogen strategies, which would complement any hydrogen ecosystem development in New Zealand – especially if this results in affordable hydrogen retrofits to the country's existing ICEV fleet.

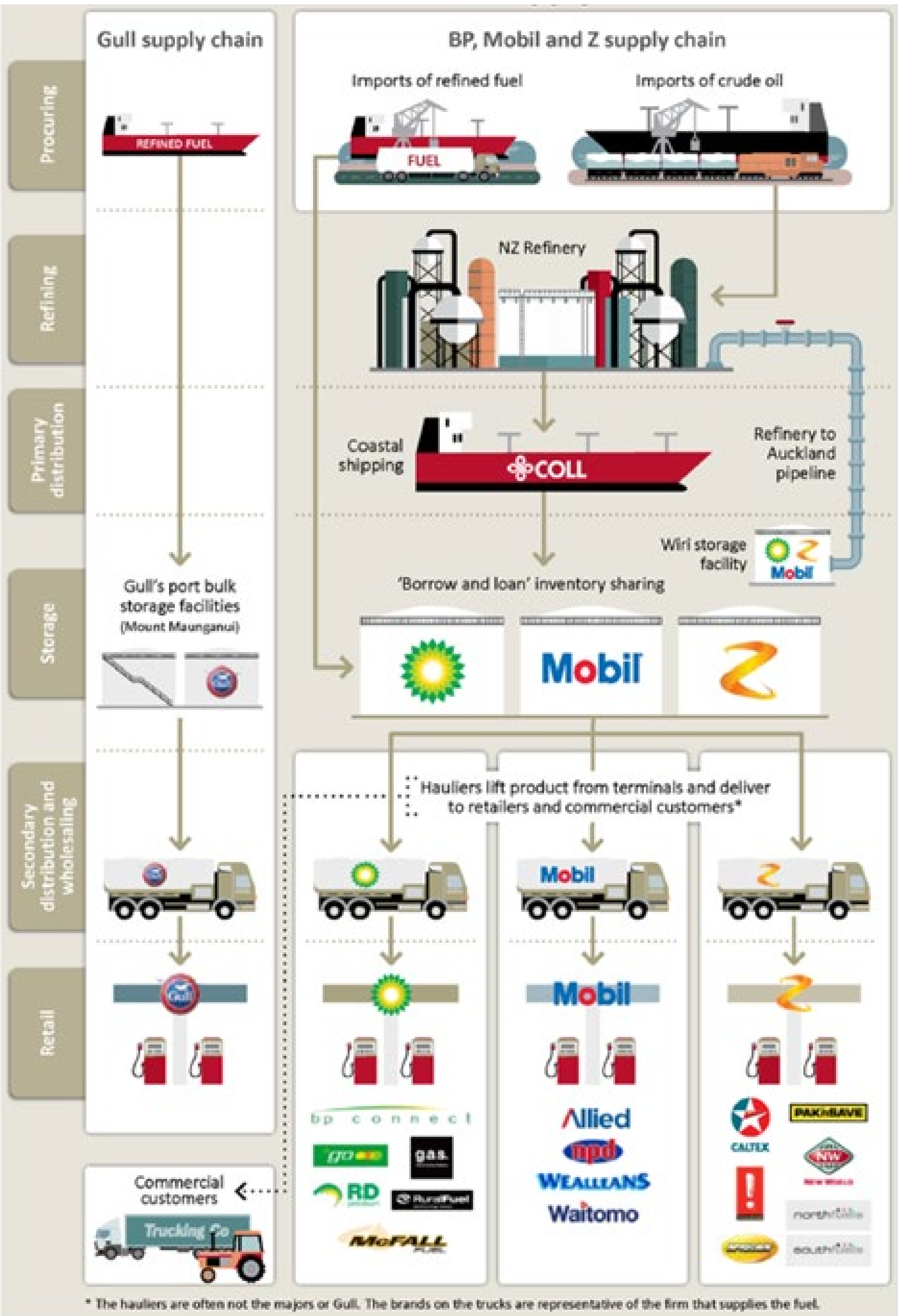
Table 5.1 – Requirements for Establishing BEV and H_2V Energy Ecosystems

	BEV Ecosystem	H_2V Ecosystem
New hardware	BEVs, BEV home chargers.	H_2Vs, gas heaters/appliances.
Retrofitting possible	Not currently.	Possibly – gas heaters/appliances, maybe even ICEVs to H_2ICEVs.[82]
Requirements for low-emissions fuel supply	Increased renewable electricity generation, plus backup storage (possibly from hydrogen production and storage, but not BEVs)[83] to manage intermittency.	Increased renewable electricity generation for green hydrogen (no backup required since stored hydrogen provides backup itself). Alternatively, CCS for domestically produced blue hydrogen, or ability to import green/blue hydrogen.
Transmission infrastructure	Can potentially use existing high-voltage grid for required long-distance electricity transportation.	Could repurpose existing gas transmission in North Island, and system for getting bottled gas to South Island – and also gas storage capacity.
Distribution infrastructure	Local networks need reinforcing for BEV charging peaks – less so with “smart charging”, or if rooftop PV becomes widespread, (provided PV combined with storage for time-shifting supply and use).	Could repurpose existing North Island distribution infrastructure, and bottled gas distribution system in South Island.
Refuelling infrastructure	Private slow/fast chargers required at homes/apartments and workplaces. Public slow/fast chargers required at shops, dedicated charging sites, etc.	Existing service station network could be repurposed (augmenting current gas supply capacity, or adding additional such capacity).
Network effects	BEV uptake makes BEV charging networks more viable and vice versa.	H_2V uptake makes modifications to existing refuelling infrastructure (or new such infrastructure) more viable, and vice versa.
Economies of scale/scope	Yes – V2G support services to electricity distributors, synergies with PV systems (using BEVs as storage), etc. Possibly greater capacity utilisation of distribution networks (and/or diseconomies of scale).	Possible V2G support services to electricity distributors (e.g. from FCEVs). Possible synergies with PV systems (small-scale electrolysis). Greater capacity utilisation and economies of scale for hydrogen infrastructure used for heavy transport, non-land transport, commercial/industrial heating, etc.

[82] Converting ICEVs to run on alternative fuels like CNG and LPG has already been achieved (Hu and Green (2011)). With H_2ICEVs already being developed, similar conversion options for hydrogen may materialise, and offer a potentially cost-effective means to rapidly convert the existing ICEV fleet to clean energy.

[83] APERC (2020). Hydrogen production from electricity much more feasible as large-scale and long-term electricity storage than using BEVs.

Figure 5.1 – New Zealand's Petrol and Diesel Supply Chain



Source: Commerce Commission (2019), Figure X6.

238. Figures 5.1 through 5. 3 provide a better sense of the extent of existing energy sector infrastructures, and compare them with the current extent of BEV recharging infrastructure.

239. Figure 5.1 depicts New Zealand's petrol and diesel supply chain. Of note for the possibility of using legacy infrastructure for the net-zero transition, key infrastructure includes:

239.1. Marsden Point Refinery port facilities, which in principle might be converted to receiving imports of hydrogen, or ammonia (its more energy-dense form);

239.2. Marsden Point Refinery itself, and associated storage capacity, which might be repurposed to convert ammonia to hydrogen, or to store hydrogen/ammonia;

239.3. The refinery to Auckland pipeline, which might be converted to transporting hydrogen or ammonia to storage facilities to Auckland, for use in aviation, or for trucking to local petrol stations (if they are converted to hydrogen distribution);

239.4. Coastal shipping operations and regional fuel storage terminals, which might be converted to shipping and storing hydrogen or ammonia; and

239.5. Truck-based fuel distribution from terminals to service stations and other fuel users.

240. Figure 5.2 depicts New Zealand's electricity system, comprising generation and transmission assets, as well as multiple local electricity distribution businesses. Of note for the possibility of using legacy infrastructure for the net-zero transition:

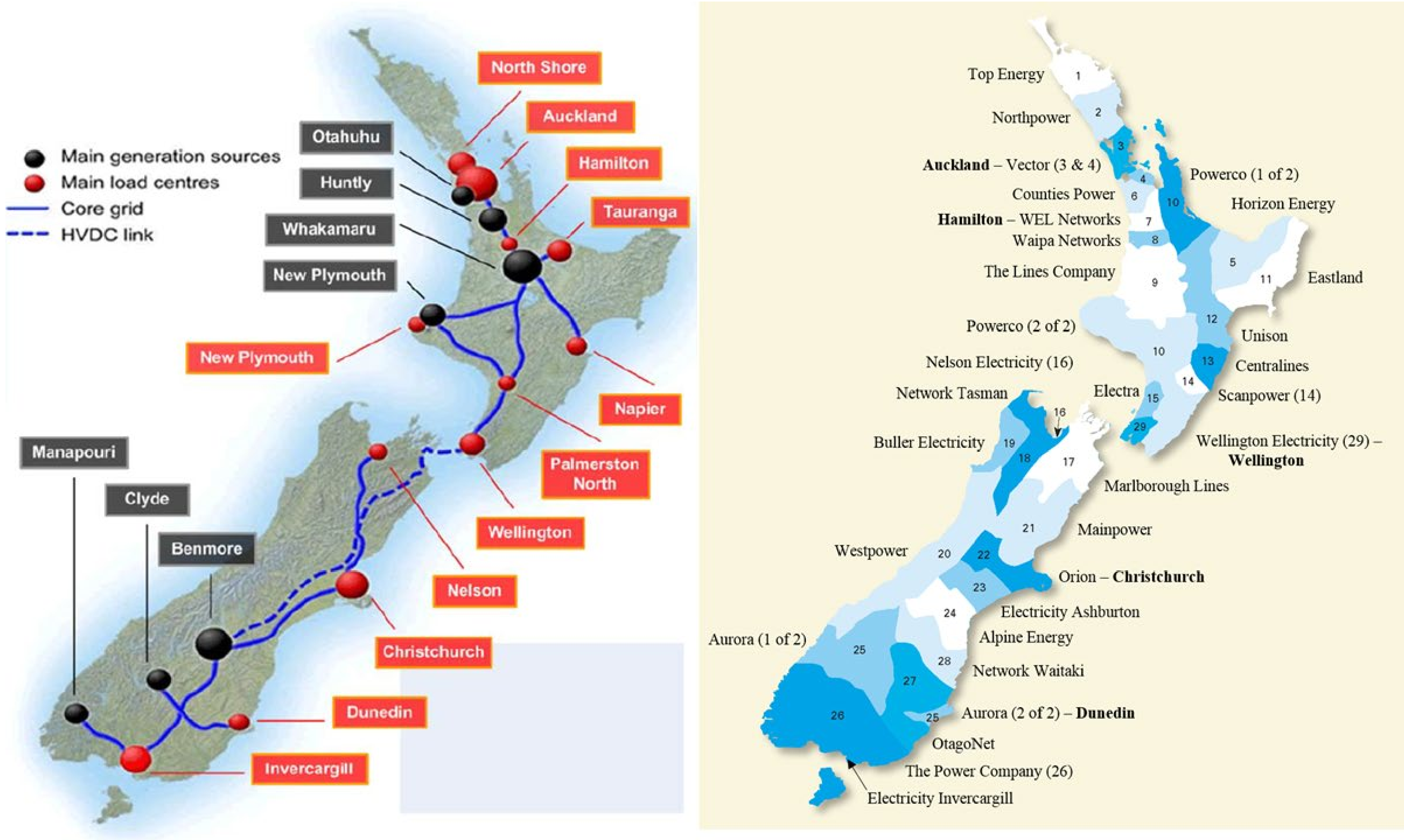
240.1. Major hydro generation in the South Island (particularly Manapouri) might become available for green hydrogen production if the aluminium smelter at Tiwai at the bottom of the South Island is shut down (releasing about 15% of annual generation for other purposes):

240.1.1. Port facilities near the smelter might be used for shipping hydrogen or ammonia to other parts of the country, or exported, and hydrogen production could be used as a form of large-scale energy storage to buffer intermittent renewables;

240.2. The high-voltage national transmission grid could pay a key role in transporting renewable generation to where it might be used for green hydrogen production, or to replace fossil fuel use for process heat in parts of the country not served by gas or biomass (e.g. South Island dairy processing); and

240.3. Taranaki- and Waikato-based electricity generation currently reliant on natural gas might be converted to use hydrogen instead.

Figure 5.2 – New Zealand Electricity Generation and Transmission Infrastructure (Left) and Distribution Networks (Right)



Source: Generation and transmission map adapted from Nair and Zhang (2009), Figure 1. Electricity distributors map from Meade and Söderberg (2021), Figure 1.

241. Figure 5.3 depicts New Zealand's current natural gas production, transmission, and reticulated distribution infrastructure, all in the North Island (bottled gas is distributed in the South Island). Of note:

241.1. Gas production is concentrated in the Taranaki region, where the country's past and present major natural gas fields have been operated – depleted gas fields may have a role to play in CCS for the production of blue hydrogen;[84]

241.2. Gas transmission and distribution infrastructure already has some capacity to transport natural gas with hydrogen blended – over time that infrastructure might be repurposed to transport and store locally produced or imported hydrogen (or ammonia) to major North Island centres; and

241.3. As above, current gas-fired electricity generation might be converted to running on hydrogen – providing on-demand zero-emissions back-up generation to buffer intermittent renewables-based electricity generation (using hydrogen storage as a form of effective electricity storage, since the stored hydrogen could be converted into electricity as required).[85]

242. All of these legacy energy infrastructures represent potential competitors to new, low-emissions infrastructures, or might conceivably be critical components of those new infrastructures. The policy challenge is to engineer the latter rather than the former.

243. Finally, Figures 5.4 and 5.5 compare the current networks of petrol stations and public BEV recharging points around the country:

243.1. As noted in Section 5.2, BEV recharging capacity needs to be far more extensive than existing ICEV refuelling capacity due to significant differences in refuelling times for each technology, for a given fleet size and need for travelling range).[86]

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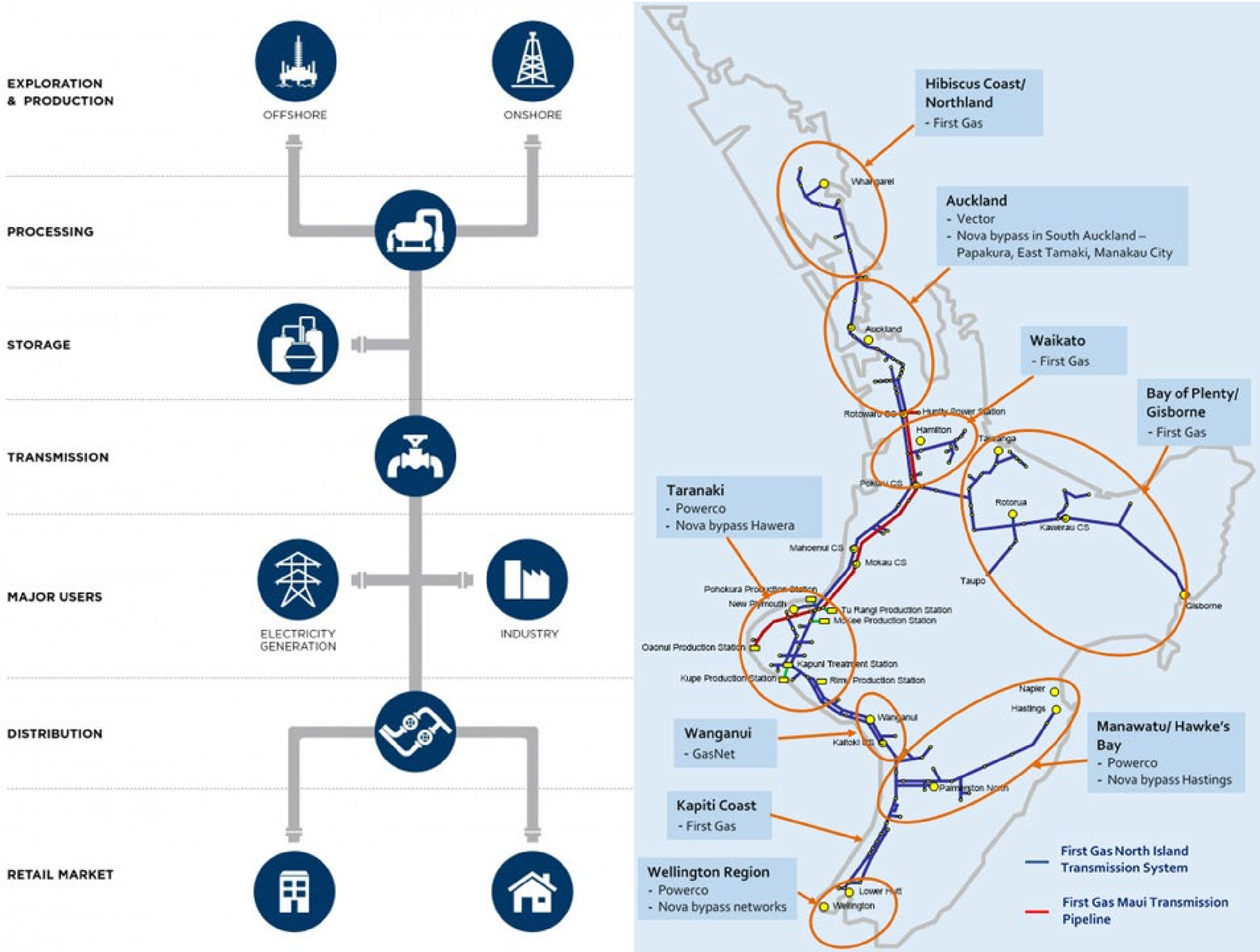
[84] An alternative possibility is that CO_2 from blue hydrogen production in Taranaki using natural gas might be transported to the site of major olivine reserves in the top of the South Island, which reserves have the potential to sequester CO_2 at industrial scale. See: https://www.stuff.co.nz/environment/climate-news/126685010/new-zealand-company-that-could-revolutionise-carbon-capture-gets-1m-funding.

[85] Clearly any process for producing and storing hydrogen, and then converting stored hydrogen (or ammonia) back into electricity involves efficiency losses. This does not render the process unviable so long as the benefits of doing so exceed the costs, and there are no superior alternatives that could be used instead.

[86] See Sallee (2021) for details, and references to relevant research.

Figure 5.3 – New Zealand's Natural Gas Industry Supply Chan (Left) and Transmission and Distribution Networks (Right)



Source: Supply chain schematic from: https://www.gasindustry.co.nz/about-the-industry/gas-industry-information-portal/structure-of-the-gas-industry/.

Network details from Gas Industry Company (2020).

244. Figure 5.4 distinguishes petrol stations owned by major oil companies and independent stations. The former represent particular opportunities for conversion to fuels like hydrogen or biofuels if those oil companies were also involved in the production, importation, storage, transmission and/or local distribution of such fuels. This is because they would internalise the value to be captured across all parts of the relevant supply chain:

244.1. In fact even the smaller but integrated fossil fuel suppliers (e.g. Waitomo, Gull) could have pivotal roles in furthering the rollout of biofuels or hydrogen, by being faster than the major oil companies to treat this as part of their business strategy (i.e. being mavericks/pioneers, to compete on dimensions not dependent on scale);

244.2. However, if the major oil companies should commit to rolling out biofuels or hydrogen refuelling infrastructure at scale through their existing petrol station networks and associate supply chains, that could be critical for resolving “chicken and egg” problems confronting H_2V uptake (and inducing H_2V supply).

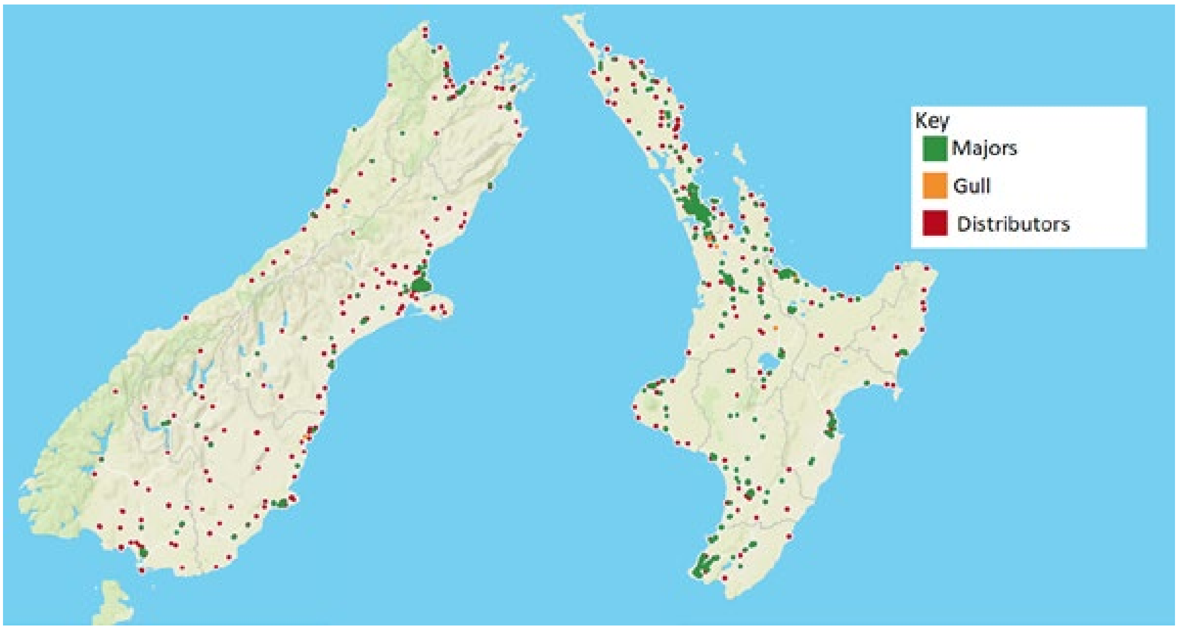
245. Independent petrol stations might also be integral so such a transition, though this might require special contracting arrangements with their suppliers (e.g. major oil companies, though possibly other fuel suppliers). Such arrangements could prove critical for ensuring any necessary long-term investments by independent station owners in clean fuel distribution technologies are viable and of the right type (e.g. standardised).

246. Figure 5.5 indicates that both slow and fast BEV chargers are emerging across all of New Zealand. However, this is for a current BEV fleet of just 23,245 vehicles, and so this network – even if augmented with home-based chargers – is likely to be just a tiny fraction of that required to enable convenient and risk/hassle-free recharging for BEV vehicle fleets in the hundreds of thousands, or possibly even millions:

246.1. Considerable investment in BEV charging networks remains a critical “chicken and egg” uptake challenge if BEVs are to prove a viable alternative to ICEVs – even supposing the other disadvantages of BEVs (e.g. high upfront cost, much lower range and longer refuelling times than ICEVs, limited models) can be overcome;

246.2. Currently BEV recharging networks are provided by a variety of companies, but as of yet no single or few large natural sponsors have emerged to resolve the “chicken and egg” problem by committing to rolling out a comprehensive charging network ahead of BEV uptake (leaving vehicle buyers to question whether buying an expensive BEV might leave them facing inadequate recharging capacity, or a stranded vehicle investment).

Figure 5.4 – New Zealand's Retail Fuel Sites



Source: Adapted from Commerce Commission (2019), Figures 2.6 and 2.7.

Figure 5.5 – New Zealand's Public BEV Recharging Infrastructure – Slow Charging for Destinations (Left) and Fast Charging for Road Trips (Right)

Source: From http://www.electricheaven.nz/.

5.4 Policy Challenges and Questions

Outline

247. Based on the following discussions, this section sets out and explains a number of key policy challenges and questions. These questions are deliberately left to be answered elsewhere, as the aim of this study is to help frame and promote reasoned and informed debate, not to reach specific conclusions or make specific recommendations.

248. The policy challenges and questions addressed relate to:

248.1. What are the trade-offs in waiting to see which clean technologies come to dominate, and what factors affect those trade-offs for New Zealand?

248.2. What are the trade-offs in committing to a particular clean technology, and what factors affect those trade-offs for New Zealand?

248.3. How should critical trade-offs in the transition be determined?

248.4. Is it sufficient for New Zealand to rely on "push" measures to achieve the desired transition, or are "pull" measures required too?

248.5. Should transition policy prioritise responses by smaller decision-makers or large ones, and if so, which?

248.6. What level of coordination is required to synchronise the demise of emitting technologies and diffusion of low-emissions technologies?

248.7. What role for vested interests in the transition?

249. Each is now discussed in turn.

What are the Trade-Offs in Waiting to See which Clean Technologies come to Dominate, and what Factors affect those Trade-Offs for New Zealand?

250. An obvious merit of waiting to see which technology platforms emerge and eventually dominate is that it provides information, and reduces the risk of going all in to a solution that turns out to be the wrong one:

250.1. Indeed, by waiting it might be possible for entirely new and more compelling solutions for the low-emissions transition to emerge.

251. Waiting does not eliminate the risk of “picking the wrong horse”, however, as countless people and numerous organisations might have decided on their own to invest in technologies that eventually turn out to be redundant – waiting and seeing effectively leaves them to bear that risk:

251.1. In any case, the pace of technological change over recent decades has been so rapid that any new technology that eventually becomes dominant is at risk of itself being disrupted by subsequent new technologies that might be coming hot on its heels, reducing the value of waiting.

252. Moreover, an equally obvious downside of such an approach is that it delays – and possibly even deters – the uptake of new technologies by leaving them to be risky bets for anyone who chooses to adopt them, and leaving the critical coordination challenges for maximising scale economies and network benefits unresolved:

252.1. In the context of an urgent decarbonisation of the transport and heating choices of 1.7 million households, thousands of commercial businesses, and possibly hundreds of large businesses, such delays may be especially costly.

253. Delayed uptake also poses the threat of New Zealand ultimately being regarded as a laggard in the low-emissions transition, and potentially face unfavourable treatment in evolving international emissions reductions regimes:

253.1. This is especially so if larger countries are more successful in rolling out the necessary new energy platforms (e.g. due to having larger and more numerous natural champions for the development of the required infrastructures).

254. One way to mitigate any downsides of waiting, so as to maximise the benefits of obtaining further information and resolving technology risks, is to lay the groundwork to be ready to rapidly adopt any new clean energy technology when it becomes clear that it will dominate:

254.1. Another is to proactively try to influence which technology is to dominate – e.g. by coordinating actions with major hardware and energy platform technology providers (such as developing global technology standards to maximise interoperability, etc).

What are the Trade-Offs in Committing to a Particular Clean Technology, and what Factors affect those Trade-Offs for New Zealand?

255. Waiting to see which, if any, new clean energy technology dominates means "picking horses after race has run". Of course we should all want this ability, but in many cases all bets are off by that stage – being in the race requires commitment to a particular horse.

256. For the reasons emphasised already in Sections 2 and 4, commitment in the context of platform competition with scale economies and network effects plays an additional, critical role. Specifically, it helps to resolve the "chicken and egg" problem that otherwise plagues the adoption of new technologies – especially when the status quo offers a sufficiently affordable and attractive option relative to the alternatives:

    256.1. Such commitment – e.g. by vested interests making large, irreversible investments in infrastructure – serves to align expectations about which way forward has the greatest prospect of success (even if it is not necessarily the inherently best way to go);

    256.2. This in turn enables network benefits to be maximised by causing users to gravitate towards a particular solution (rather than holding back to hedge their bets).

257. New Zealand policymakers have long been reluctant to "pick winners" due to the enduring legacy of the country's controversial "Think Big" projects of the 1970s and 1980s. This is not to say the country does not pick winners, as it clearly does – such as when the government committed to funding fibre-based ultra-fast broadband (UFB) rollout in the past decade:

    257.1. That rollout occurred despite ongoing technological advances which meant that existing copper networks could deliver increasingly faster broadband speeds (albeit within limits), and the use cases for greater broadband speeds had not yet materialised (though video streaming services quickly appeared to fill that gap);

    257.2. It also occurred despite the impending threat of advances in mobile data technologies (e.g. 5G) which could make much of the UFB rollout ultimately redundant – ironically, the UFB rollout serves to delay the uptake of 5G (e.g. by providing UFB to users who do not require mobile data) but also to accelerate it (by providing the backbone infrastructure needed for 5G rollout, and by having developed multiple use cases for UFB).

258. However, even if 5G or other technologies should cannibalise the market for fibre-based UFB not long after its rollout, the fact that New Zealanders have had access to UFB over the past decade has enabled vast gains that would otherwise have been delayed or deterred if the country had instead chosen to wait (e.g. to see if 5G proved superior):

258.1. This points to the key benefit of commitment being earlier uptake than would otherwise occur – in the context of the need for urgent decarbonisation of New Zealand's transport, space/water heating and cooking, and process heat, the benefits of "picking a winner" and committing to a course of action could be especially important.

259. Similarly, New Zealand "picked a horse" when it mandated digital television to replace analogue television broadcasts in 2012-2013:

259.1. By creating a "hard sunset" on the availability of analogue broadcasts – i.e. a fixed date in each region beyond which analogue broadcasts would no longer be available – this created a market for digital-ready hardware (e.g. television sets), and also after-market set-top boxes for converting digital broadcasts to be able to be watched on analogue hardware (i.e. retrofitting existing hardware);

259.2. It also created a clear focal point for viewers, hardware suppliers, content producers and broadcast network operators to coordinate upon (and not worry about whether some other technology might disrupt their choices – albeit streaming supported by UFB will have done so to a large degree, only years later);

259.3. Table 5.2 compares UFB and digital television uptakes with the transition to low-emissions transport.

260. The potential downsides of committing to a particular technology could be mitigated by various means. Important amongst these is prioritising options with greatest optionality/potential and least regrets. Greatest optionality/potential refers to things like a particular clean technology option, compared to its clean technology rivals:

260.1. Offering the greatest cost-performance advantages relative to existing emitting technologies across the widest range of users – i.e. the most compelling consumer benefits from transitioning – and/or economises on the necessary infrastructure investments required to access those advantages;

Table 5.2 – Comparing Transitions for Ultrafast Broadband, Digital Television and Low-Emissions Transport

	Ultrafast broadband (Fibre)	Digital television	Low-emissions transport
Incumbent infrastructure	Copper telephone network, mobile data	Analogue television	Fossil fuel vehicles
Chicken and egg resolved by	Government co-funding, and tendering of investment rights (inducing incumbents to participate, despite interests in defending incumbent infrastructure, rather than face competitive entry)	Mandated switching date	To be determined
User transition costs	Low – new modem, and set-up time	Low – existing equipment could be used with low-cost converter, and new televisions were digital capable	High if new vehicles required. Moderate or low if existing vehicles could be retrofitted to use clean fuels (hydrogen, e-fuels, biofuels)

260.2. Relatedly, being most likely to have compelling applications for large users, who might find it privately beneficial to invest in the new energy platforms themselves, especially if their private benefits are further increased by capturing some of the benefits enjoyed by other users of the platforms they invest in (just as 18^{th} and 19^{th} century industrialists in the UK improved the profitability of their industrial concerns by investing in canals and then rail, but also gained from other profitable uses of their networks such as passenger transport);

260.3. Being most likely to provide a continuing platform for even more transformative disruptions – e.g.:

260.3.1. Electric vertical take-off and landing vehicles (eVTOLVs), which could offer the sort of massive leaps in cost-performance that might naturally induce ICEV users to migrate to cleaner technologies (which neither BEVs nor H_2Vs currently offer – as highlighted in Section 2.2); or

260.3.2. Enabling the existing ICEV fleet, and other fossil fuel technologies (e.g. space/water heaters, cooking appliances, process heat systems) to be affordably, conveniently and reliably retrofitted to run on clean energies – which could address equity issues as well as accelerate the transition;

260.4. Being more able to be repurposed to other uses if the intended uses turn out to be better provided by alternative technologies; and

260.5. Being the most likely to lead to an entirely new energy ecosystem, with wide-ranging existing and new potential applications (as opposed to simply offering a lower-emissions version of existing technologies in an existing application) – as depicted in Figure 5.6.[87]

261. These questions are highly pertinent given the New Zealand government's apparent "balanced" approach towards rival clean energy platforms:[88]

261.1. One the one hand, policy-makers have signalled a preference for the uptake of BEVs as a means to reduce transport emissions;

261.2. On the other, they have also signalled support for developing alternative clean energy solutions like hydrogen;

261.3. Given the discussions in Sections 2 and 4, such policy ambivalence could serve to delay or impede the uptake of clean vehicle technologies, and the large infrastructure investments required to induce them.

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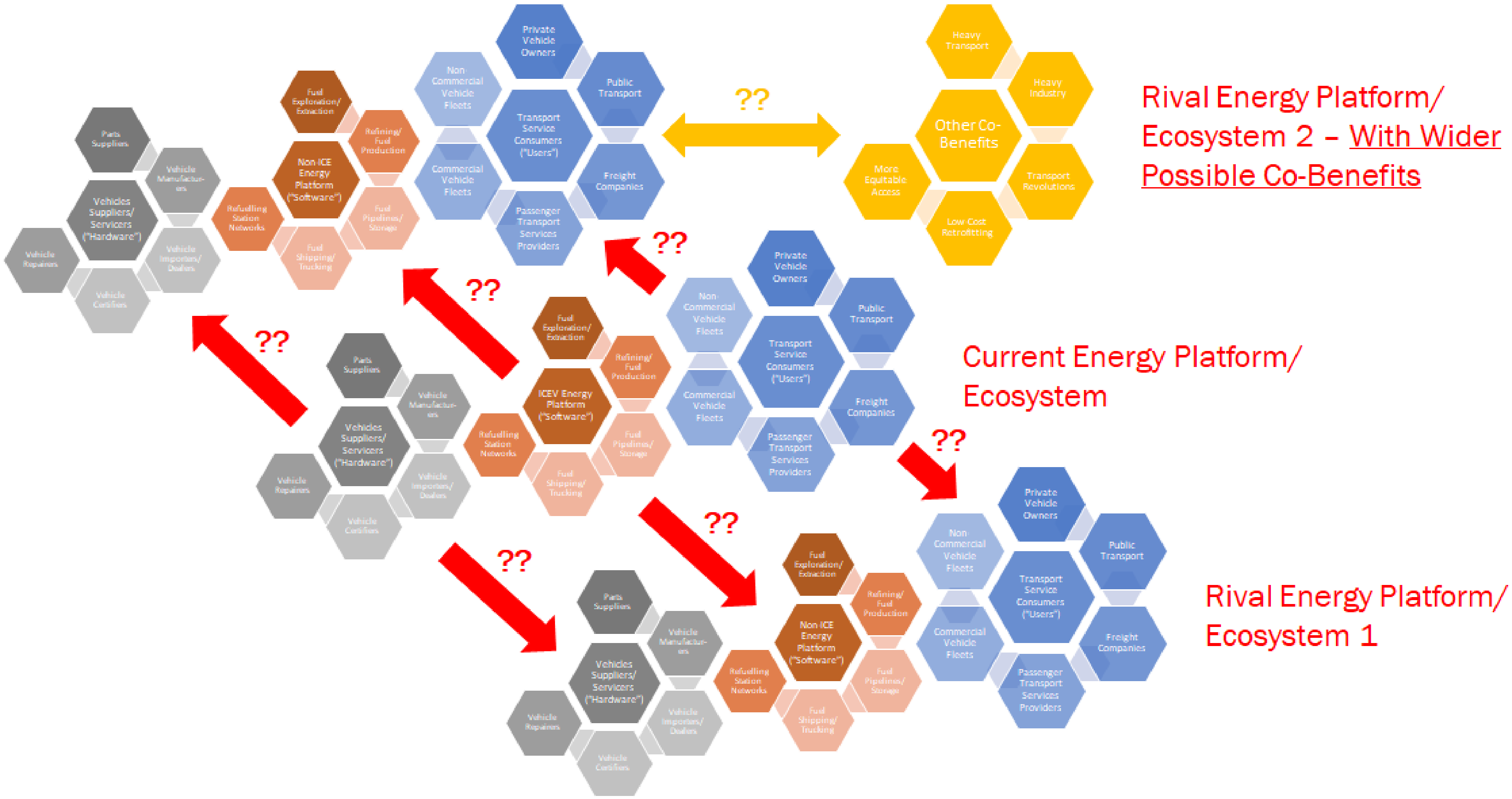
[87] Another example is the transition from coal to gas for domestic cooking in New Zealand, and then to electricity, in the early 20th century – e.g. see Rennie (1989). While gas offered clear advantages over coal for applications like cooking (e.g. being cleaner, more immediate, etc), its applications were limited relative to electricity. The latter was able to revolutionise modern life, in particular through labour-saving innovations like electric washing machines (with laundering taking a day of effort each week for most households). Gas continues to dominate certain applications, but electricity is used much more widely due to its wider range of applications.

[88] For example, see Ministry for the Environment (2021).

Figure 5.6 – Choosing between Clean Technologies when One Offers Wider Ecosystem Benefits

In weighing the pros and cons (including risks) of favouring one clean energy technology platform over another, it is useful to consider if one is better than the other in terms of possible co-benefits – e.g. unlocking applications in heavy transport (including rail, aviation, maritime) and heavy industry (including process heat), greater potential for revolutionising transport (e.g. personalised flight), enabling low-cost retrofitting of existing vehicles and industrial equipment, more equitable access, etc – i.e. enabling a wider clean energy ecosystem.



How Should Critical Trade-Offs in the Transition be Determined?

262. While the failure of New Zealand's "Think Big" projects of the 1970s and 1980s reflects a variety of factors, two commonly implicated in policy circles are the role of centralised planning and overly-concentrated political control:

262.1. If New Zealand was to commit to a course of action for its transition to net-zero emissions – including committing to waiting and seeing – this creates a wide range of costs, benefits and risks differentially affecting a diverse range of parties (households, businesses, industries, etc);

262.2. Striking the right balance of costs, benefits and risks across relevant groups – including in an equitable way – lies at the heart of the political process, and hence highlights an unavoidable and key role for government policy and regulators.

263. This does not, however, mean that private choices are any less important:

263.1. If anything, this study has highlighted how any transition to net-zero emissions is fundamentally about coordinating the choices of countless numerous private parties, each of which can be assumed to prioritise their own interests when making their choices, but who might change their choices if they knew how others were going to make their choices;

263.2. Hence the choices of numerous individuals and private parties (including overseas parties – like standards designers, hardware manufacturers, technology platform investors, etc – will also play an unavoidable and key role in the transition.

264. In fact New Zealand's choices might become constrained if large key sponsors of new technologies – local or foreign – commit to a certain course in New Zealand:

264.1. This is not irrevocably so, since government has the capacity to regulate or override such commitments (albeit with potential costs, and perhaps limitations under international agreements);

264.2. However, it highlights that the initiative for shaping the transition to net-zero emissions is not entirely in New Zealanders' "collective" hands.

265. Hence, to ensure that initiative is not lost, there is likely to be virtue in either large potential sponsors of key new technologies and/or government – those able to shift the dial on any

clean technology transition – facilitating processes for consumers (large and small), hardware suppliers, technology platform providers, regulators and government to coalesce around preferred pathways forward:

265.1. If any resulting social consensus is that it is better to wait and see which technology platforms emerge as dominant, even though that creates the risk of a delayed or deterred transition with associated costs (e.g. sanctions by other countries), then at least that would be a shared risk arrived at through due process;

265.2. Conversely, if the resulting social consensus is to commit to a particular course of action despite the risk that this might involve technologies that later prove to be superseded by others, then that too would be a risk collectively shared on an agreed basis, and enables more rapid action at potentially much lower cost;

265.3. If no social consensus emerges, either government or major private parties could play decisive roles in spearheading their preferred solution.

Is it Sufficient for New Zealand to rely on "Push" Measures to achieve the Desired Transition, or are "Pull" Measures Required Too?

266. "Push" measures (i.e. "stick") are measures such as bans or taxes on certain existing or new technologies, making them less attractive. Conversely, "pull" measures (i.e. "carrot") are measures such as subsidies or other supports for new or old technologies, making them more attractive. The former serve to cause the affected technologies to decline, while the latter serve to cause the affected technologies to prosper, if only to a degree in each case (since no measure is perfect, and all measures can have unintended side-effects).[89]

267. It is clearly much simpler to dismantle existing networks that have taken decades and a multitude of private choices and investments to construct than it is to rapidly build new ones depending on other numerous choices and investments:

267.1. As illustrated in Section 4.5, being too successful in dismantling existing platforms while not being successful enough in developing their replacements in a timely way risks causing a disorderly collapse in the services available to users of these platforms (e.g. transport, heating/cooking and process heat services);

[89] The appropriate type or level of any such measures could reflect social consensus, or political decisions failing such consensus emerging.

267.2. This emphasises the risk to relying just on “push” measures – doing so could effectively eliminate emissions, but also create widespread social and economic costs.

268. Similarly, sole reliance on “pull” measures might be extremely expensive, and raise equity concerns (e.g. regarding the burden of financing them, relative to how their benefits are shared). More importantly, they might ultimately be frustrated if users and providers of existing energy technologies find it preferable to continue using existing technologies rather than migrate to new ones, even with pull measures in place:

268.1. This points to both push and pull measures being complementary, and likely also necessary – especially if the transition to net-zero emissions is to be not just timely, but also orderly (which will also affect its equitableness).

269. The policy challenge is to make the status quo sufficiently unattractive, while also making the alternative sufficiently attractive – to all relevant decision-makers – in a coordinated and achievable way.

Should Transition Policy Prioritise Responses by Smaller Decision-Makers or Larger Ones, and if so, Which?

270. As emphasised above, as well as in Sections 3.5 and 4.3, large vested interests can play a pivotal role in resolving the “chicken and egg” problem that often plagues the development of new technologies:

270.1. They often have sufficient self-interest in developing the new technologies that they don’t need others to also wish to use their platforms, overcoming coordination difficulties, even if this means they under-invest or invest too late from a wider social perspective (in which the societal gains from the platform are higher); and

270.2. By making large, irreversible investments in new infrastructure, they more credibly signal to other possible platform users that their platform is here to stay, and that they believe it will win any standards wars.

271. This means that large, irreversible platform investments by large vested interests can have indirect benefits over and above simply providing infrastructure sooner (or at all) than would occur otherwise:

271.1. Specifically, by helping to shape expectations of other potential platform users, they can create a snowball effects which makes their investments even more profitable than from simply improving the profitability of their existing activities;

271.2. If other users start to use their platforms, this can create additional sources of revenue – e.g. from fare-paying passengers on railways created to more efficiently transport raw materials or manufactures.

272. This then points to complementary policy approaches:

272.1. On the one hand, policies that help large vested interests to spearhead new technology developments could induce other users to also coordinate on using those platforms;

272.2. On the other, policies to encourage small users to migrate towards platforms preferred by large vested interests would further improve the viability of those platforms, by creating additional demand for their platforms' services.

273. Clearly the latter is more likely to be successful if there is already a commitment to building the relevant platforms:

273.1. Hence, while encouraging smaller users to migrate towards a particular platform complements large vested interests taking a lead in the development of such platforms, getting such large vested interests to take the first step is likely to create the greatest momentum for uptake of new platforms in the first instance;

273.2. Absent finding large vested interests to take such a leadership role, government commitments to building the required infrastructure could be considered as a substitute – providing the critical focal point for smaller users to then migrate towards.[90]

[90] Regional and then central government took a lead role in developing rail and electricity generation/transmission infrastructure in New Zealand. However, private developers either pre-dated or played supporting roles in such developments (see Rennie (1989) for electricity, and https://www.kiwirail.co.nz/our-story/history/ for rail).

What Level of Coordination is Required to Synchronise the Demise of Emitting Technologies and Diffusion of Low-Emissions Technologies?

274. The above discussion highlights that there can be no presumption that dismantling existing infrastructures while attempting to construct new ones will occur in a timely, efficient, equitable or orderly way. There is a very real risk of causing a collapse in services if existing platforms are dismantled before new ones emerge to take their place. This calls for the use of coordination mechanisms to achieve a more synchronised transition:

274.1. Coordinating across a variety of interests will likely be an important component of helping to chart New Zealand's overall strategy for achieving the transition, to ensure that the incidence of the costs, risks and benefits of the chosen strategy have been appropriately balanced.

275. Coordination can be achieved by a variety of means, such as:

275.1. Centralised coordination and oversight – e.g. via regulators – is one;

275.2. Creating common standards, and industry oversight bodies, is another;

275.3. Strategic alliances and joint ventures, either through contracting and/or partial shared ownership, is a solution often finding favour in automotive and other technology-focused industries; and

275.4. More generally, shared ownership of different parts of the supply chain – e.g. through joint ownership of successive parts of the chain (vertical integration), or through tie-ups of operators at the same industry level (horizontal integration) – can be an especially effective way of achieving synchronisation across technically-complex coordination problems.[91]

276. In practice a variety of such coordination mechanisms should be expected to operate alongside each other. For example, joint ownership of existing and new technology platforms could provide natural synchronisation benefits. However, regulation might still be

[91] Ownership tie-ups can also be thought of as a market-based form of coordination. While it is unlikely that a market for entire technology ecosystems will emerge, the market for corporate control (i.e. through mergers, acquisitions, privatisations, etc) represents a proxy for such a market, enabling bespoke tie-ups to emerge as a means of trading different technology platform bundles.

required to ensure this doesn't simply entrench or prolong the use of emitting technologies and prejudice the migration to low-emissions technologies.

277. Finally, given New Zealand's reliance on vehicles, appliances and energy technologies developed or manufactured overseas, this highlights a particular set of cross-border coordination challenges. The country is likely to be a technology follower rather than a technology developer in key parts of the supply chain, so any local coordination mechanisms would necessarily need to include coordination with overseas producers and technology developers. This could be achieved through, e.g.:

277.1. Participation on global standards-setting bodies;

277.2. Bilateral agreements between states, or between New Zealand and key manufacturers; or

277.3. Agreements between key local large vested interests and major equipment suppliers or technology developers.

What Role for Vested Interests in the Transition?

278. The preceding discussions point to large vested interests potentially playing a pivotal role in leading the uptake of any given new energy platforms. As discussed in Sections 5.2 and 5.3, New Zealand's large energy sector interests are leading contenders, though not exclusively so. Large non-energy industrial concerns could also be pivotal, including via joint ventures. However, absent large equipment or energy technology interests in New Zealand, it is less likely that they will play a key role in the net-zero transition:

278.1. As well as having large interests which might benefit from access to better technologies, such parties are also likely to have the balance sheets and technical expertise required to successfully make the transition.

279. In principle three options are possible:

279.1. Existing emitting energy platforms could be left in place, while clean energy platforms grow out of other platforms, or are built from scratch;

279.2. Existing emitting energy platforms could be retired, while clean energy platforms grow out of other platforms, or are built from scratch; or

279.3. Existing emitting energy platforms could be repurposed to be low-emissions platforms, either alone, or in conjunction with the development of other clean-energy platforms.

280. Which option will be the most effective in achieving a timely, efficient, equitable and orderly transition will be affected by how the declining and rising platforms will be owned. Under the first option:

280.1. If the existing platforms are separately owned from the emerging ones, this presents owners of the existing platforms with downside, but no upside, and could cause them to resist the transition (e.g. by improving the attractiveness of their offerings – the sailing ship effect);

280.2. Conversely, if the technologies are jointly owned, the joint owners benefit from the rising technology to offset their losses from the declining one, but without necessarily facing an incentive to make the transition (absent specific nudges – e.g. by changes in consumer tastes, regulation, etc).

281. The second option features similar incentives, just more pronounced (since the existing technology faces a more certain demise). The third option presents subtly different trade-offs. With incumbent energy providers effectively owning both the old technology and new through one and the same platform, their incentive to favour the old technology over the new or vice versa will depend on the relative costs and benefits of maintaining the status quo relative to making the transition (rather than on what they lose on one technology, but gain on another):

281.1. It is, however, possibly the most viable of the three options (subject to technical feasibility), since it requires coordination and investments to adapt an existing infrastructure with an existing user base, rather than having to potentially create entirely new ones and attract users from old platforms to new ones.

Conclusions

282. The policy challenges and questions posed in this sub-section are not small or insignificant. They represent very significant challenges deserving of very serious policy attention. Just as achieving net-zero emissions is a critical goal deserving of careful consideration, so too is the challenge of doing so in a timely, efficient, equitable and orderly way. It would certainly be unwise to attempt the transition to net-zero emissions without giving these challenges and questions serious thought.

6. Policy Levers for Achieving a Timely and Efficient Net-Zero Transition, and Future Work

Key points from this section:

1. Achieving a timely, efficient and efficient – as well as orderly – transition to net-zero emissions in transport, space/water heating and cooking, and process heat will require a complementary suite of "push" and "pull" measures.
2. These include policy levers designed to simultaneously make ongoing use of high-emissions technologies less attractive, and the greater use of low-emissions technologies more attractive – to all relevant users, and in a synchronised way.
3. Policy levers that best harness the incentives of vested interests to lead the transition could be especially effective, absent which more punitive and costly measures would be required (and likely less effective).

6.1 Overview

283. This section discusses which policy levers are – or are not – available to New Zealand in achieving a timely, efficient, equitable and orderly transition to net-zero emissions. The suite of available levers reflects opportunities or constraints created by past choices and investments (i.e. path-dependencies), as well as choices being made by parties New Zealand is critically reliant upon (e.g. vehicle manufacturers).

284. Policy levers to discourage reliance on emitting technologies ("push" measures) are first discussed, followed by policy levers to encourage uptake of clean technologies ("pull" measures). Where relevant, interactions between the two types of measure are also discussed. Such levers can also be demand-side or supply-side focused (although each side can affect the other indirectly), which will be separately discussed, as are general policy levers.

285. The point of this discussion is not to recommend specific policies to support the required transition. Rather the aim is to discuss possible policy approaches in general terms, and discuss their pros and cons. Just as this study seeks to provide useful framing and pose useful questions and approaches, it does not seek to make specific recommendations per

se. Rather they would flow from any informed and reasoned debate that this study intends to stimulate.

6.2 Policy Levers to Discourage Reliance on Emitting Technologies ("Push" Measures)

Demand-Side Policy Levers to Discourage Emitting Technologies

286. Two obvious policy levers to discourage use of emitting technologies are emissions taxes, and purchase taxes on emitting hardware (the "fee" part of "feebate" schemes for high-emissions vehicles):

    286.1. As noted in Section 4.4, optimal emissions taxes for technologies involving network effects are not as simple as making consumers bear the cost of environmental damage caused by their emissions – additional tax components are required to account for network effects, as well as how competitive or otherwise is the pricing on clean energy platforms. Simple reliance on pan-sectoral emissions trading schemes is unlikely to deliver the range of emissions prices appropriate to each emitting sector;[92]

    286.2. While emissions charges primarily affect the cost of using emitting technologies, they indirectly affect the decision to adopt emitting technologies in the first place. However, more direct – and material – charges on purchases of emitting technologies are more likely to affect users' decisions to purchase emitting technologies.

287. Non-price measures can also play key roles in discouraging the purchase and use of emitting technologies. One approach is to impose "sunset clauses", of which there are two main varieties:

    287.1. "Soft sunsets" simply ban the purchase of new emitting technologies beyond a certain date;

    287.2. "Hard sunsets" ban the use of such technologies from a date.

[92] Additionally, emissions caps or prices should be tailored to each sector, reflecting differences in levels of emissions, equity considerations, and also the marginal cost of emissions abatements (if reductions are to be achieved at least cost).

288. Soft sunsets are of questionable value, since the default for most owners of emitting technologies (e.g. ICEVs) is not to buy an expensive and/or inferior low-emissions technology when it comes time to update their existing hardware, if they are banned from buying a newer version of the emitting technology:

288.1. Their default is to simply keep using their existing old technology for longer, or buy a newer version on the second hand market;

288.2. This could serve to worsen average emissions rather than reducing them, by locking users into ageing technologies that are likely to become more inefficient over time, instead of allowing them to purchase more efficient emitting technologies.

289. Hard sunsets can cause the opposite problem of accelerating purchases of the emitting technology ahead of the ban. However, this is likely to be a relatively short-term problem, and if the ban is sufficiently far into the future, it simply creates a focal point about which suppliers, consumers and platform providers can coordinate their decisions. It is also likely to cause decision-makers to start migrating to new technologies years ahead of any hard bans.

290. A more constructive approach to sunset clauses is simply to mandate that all hardware (i.e. vehicles, appliances, process heat technologies, etc) using emitting energies must be capable of running on clean energies from a date:

290.1. A particular merit of such an approach is that it creates demand for retrofitting clean technologies in existing hardware, as well as for new or used clean hardware;

290.2. As for hard sunsets, if the relevant date is sufficiently far into the future, then consumers have plenty of time to choose and finance their clean alternatives.

291. As discussed in Section 4.5, it is important that hard sunsets do not induce premature death spirals for emitting technologies before new technologies have been adopted to ensure hardware (e.g. vehicle) stocks and service levels (e.g. transport services) can be maintained, including for those facing obstacles to adopting new technologies (e.g. due to income or housing tenure constraints):

291.1. Boosting public transport or shared transport options could be important complements to any such sunsets, though are likely to be less feasible in many of New Zealand’s remote, low-population centres.

Supply-Side Policy Levers to Discourage Emitting Technologies

292. Environmental taxes, and taxes on purchases of emitting technologies, will affect the supply side as well as the demand side. They make emitting hardware and fuels more expensive to purchase and to operate, creating a penalty for suppliers that do not change their offerings to include relatively (if not absolutely) more affordable low-emissions alternatives. As above, purchase taxes (e.g. under feebate schemes) are likely to have a more material impact on emissions than emissions charges:

    292.1. This is because they are more material, and also because many users' emissions profiles are constrained by their existing choices over where to live, what heating technology to use, and what type of transport hardware they use – until those longer-term decisions change, they simply bear emissions charges rather than reduce their emissions – as illustrated in Figure 6.1.[93]

293. In general, any measures affecting the demand for emitting technologies (hardware and energy) will also affect the supply side, by changing the profitability of providing emitting technologies. Soft and hard subsets will therefore also affect suppliers' incentives to continue offering emitting technologies:

    293.1. As above, mandating that all hardware must be capable of running on clean energies for a specified future date could create new markets for existing or entrant suppliers to service – such as markets for retrofitting clean technology solutions to existing emitting technologies, or providing new or used clean technology hardware.

294. Suppliers of hardware and emitting energy will respond to any such sunsets or future changeover dates ahead of those dates. As long as the dates are sufficiently in the future, they can start to make the investments and other changes required to be ready to meet the requirements for low-emissions technologies from that date:

    294.1. As above, it will be important that they have the incentives and ability to offer affordable and attractive clean alternatives to consumers in a way that avoids any unwanted collapses in service levels (transport, heating, etc) as emitting technologies are retired (and go into death spirals).

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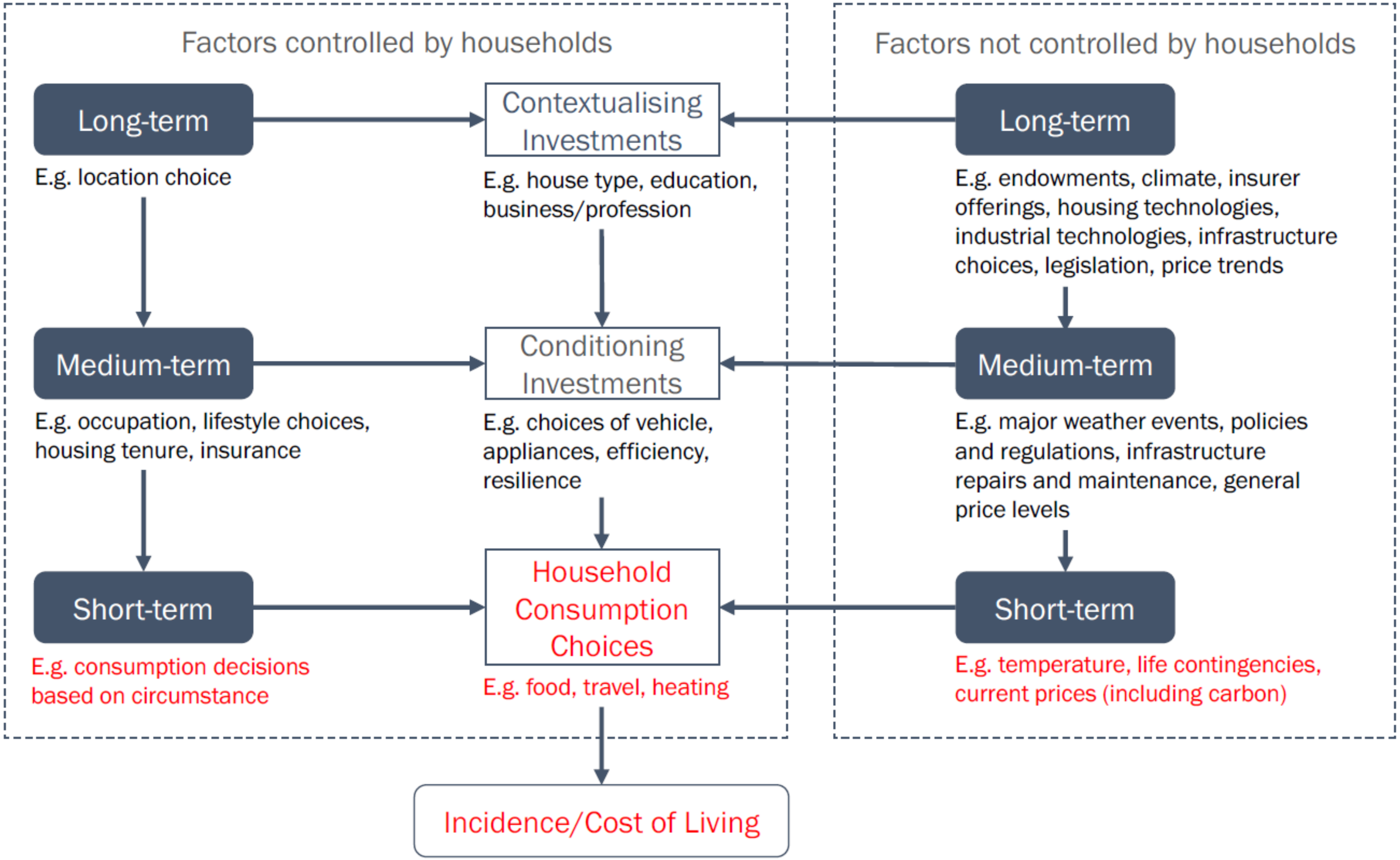
[93] See Meade (2017) for a more comprehensive discussion of the incidence of emissions charges, and how they are affected by longer-term choices.

Figure 6.1 – Impacts of Long-Term Choices on Short-Term Energy Choices and Associated Cost of Living



Source: Meade (2017), Figure 3.3.

295. Bans on further exploration for fossil fuels, or on new connections to fossil fuel infrastructures, could be counterproductive:

295.1. In particular, they could serve to impede or deter low-cost retrofitting on existing vehicles/appliances, and/or efficient repurposing of existing fossil fuel infrastructures;

295.2. This could make it necessary to invest in higher-cost alternative infrastructures, and to convince users and suppliers to coordinate on migrating to such infrastructures.

296. Bans on emitting uses of fossil fuels and their associated infrastructures – rather than on those fuels and infrastructures themselves – would seem to better fit the objective of transitioning to net-zero emissions, to the extent retrofitting and repurposing is a more viable alternative to building entire new infrastructures and requiring the wholesale replacement of fossil fuel based vehicles and appliances.

6.3 Policy Levers to Encourage Uptake of Low-Emissions Technologies ("Pull" Measures)

Demand-Side Policy Levers to Encourage Low-Emissions Technologies

297. Emission taxes and purchase taxes make the ongoing use of emitting technologies less attractive. Natural flipsides of these to encourage the uptake of clean technologies include:

297.1. Clean fuel subsidies – e.g. making clean fuels low-cost or even free, to enhance the attractiveness of running clean technologies;[94] and

297.2. Clean hardware subsidies – e.g. the "rebates" part of "feebates" for low-emissions vehicles.[95]

[94] This is more feasible for BEVs charged from special chargers, since they can be charged different prices than for other electricity uses. It would be facilitated more widely by smart metering technologies that could distinguish preferred uses such as heating using energy-efficient hardware.

[95] How feebate schemes are funded can have important equity implications. If low-income households cannot afford low-emissions technologies they could bear a disproportionate share of the cost of feebate schemes while higher-income households benefit from them. Meade (2021b) discusses equity issues arising with feebate schemes, and associated research.

298. Evidence on the uptake of alternative fuels like CNG and LPG show that such support measures are important for inducing uptake.[96]

299. Subsidies for the purchase of low-emissions hardware can be doubly beneficial for uptake:[97]

299.1. They directly encourage uptake by reducing the cost of buying such hardware; and

299.2. They also do so indirectly by increasing the market for the associated clean energy infrastructure (e.g. BEV recharging networks), which supports greater rollout of such infrastructure, reinforcing the attractiveness of buying the low-emissions hardware (e.g. by reducing range anxiety for BEV buyers).

300. As well as reducing the costs of buying and using low-emissions technologies, other policies can help with positively encouraging uptake by consumers. These include de-risking users' decision to adopt low-emissions hardware (vehicles, appliances, etc) – e.g. by:

300.1. Mandating general use of the relevant technologies from some fixed future date – reducing the risk that earlier adopters are left holding redundant technologies that fail to take off;

300.2. Establishing certification schemes and providing consumer information to make buying of used low-emissions hardware easier to understand and more assured;

300.3. Enabling leasing of new hardware (instead of requiring purchasing), or guaranteeing minimum buyback/trade-in prices for the purchased hardware; and

300.4. Establishing recycling or repurposing infrastructure – e.g. for end-of-life BEV batteries.[98]

301. This also includes "soft" subsidies like free parking, exemptions from road tolls, and access to bus/transit lanes – such measures either further reduce direct travel costs, or indirect travel costs (e.g. travel time, travel time variability, etc).

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[96] Hu and Green (2011).

[97] Yu et al. (2016).

[98] BEV batteries can be suitable for less-demanding uses even when they are no longer adequate for transport purposes – hence "second life" applications such as providing low-cost storage for residential PV systems.

Supply-Side Policy Levers to Encourage Low-Emissions Technologies

302. As for supply-side "push" measures, any "pull" measures that induce greater demand for low-emission technologies helps to establish markets for suppliers of the required hardware and energy infrastructure. This serves to indirectly encourage greater supply of the required hardware and energy infrastructures:

302.1. Mandating that energy infrastructures must be capable of a certain level of low-emissions service delivery from a specified future date can also encourage the required level of supply – it diminishes the ability of suppliers to differentiate themselves in terms of low-emissions offerings, but it gives them greater confidence that investing in new technologies will not become stranded (as they might if they act unilaterally);

302.2. This could be achieved, for example, by requiring electricity distribution networks to be able to support a certain number of BEV rechargers, or petrol station operators to have a minimum number of hydrogen refuelling pumps per station, from a specified date.

303. Previous sections have emphasised the likely pivotal role that large vested interests are likely to play in resolving "chicken and egg" issues that plague the uptake of new technologies. By taking the lead in developing new infrastructures, out of their own self-interest, this creates benefits for other users by giving them greater confidence that they and other users will be able to access the new hardware and infrastructure supported by those vested interests' investments:

303.1. Such commitments can provide critical and credible focal points for the rollout of new technologies, especially those featuring large scale economies and network effects.

304. In fact these private incentives for uptake new technologies may not be strong enough to induce uptake at the socially-desirable pace or scale. This is because of public good aspects of the associated networks (i.e. once they are established, it is not always possible to preclude others from using them, and hence from free-riding on previous investments):[99]

[99] Katz and Shapiro (1994).

304.1. This means public subsidies or co-funding for the required infrastructure can be justified if accelerated infrastructure rollout, or rollout of a specific type or quality, is desired;

304.2. New Zealand's subsidised rollout of fibre-based UFB is an example of such a policy being used (as discussed in Section 5.4).

305. Such public funding could have the dual benefit of providing a certain degree of government commitment to low-emissions technologies being rolled out, though see the discussion below of commitment issues in Section 6.4.

306. Other supply-side "pull" measures include government assistance with other forms of coordination, e.g.:

306.1. To assist local suppliers to participate in global standard setting processes, and to create and tailor standards appropriate to local circumstances;

306.2. Creating forums for local hardware suppliers and energy infrastructure providers to coordinate with major vehicle manufacturers and infrastructure technology providers (as well as organisations responsible for training installers and repairers of new energy technologies); and

306.3. Perhaps even considering transitioning New Zealand roads to left-hand drive (i.e. driving on the right) – to enable local suppliers, users, and infrastructure providers to access deeper global supplies of hardware and technology.

307. Given the likely pivotal role to be played by large vested interests in rolling out clean energy infrastructures – including by New Zealand's existing major energy companies (but also other companies) – policy levers to support their rollout could also be considered if those parties' self-interest is insufficient to induce them to spearhead investment. These policy levers would likely involve a suite of both push and pull measures, such as:

307.1. A pre-specified phased reduction in fossil fuel energy supply over time;

307.2. Targets or mandates for clean energy infrastructure rollout, perhaps supported by regulatory bonuses or penalties;

307.3. Regulatory oversight of platform investment, service delivery and pricing; and

307.4. Franchise bidding to have exclusive rights to own and operate new clean energy infrastructures, enabling platform providers to charge below-cost prices for platform usage in early phases to encourage platform adoption buy users (penetration pricing), but be able to charge prices high enough to provide required investment returns over the infrastructure's entire life.

308. Franchise bidding means effectively auctioning the right to have exclusive ownership and operation rights:

308.1. The rights would be time-limited, and could provide for the infrastructure to be surrendered to public ownership at conclusion of the franchise (at which point it could be re-auctioned) – much like "build, own, operate, transfer" (BOOT) schemes used to develop toll roads and other infrastructure;[100]

308.2. Auction proceeds could be used to subsidise the cost of hardware purchasers by platform users (with targeting to address equity issues), reinforcing the viability of the new infrastructure by supporting demand for its services – this serves to not only encourage users to migrate to the new platforms, but also provides them with a degree of insulation against any over-charging by the platform owner once take-off penetration levels have been achieved.

309. The purpose of such a scheme would be to change the payoffs of vested interests, inducing parties who can generate the most value from building new clean-energy infrastructures to do so:

309.1. Those parties could include individual large energy companies or other vested interests, or consortia of such interests;

309.2. Owners of existing energy infrastructures could have particular incentives to buy the right to develop the new ones, to ensure they minimise value losses from their existing assets, maximise the value that can be generated from new energy infrastructures, and at the same time achieve a pre-set transition to low-emissions technologies in a phased and orderly way.

[100] An alternative would be for the government to purchase the infrastructure at market value at a certain date, which better preserves the infrastructure owner's investment and maintenance incentives in the lead-up to any such purchase.

310. New Zealand's transition from copper-based internet to fibre-based UFB (as discussed in Section 5.4) is an example of a similar mechanism working in practice:[101]

310.1. Incumbent internet providers initially opposed the scheme;[102]

310.2. However, in the event, the lion's share of the UFB investment was awarded to Chorus, the dominant internet services provider with a vested interest in its copper telephone lines infrastructure, who stood to lose the most if a rival rolled out UFB and stranded its copper network with no countervailing revenue stream.[103]

6.4 General Policy Levers

311. More generally, the following policy levers should also be considered:

311.1. Tools for creating focal points about which suppliers, users, and platform providers can coordinate their transition to low-emissions technologies (e.g. mandating use of specific technologies from pre-specified future dates) – reducing strategic uncertainties, and thereby accelerating uptake;

311.2. Tools for increasing the commitment power of policymaking – such as devolving relevant policymaking to independent bodies with objectives set by statute and insulated from political whims (like independent central banking legislation, and perhaps using a variation on New Zealand's Climate Change Commission);

311.3. Wider regulatory/policy coordination – i.e. across urban design, transport policy, energy sector, etc, to avoid conflicts and to ensure policies and regulations work in a complementary way to achieve net-zero objectives;

311.4. Creating suitable safe harbours from competition laws that would otherwise prohibit firms within industries from coordinating their investments and other business decisions to maximise uptake of clean technologies;

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[101] For details, see https://www.crowninfrastructure.govt.nz/ufb/who/.

[102] For example, see https://www2.computerworld.co.nz/article/492710/opinion_castalia_report_-_right_diagnosis_wrong_prognosis_/.

[103] The other successful bidders were either customer-owned electricity distribution businesses that saw an opportunity to accelerate UFB access to populations that might otherwise be underserved, or a municipal-owned concern with a similar local development focus. See Meade (2021a).

311.5. Government sponsoring sectoral and pan-sectoral bodies to coordinate complementary investments across sectors in order to support the development of entire new clean-energy ecosystems (again, with suitable safe harbours from competition law prohibitions);

311.6. Relatedly, regulatory forbearance of post-take-off pricing on new clean energy platforms, if sub-cost (penetration) pricing was adopted earlier in order to support platform adoption – perhaps accompanied by hypothecating proceeds from franchise bidding auctions to provide subsidies to purchasers of clean energy hardware (targeted to minimise equity issues); and

311.7. Government supporting coordination activities by regulators and private parties with key international partners, such as major vehicle manufacturers, standards setting bodies, clean energy technology providers, etc.

312. Table 6.1 summarises the push, pull and general policy levers relevant to achieving New Zealand's net-zero transition.

Table 6.1 – Policy Levers that might be used to Accelerate the Transition to Net-Zero Emissions

	"Push" levers (Discouraging emissions)	"Pull" levers (Encouraging low-emissions)	General levers
Demand-side levers (interact with supply-side due to indirect network effects)	Price measures: • Emissions pricing (reflecting network effects as well as environmental costs) • Levies on emitting hardware	Price measures: • Clean fuel subsidies • Clean hardware subsidies • Parking or toll road subsidies for clean transport users	• Creating coordination focal points for hardware suppliers, consumers/users, and infrastructure providers • Increasing commitment power of long-term policies (e.g. independent policy-making and implementation) • Wider regulatory/policy coordination – urban design, transport, energy, etc • Safe harbours from competition law prohibitions on desirable industry coordination • Regulatory forbearance for whole-of-life infrastructure pricing – e.g. sub-cost initial pricing to accelerate uptake, followed by higher later pricing to achieve required lifetime fair returns)
	Non-price measures: • Sunset clauses (hard, soft) • Technology targets/ mandates	Non-price measures: • Sunset clauses (hard, soft) • Technology targets/ mandates • Certification/consumer information • Hardware leasing, or guaranteed buy-backs/trade-ins • Solutions for new technology end of life (e.g. battery recycling)	
Supply-side levers (interact with demand-side due to indirect network effects)	Price measures: • Emissions pricing • Levies on emitting hardware	Price measures: • Subsidies or co-investments for new infrastructure	
	Non-price measures: • Sunset clauses (hard, soft) • Technology targets/ mandates • Progressive bans on emitting uses of fossil fuels, or on fossil fuel exploration • Coordination/cooperation measures	Non-price measures: • Targets/mandates for minimum clean infrastructure capacity and service levels • Franchise bidding for monopoly rights to develop clean infrastructure(s)	

7. Conclusions

Key points from this section:

1. We should heed the lessons of both history and research for what matters in migrating from existing technology platforms to new ones.
2. Resolving coordination issues will be key to ensuring a timely, efficient, equitable and orderly transition to low-emissions technologies.
3. Many policy levers exist to influence the transition, but using them to harness the resources (including legacy infrastructures), capabilities and incentives of large vested interests to spearhead the transition will be critical to success.

313. It is perhaps surprising that the challenges facing New Zealand in achieving its transition to net-zero emissions are in many ways similar to those arising at the dawn of the age of the automobile in the late 19th century:

313.1. Then, as now, ICEVs vied with BEVs (and steam road vehicles) to be the successor to a transport technology that had been dominant for millennia – the horse;

313.2. Then, as now, ICEVs enjoyed a head start – an established infrastructure for refuelling (petrol as a by-product of kerosene production sold as a solvent in general stores or pharmacies), and fundamental advantages over BEVs in terms of travelling range and refuelling time;

314. Figure 7.1 represents a reminder from New Zealand's own past, when battery electric vehicles were temporarily popular before being displaced by ICEVs.

315. The difference between then and now is that ICEVs are already dominant, their alternatives are not clearly superior in all material dimensions, and allowing them to remain dominant over lower-emissions alternatives is not tenable given the urgency of transitioning to net-zero. Active measures are required, but not simply dismantling the ICEV energy ecosystem without having a viable means of replacing it with a low-emissions alternative. That would risk major social and economic disruption. Synchronising the reduction in fossil fuel use with the rise of clean energies from supply chains that are not yet formed will be no mean feat.

Figure 7.1 – Reminder from New Zealand's Past – Temporary Popularity of Electric Passenger and Delivery Vehicles in 1920s

Source: Rennie (1989, p. 82). Parade of all Christchurch electric vehicles in 1921. Christchurch electricity supply benefitted from the government's first generation and associated transmission construction project at nearby Lake Coleridge (operating from 1914). Dairy processors were also early adopters of electric vehicles, with processing factories having electricity supplies that could be used for recharging. As in other countries, ICEVs soon displaced electric vehicles, due to their greater range and speed, and shorter refuelling times.

316. The challenge is not simply confined to a wicked coordination problem among 1.7 million households, thousands of businesses, and perhaps hundreds of large industrial concerns as to what transport technologies they might prefer. It extends to entire energy ecosystems, taking in a wide range of sectors, and touching on domains like housing design, urban design as well as public and private transport infrastructures, and choices about heating/cooking and process heat technologies. This is especially the case allowing for the fact that choices will need to be made among competing alternatives, only one or few of which might prove viable in the longer-term.

317. Policy can quite easily undermine the decades of investment and coordination that resulted in the current fossil fuel system. It is a much more challenging balancing act for

policy to help engineer the many investments in hardware (vehicles, appliances, equipment) and energy infrastructure (i.e. clean energy supply chains) required to produce something to replace that system. Certainly if policymakers wish for the required transition to occur in a timely, efficient, equitable and orderly way.

318. In engineering the required transition it will be important not to throw the baby out with the bathwater. Preconditions matter, and legacy infrastructures can either be policymakers' best friend or worst enemy in the transition. The owners of those legacy infrastructures represent large vested interests that would prefer not to have their decades of vast investments rendered worthless by the transition to net zero, and have the resources to defend those interests.

319. More importantly, given the surety of a migration away from burning fossil fuels, they also have an immense vested interest in being part of the solution, with the balance sheets and technical capabilities to do so. The challenge for policymakers is to harness – or engineer – this incentive. Repurposing existing energy infrastructures to develop low-emissions alternatives is a potential means of doing so. Where doing so is not naturally in the interests of existing infrastructure owners, policy might be used to make this the case.

320. Not only could this be the most cost-effective pathway to developing viable low-emissions energy infrastructures without having to establish them from scratch (which could take decades – much longer than an urgent transition to net-zero allows). It could also represent the most viable way of harnessing the interests of existing energy suppliers to lead the way to the net-zero transition.

321. Doing so would credibly signal commitment to developing a particular low-emission pathway, which then helps hardware suppliers and consumers determine which technology they should coordinate on. In turn that would create a virtuous circle with clean energy infrastructure development, with both investors and users clear about the pathway ahead.

322. Much of this study has focused how to resolve the complex coordination problems arising in transitioning New Zealand's 1.7 million households from using their 3.5 million ICEVs to clean alternatives. This is because the emissions from private transport are significant, and the coordination problems are most pronounced.

323. However, in practice, the pathway to achieving net-zero emissions will start with the smaller number of large concerns whose choices could prove pivotal in spearheading the

development of clean energy platforms. These include large industrial energy consumers, large transport system users, and large energy providers.

324. There are many policy levers that can be used to engineer an orderly migration from fossil fuels to low-emissions energy platforms – once key strategic questions are resolved about whether to simply let rival low-emissions technologies vie for ascendancy, or to accelerate the transition by committing to a particular low-emissions platform. Using those levers to harness the incentives of those large concerns to spearhead the transition will be critical to success.

325. Using policy to coordinate the transition of smaller users will support this, but recruiting those larger users could not only be the line of least resistance to net-zero. Absent a large and credible government commitment to build the necessary low-emissions technology infrastructures well ahead of demand materialising, it could be the only way to achieve a timely, efficient, equitable, and orderly transition.

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