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Economics of using green hydrogen to decarbonise long-distance heavy freight in New Zealand: Stage 1 review of existing studies

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Executive Summary

Motivation

Ara Ake has engaged NERA Economic Consulting to conduct a review of the economics of using green hydrogen[1] to decarbonise long-distance heavy freight (LDHF) in New Zealand. The research question we were asked to address is, **"what needs to be true for green hydrogen to be the most economic path to decarbonising LDHF?"**.[2]

New Zealand's heavy truck fleet contributes 27% of all transport emissions but accounts for only 7% of total annual travel.[3] As MBIE's *A Vision for Hydrogen* green paper notes, it is unlikely there will be a single pathway that will decarbonise the entire transport sector.[4] Even narrowing to heavy freight, categorised as goods vehicles over 12 tonnes,[5] multiple decarbonisation alternatives will likely be required. This is due to the differing demands of vehicle tasks (such as distance, weight carried or number of stops) and the suitability of different low- and/or zero-emission alternatives for each task. The appropriate decarbonisation path for LDHF (distinct from heavy freight) is particularly uncertain due to the range and weight demands of the task.

Fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs) represent different onboard fuel storage options to power an electric motor. Both "e-trucks" are being promoted as solutions to decarbonise LDHF. The current advantage FCEVs have is that, relative to BEVs, they can carry more cargo and complete long-distance trips without needing to refuel as often. This is because of the current low energy density of batteries; put simply, batteries are currently heavy relative to the energy they carry. In freight applications, this results in a trade-off whereby BEVs must either carry more batteries (and therefore less freight) to avoid needing to stop and recharge or carry fewer batteries (and more freight) but need to stop and recharge more often. FCEVs and traditional diesel-powered internal combustion engine vehicles (ICEVs) do not experience this trade-off to the same extent and, therefore, can carry more freight for longer without stopping.

A primary argument against FCEVs is that converting electricity into hydrogen for the purpose of then returning it to electricity to power an electric motor is inherently less efficient than powering that motor directly with electricity. This is due to the energy losses associated with producing hydrogen, compressing it, storing it and converting it back to electricity. Example estimates of electrical efficiency are about 70% to 90% for BEVs compared to about 25% to 35% for FCEVs.[6]

The question of whether BEVs or FCEVs are the more economic option for LDHF therefore depends predominantly, but not exclusively,[7] on whether the payload and refuelling advantage FCEVs have

[1] Hydrogen is not a primary energy source, but a form of storing potential energy converted from a primary energy source that can then be used towards a wide range of applications, for example, industrial feedstock and/or process heat, grid energy backup, or heating businesses and residences. "Green hydrogen" is hydrogen produced using renewable electricity. In the context of LDHF, hydrogen can be converted back into electrical energy in a device called a fuel cell, which emits only heat and water as a by-product, to power an electric motor in a vehicle. Green hydrogen is therefore regarded as a zero-emission fuel.

[2] By "needs to be true", we mean "under what assumptions".

[3] Ministry of Transport, *Annual fleet statistics 2018*, p15. Emissions profiles for more recent years are, to our knowledge, unavailable.

[4] MBIE, *A Vision for Hydrogen in New Zealand*, September 2019 (MBIE Green paper), p48.

[5] New Zealand Transport Agency (NZTA), NZTA – Vehicle Classes webpage, accessed 15/12/20 from: https://www.nzta.govt.nz/vehicles/vehicle-types/vehicle-classes-and-standards/vehicle-classes/#NC

[6] Volkswagen. See Figure 1.1.

[7] For example, using hydrogen in place of freight is also argued to have additional benefits to the energy system by nature of its ability to more easily store large volumes of energy than is possible with batteries.

over BEVs offsets (and is expected to continue to offset) the electrical inefficiency of using electricity to produce hydrogen and power a FCEV.

There are, of course, other options for decarbonising LDHF, such as blue hydrogen (hydrogen produced from hydrocarbons such as natural gas, with the carbon sequestered and permanently stored using carbon capture and storage (CCS) technology), biofuels, cleaner-burning fossil fuels, modal shift (rail and coastal shipping) or combinations of alternative fuels and modal shift.

In theory, if there are no market failures or coordination problems requiring government (or other) intervention or funding, market forces should determine whether a technology such as green hydrogen forms part of the least-cost path to decarbonisation. Indeed, the idea behind market-based approaches such as the New Zealand Emissions Trading Scheme (ETS) is that if a high enough price for carbon is signalled, then the role of government in determining what technologies should be adopted to decarbonise LDHF (or any other sector for that matter) is limited.

However, governments' decarbonisation objectives coincide with many low-emission technologies still being in nascent stages of adoption and commercialisation. At the same time, the current NZ ETS price is substantially lower than the prices required to achieve a material amount of decarbonisation activity in the near-term.[8] This means that centralised funding and decision making by governments and other bodies, rather than market forces, are influencing the decarbonisation path.

Although government action can help resolve coordination problems, when there is material uncertainty (as is the case for LDHF), this creates a risk of investing in technology that is subsequently overtaken by technology which progresses at a faster rate. This is particularly a risk for New Zealand, compared to major global players, as we are likely to be a "technology taker".[9] This could result in outcomes where New Zealand becomes locked into an inferior technology (and thus pays higher prices and/or receives lower quality in the long run) with the risk that assets could eventually become stranded.[10] Another risk is that present investments may not be made to progress a particular technology, based on the assumption that a different technology will become more affordable at a later date. If this fails to occur, then decarbonisation targets may be missed or could be more costly to achieve if a sharper decarbonisation path is subsequently required.

Given these risks and that New Zealand is likely to be a technology taker, a prudent approach could be for government to adopt a diversified investment strategy and invest in numerous technologies. This would mean that when the uncertainty is resolved or reduced, New Zealand is well-positioned to efficiently progress those technologies that provide an economic means of decarbonising freight movements.

Scope of the project and this report

To account for these risks and to reconcile the divergent views on the economics of using green hydrogen to help decarbonise LDHF, Ara Ake asked us to provide an independent review of the economics of green hydrogen in LDHF. This review has four potential stages:

- **Stage 1:** Review the existing literature on green hydrogen applied to LDHF in New Zealand;

[8] New Zealand Productivity Commission , *Low-emissions economy: Final report*, August 2018. (NZPC Low-emissions economy report)

[9] New Zealand is a very small market compared to major economies such as the United States and China, which have large markets and invest heavily in developing technologies. Any new technologies would be imported from overseas, and therefore New Zealand's investment will not influence any economies of scale achieved in these technologies.

[10] This risk is, of course, a function of the level of investment required – the smaller the necessary investment, the less of a concern lock-in and stranding are.

- **Stage 2:** If gaps are identified in Stage 1 in answering the research question thoroughly, conduct our own modelling of the economics of green hydrogen in LDHF with a focus on filling those gaps;
- **Stage 3:** If green hydrogen appears to be economic, identify risks and potential impediments (funding, coordination/public good issues, externalities, market structure, business models, etc) that might impede the development of green hydrogen; and
- **Stage 4:** Identify potential solutions to issues identified in Stage 3.

This report covers Stage 1. We have reviewed all *publicly available* New Zealand-focused studies that discuss the potential role of green hydrogen for decarbonising LDHF.[11] We restrict our focus to studies which account for the nuances of the New Zealand economy and geographic nature of the freight task, although we have relied on international literature for support in our review where appropriate.

To review the existing body of evidence on this question, we developed a framework for assessing the economics of green hydrogen. This framework, referred to as the "**economic framework**", is how we think the research question should be answered. It **compares the net social benefit (i.e. total social benefit less total social costs) of each decarbonisation alternative examined**.[12] Note that "social" in this context means considering the economic costs and benefits from a national or economy-wide perspective, rather than assessing non-economic considerations such as equity and fairness.[13] The economic framework gives us a benchmark against which to assess the robustness of existing studies, while remaining "fuel agnostic". That is to say, while the motivation for the report is the recent increase in interest and investment in green hydrogen, our focus is on assessing the most economic path for decarbonising LDHF, regardless of the fuel (or indeed mode) used.

The economic framework forms part of the **"assessment framework"**, which involves assessing:

- Whether the studies apply the appropriate economic framework;
- Whether the studies adequately capture the relevant costs and benefits; and
- The robustness and transparency of any modelling that is conducted.

Of course, each past study had its own specific research question(s) and each presented its results in a different way to the ideal set out in our assessment framework. This is to be expected. The critiques in this report should therefore not necessarily be interpreted as an indication of the quality of the past work we have reviewed – it may simply indicate that the studies are answering a different question and have a different purpose.

That being said, transparency of any modelling is paramount to ensure that future funding and policy decisions are supported by complete and accurate information. Providing transparency around the assumptions used in the different studies and reconciling the different conclusions reached is one of the major purposes of the Stage 1 review.

As part of this first stage, we have engaged with numerous stakeholders in the transport and energy sectors in New Zealand to obtain feedback on the economic framework we have adopted and to

[11] This is an important caveat to conclusions drawn from our Stage 1 review. Given the nascent application of the technologies we are discussing, information from public studies that are only a year or two old can quickly become out of date.

[12] Noting that the scope of this report is such that we examine only the alternatives considered by the studies reviewed. This is discussed further in section 3.5.

[13] See, e.g., New Zealand Treasury, *Guide to Social Cost Benefit Analysis*, July 2015, accessed 16/12/20 from: https://www.treasury.govt.nz/sites/default/files/2015-07/cba-guide-jul15.pdf. For example, a carbon tax is one way to create a "price" for a social cost which can be considered in an economic framework.

ensure we are reviewing the right studies (i.e., a complete list of existing studies which examine the future of LDHF in New Zealand specifically including consideration of green hydrogen and FCEVs).

Table X.1 sets out the public domain studies we have reviewed. The colour coding indicates whether the studies contain quantitative economic modelling of using green hydrogen for LDHF (blue shading) or are a qualitative review of LDHF alternatives including green hydrogen (green shading).

Table X.1
New Zealand studies assessing the future of LDHF that consider green hydrogen

Study	Year	Depth
Modelling Hydrogen Pathways for MBIE, Castalia	2020	Economic analysis (model results)
Hydrogen in NZ, Concept Consulting for MBIE, Energy Efficiency & Conservation Authority (EECA), Contact, Meridian, Powerco, First Gas	2019	Economic analysis
H2 Taranaki Roadmap, Venture Taranaki/Hiringa Energy/New Plymouth District Council	2019	Review/Economic analysis
Gas Infrastructure Futures in a Net Zero New Zealand, Vivid Economics for First Gas and Powerco	2018	Economic analysis
Green Freight Strategic Working Paper and Background Paper, Ministry of Transport (MoT)	2020/ 2019	Review and qualitative discussion of costs and challenges
A vision for hydrogen in New Zealand: Green Paper, Ministry of Business, Innovation and Employment (MBIE)	2019	Review and qualitative discussion of costs and challenges
House View: Hydrogen, Z Energy	2019	Review and qualitative discussion of costs and challenges
Low Emissions Economy Report, New Zealand Productivity Commission (NZPC)	2018	Review and qualitative discussion of costs and challenges

Findings based on existing quantitative studies

All existing quantitative modelling we have reviewed focus on estimating only the private costs of using different fuels for a given truck. Private costs represent only one component of a potentially broader question that looks at the socially optimal[14] method of reaching net zero carbon emissions for LDHF, noting that if there were no market failures or externalities, these would be the same thing. The studies do not, and were not scoped to, look holistically at the heavy freight fleet in New Zealand and its fuel use and mode of transport, including:

- The ability of owner-operators *en masse* to purchase new-technology vehicles;
- What happens in the interim "waiting period" before the commercial availability of technology becomes widespread and its total cost of ownership becomes competitive with conventional options;
- Modal shift – the shifting of some freight to rail and coastal shipping would reduce total emissions, with other benefits including less traffic congestion and less wear and tear on the roads; and
- A full life cycle analysis of alternative options with a New Zealand lens, taking into account impacts on the environment, emissions concerning the construction and disposal of trucks, human

[14] Note that by socially optimal, we mean this in an economic sense, i.e., considering economy wide costs and benefits.

health and supply-chain economic impacts (e.g., transitional costs due to job dissolution and creation).

The quantitative studies to date define an “end point” under their various assumptions, being a comparison of the total cost of ownership (TCO) for different vehicles and fuels at some point in the future. They do not reach conclusions on the cost of a transitional path with the points above in mind. These studies also almost exclusively analyse green hydrogen FCEVs and BEVs against diesel ICEVs, and do not consider other alternative fuels or modal shift, as demonstrated by Table X.2. Table X.3 sets out the conclusions of these analyses.[15]

Table X.2
Alternatives to decarbonise LDHF quantitatively modelled in each study[16]

	Castalia	Concept	H2 Taranaki Roadmap	Vivid
Green hydrogen / FCEVs	✓	✓	✓	✓
Blue hydrogen / FCEVs	✗	✗**	✗**	✗
Direct electrification / BEVs	✓	✓	✓	✗
Advanced biofuel / ICEVs	✗	✗	✗	✗
Diesel + carbon offset / ICEVs	✓	✓	✓*	✓
Modal shift to rail or coastal shipping	✗	✗	✗	✗

** These studies review blue hydrogen for uses other than LDHF.
* It is not clear that a carbon price is included in the assessment of diesel.

Table X.3
Summary of quantitative findings in studies reviewed

Study author	Commissioned by	Quantitative conclusions
Castalia	MBIE	The base case finds that FCEVs are more expensive per kilometre than BEVs until after 2040 but converge with BEVs before 2050. ICEV cost per kilometre passes above a BEV before 2030 and above a FCEV before 2035. However, vehicle weights and payloads are not provided and could have significant influence on results (e.g., lighter trucks).
Concept	MBIE, EECA, Contact, Meridian, Powerco, First Gas	Across all scenarios, BEVs are likely to be the least-cost option per kilometre and per tonne-kilometre for heavy vehicles, although both e-trucks are likely to become less expensive than ICEV use by 2040. FCEVs only begin to be competitively priced in the long term with BEVs in the scenario where battery technology is not assumed to improve.

[15] A detailed review of each of these analyses is provided in section 6 of this report.

[16] The scope of this report is such that we examine only the alternatives considered by the studies reviewed. This is discussed further in section 3.5.

Study author	Commissioned by	Quantitative conclusions
H2 Taranaki Roadmap	Venture Taranaki, Hiringa Energy, New Plymouth District Council	The single scenario modelled finds that per tonne-kilometre, FCEVs are immediately less expensive than BEVs, even using a fast charger, and become competitively priced with ICEVs using diesel by 2030.
Vivid	First Gas and Powerco	Vivid only models diesel ICEVs against a high and low FCEV scenario in 2050, which is quite distant. Vivid's conclusion is by 2050, FCEVs are likely to be roughly the same price per kilometre as diesel ICEVs *before* applying a carbon price for the heaviest class of freight vehicles.

Each of these studies reaches different conclusions due to the fact that each analysis applies differing inputs and assumptions in terms of both the costs included and the level/path for each cost. Through our review, we have found that the factors set out in Table X.4 appear to have a large influence on the study conclusions about the competitiveness of FCEVs and BEVs.

Table X.4
Influential factors driving conclusions in quantitative studies comparing FCEVs and BEVs

Factor	Discussion
Speed of underlying technology cost reductions will likely determine which e-truck has a lower TCO.	Even allowing for the reduced capability of BEVs to carry large payloads presently, the capital cost of FCEVs and electrolysis would need to reduce more quickly than costs for battery technology. The Concept, Castalia and H2 Taranaki Roadmap analyses each show that the longer term TCO of FCEVs using green hydrogen depend on costs dropping more quickly for this alternative than for BEVs.
Battery recharging and weight issues persisting into the future will disadvantage BEVs for LDHF in the longer term.	If the disadvantages faced by BEVs in terms of reduced payload and the need to stop and recharge during a long-distance freight trip persist into the future, BEVs will be unlikely to compete with FCEVs in LDHF. Both Concept and the H2 Taranaki Roadmap modelling demonstrate that BEVs' TCO is highly impacted by these issues.
A substantially higher carbon price is needed to disincentivise continued diesel use.	As an indicative price reference, Concept applies a \$100/t CO_2e in 2040, finding that e-trucks would be cheaper than diesel in ICEVs by that point in time. Castalia does not disclose its carbon price assumption, but its analysis implies the price would need to rise to at least \$75/t CO_2e by 2035 for FCEVs to outcompete diesel. If restrictions on diesel imports are imposed, this would also likely increase the TCO of diesel.
Off-peak production (or dedicated renewable generation) is needed for green hydrogen to take advantage of lower electricity prices.	The Concept and Castalia modelling demonstrate that the assumed cost of electricity has a significant impact on the cost of producing green hydrogen. Because hydrogen is essentially a method of storing energy, it breaks the link between the time electricity is generated and when the vehicle needs to be refuelled (unlike present BEV charging). This means production of hydrogen can occur largely outside of peak hours (if grid connected) or by direct connection to embedded renewable generation. Green hydrogen can thus take advantage of non-peak electricity prices or the low cost of intermittent renewable generating capacity while still providing refuelling outside of the hours it is producing. If electrolysers were impeded from taking advantage of this lower cost of electricity, it would increase the barriers for hydrogen FCEVs to become economic by orders of magnitude due to green hydrogen fuel's greater (relative to BEV) demand for renewable energy. The Concept analysis and Castalia modelling assume the same underlying electricity pricing for BEVs and FCEVs; however BEVs may not be able to achieve the same price in practice (see Table X.5).

Factor	Discussion
Road User Charge (RUC) exemptions on e-trucks don't appear to be needed in the longer term for FCEVs or BEVs to become competitive with ICEVs.	RUC exemptions, which currently only exist for BEVs, don't appear to be needed in the longer term for e-trucks to be competitive with ICEVs if the other factors in this table hold. For example, the Concept modelling includes no RUC exemptions and finds that BEVs and FCEVs will become competitive with diesel ICEVs. The H2 Taranaki Roadmap modelling has RUC exemption initially and then removes it. This analysis demonstrates that RUC exemptions appear to have a significant effect on the cost per tonne-kilometre.

As already noted, the quantifications in these studies focus on the end point and do not consider whether alternatives such as biofuels, blue hydrogen, cleaner-burning fossil fuels (e.g., methanol) or modal shift might form part of either the immediate path or longer term end point of decarbonisation in this sector. Therefore, we find that existing studies and the relevant analyses within have not provided a thorough answer to the most economic method of decarbonising LDHF in New Zealand.

Unquantified issues and opportunities across all studies

In addition to the quantitative analyses, the studies listed in Table X.1 contain discussion on unquantified issues and opportunities around each of the alternatives set out in Table X.2.[17] Our review identified a number of factors that were not explicitly quantified in the analyses of green hydrogen FCEVs, BEVs and diesel ICEVs and considerations around the other unquantified alternatives that in our view would have a material impact[18] on the factors that need to be true for green hydrogen to be the most economic method of decarbonising LDHF. These are summarised in Table X.5.

Table X.5
Material non-quantified issues and opportunities using alternative decarbonisation methods for LDHF[19]

Alternative	Non-quantified issues	Non-quantified opportunities
Green hydrogen / FCEVs	▪ The platinum problem, including sourcing and recycling.[20] ▪ Availability and pricing of FCEVs suitable for NZ conditions. ▪ Opportunistic production when electricity prices are low may not be viable if peak/off-peak differentials reduce and TPM pricing increases charges for off-peak use.	▪ Longer life of fuel cells vs batteries reduces lifetime costs of FCEVs compared to BEVs. ▪ Increased energy security/resiliency if produced locally. Additional benefit from decentralised production.

[17] That is to say, across the entire list of studies each alternative is discussed. Not all studies discuss each alternative. See section 5 for detailed discussions of each study.

[18] We discuss various other factors in section 7 that are viewed as less material, in an economic sense, either because their impact is not expected to be great or because there are potential mitigations.

[19] The scope of this report is such that we examine only the alternatives considered by the studies reviewed. This is discussed further in section 3.5.

[20] Platinum is a critical component to fuel cells (under current technology), and platinum is a rare and expensive metal. Therefore, large-scale adoption of FCEVs globally will likely require a substitute for platinum to be developed or technological advances that reduce the amount of platinum required to run an FCEV. Additionally, recycling platinum at the end of the life of the fuel cell is costly. As we discuss in section 3.1, research is already underway to find alternatives to platinum as a fuel cell catalyst.

Alternative	Non-quantified issues	Non-quantified opportunities
Blue hydrogen / FCEVs	▪ Same platinum and FCEV issues as per green hydrogen. ▪ CCS technology is developing but not yet widely established. ▪ If only a transition fuel, stranding risk if zero-emission alternatives become commercial earlier than anticipated.	▪ Blue hydrogen may initially be much cheaper to produce than green hydrogen.
Direct electrification / BEVs	▪ The lithium and cobalt problems, including sourcing and recycling.[21] ▪ As per FCEVs, availability and pricing of BEV trucks meeting NZ specifications. ▪ Use of ultra-fast chargers could reduce battery life and performance. ▪ If ultra-fast charging leads to charging during peak demand periods, could result in increased grid costs and therefore increase BEV running costs.	▪ Resiliency/security of supply, vs imported fuels, of domestic energy production.
Advanced biofuel / ICEVs	▪ Road user charge (RUC) exemptions for BEV (and potentially FCEV) distort decisions away from biofuels. ▪ Supply constraints due to demand in other sectors could strain uptake.	▪ More immediate use than FCEVs/BEVs. ▪ Use of existing ICEV fleet means existing fleet does not need to be replaced in near term.
Modal shift to rail or coastal shipping	▪ Less flexible than road freight, and cost and emissions savings still may not be enough to offset this. ▪ Investment will likely also be required to update infrastructure for these modes.	▪ More efficient from both a cost and an emissions perspective. ▪ Hydrogen FCEV trains could be cheaper than electrifying the remainder of the North Island Main Trunk Rail line. ▪ LDHF, promoted as most amenable to using FCEVs, may also be the portion of the freight task most amenable to modal shift, given distances involved.

Our key observation upon review of these studies is that there are significant factors outside the private costs borne by a freight operator which must be taken into account to determine the total societal cost of adopting any or each of the above alternatives in LDHF in New Zealand. Significant issues for e-trucks are scaling up these technologies while relying on rare earth metals (platinum, cobalt and lithium) and the immediate issue of the legacy fleet of ICEVs in the "waiting period" until either e-truck becomes widely commercially available. Moreover, continuous advances in battery and fuel cell technology leave significant uncertainty over the next decade in terms of private costs.

Additionally, from a total societal cost standpoint, applying RUC on some vehicles but not others is essentially a cross-subsidy. Presently, RUC exemptions only exist for BEVs, but moving forward this is likely to evolve to include other low- and zero-emission options. The RUC in part funds road maintenance, charged as a function of weight, not fuel choice. There is therefore a risk that applying RUC exemptions to promote decarbonisation in a way that is not technology-neutral could inefficiently distort fuel and vehicle choice away from other decarbonisation alternatives. This risk is particularly important given the uncertainty and technological immaturity of decarbonisation options for LDHF.

[21] Lithium and cobalt are both critical components to lithium ion batteries (which run BEVs under current technology). These are both rare and expensive metals, and cobalt mines in particular are extremely concentrated geographically. The recent spikes in demand for these materials due to their use in a range of electric technologies has led to major concern about future price and availability, and current ethics in the supply chain. Therefore, continued adoption of BEVs at larger scale will likely require substitutes for, or major reductions of, these materials moving forward. Additionally, recycling these materials from batteries at the end of life is costly. As we discuss in section 3.2, research is underway to find alternatives to lithium and cobalt in batteries for electric vehicles.

Our analysis also highlights that quantitative analyses comparing the TCO of green hydrogen-powered FCEVs against advanced biofuels or blue hydrogen have not yet been performed, although they have been qualitatively considered.[22] Additionally, the TCO for conventional biofuels and other lower-emission options (e.g. methanol and LNG) has not been quantified, although these could also potentially be effective as more immediate transitional fuels.[23]

Looking outside the more narrow lens of what fuel should be used in trucks, modal shift to rail and/or coastal shipping could potentially result in material cost and emissions savings across the transport sector, as well as other benefits including a substantial reduction in truck movements, road congestion and highway maintenance. We consider that modal shift should be further explored.

Our overall conclusion from our review of these studies is that there remains uncertainty as to what is the least-cost path to decarbonising LDHF in New Zealand, particularly where "path" is defined to include goals for both short-term and longer-term emissions reduction as the answers to each question might be different.

Areas for further investigation

The key gaps we have identified after reviewing the existing studies are:

- Existing studies focus on comparing green hydrogen FCEVs and BEVs with ICEVs, but do not consider broader alternatives for decarbonising LDHF such as biofuels, blue hydrogen, cleaner burning fossil fuels or modal shift;
- Relatedly, the studies focus on long-run economics (the "end point") but do not consider in detail the economics of more immediate options to decarbonising (the "path");
- The studies were often completed with a different purpose to ours, and therefore the modelling and assumptions are not available in a way that the findings can be rigorously tested and updated to account for future technology and cost changes; and
- The public data that exists on the LDHF task in New Zealand is relatively sparse and aggregated, which makes it difficult to define what LDHF means in a New Zealand context.

Our review suggests that the public policy debate surrounding both the "end point" and the more immediate-term "path" for decarbonising LDHF would benefit from a publicly available TCO model, with overlays for social costs and benefits. This would ideally compare the full identified range of options against each other and allow comparisons to be made both in the longer and more immediate terms. Such a model would facilitate answering a more holistic question such as "**what economic options exist to decarbonise LDHF in both the immediate and long term?"**

This model would allow assumptions to be transparently tested, updated and challenged. Much of the analysis that would go into a modelling exercise like the described public TCO model already exists but is contained in disparate reports and models which focus on a subset of the options.

Similarly, a more disaggregated and detailed public data set on truck movements would make such a model more useful and progress the policy discussion more generally. In particular, a better understanding of how far trucks travel in a day, how much freight they carry and how many trucks fit into different bands of daily tonne-kilometres would enable better identification of the segments of the LDHF task that are amenable to different decarbonisation options. This is particularly the case with respect to BEVs where the current trade-off between range, payload and charging time may not yet economically support the needs of LDHF.

[22] In particular, the Ministry of Transport papers and the NZPC report.

[23] Noting that this is not considered at length by any of the studies reviewed.

1. Introduction

1.1. Motivation

Ara Ake has engaged NERA Economic Consulting to conduct a review of the economics of using green hydrogen[24] to decarbonise long-distance heavy freight (LDHF) in New Zealand. The research question we were asked to address is, **"what needs to be true for green hydrogen to be the most economic path to decarbonising LDHF?"**.[25]

New Zealand's heavy truck fleet contributes 27% of all transport emissions but accounts for only 7% of total annual travel.[26] As MBIE's *A Vision for Hydrogen* green paper notes, it is unlikely there will be a single pathway that will decarbonise the entire transport sector.[27] Even narrowing to heavy freight, categorised as goods vehicles over 12 tonnes,[28] multiple decarbonisation alternatives will likely be required. This is due to the differing demands of vehicle tasks (such as distance, weight carried or number of stops) and the suitability of different low- and/or zero-emission alternatives for each task. The appropriate decarbonisation path for LDHF (distinct from heavy freight) is particularly uncertain due to the range and weight demands of the task.

Fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs) represent different onboard fuel storage options to power an electric motor. Both "e-trucks" are being promoted as solutions to decarbonise LDHF. The current advantage FCEVs have is that, relative to BEVs, they can carry more cargo and complete long-distance trips without needing to refuel as often. This is because of the current low energy density of batteries; put simply, batteries are currently heavy relative to the energy they carry. In freight applications, this results in a trade-off whereby BEVs must either carry more batteries (and therefore less freight) to avoid needing to stop and recharge or carry fewer batteries (and more freight) but need to stop and recharge more often. FCEVs and traditional diesel-powered internal combustion engine vehicles (ICEVs) do not experience this trade-off to the same extent and, therefore, can carry more freight for longer without stopping.

A primary argument against FCEVs is that converting electricity into hydrogen for the purpose of then returning it to electricity to power an electric motor is inherently less efficient than powering that motor directly with electricity. This is due to the energy losses associated with producing hydrogen, compressing it, storing it and converting it back to electricity. Example estimates of electrical efficiency are about 70% to 90% for BEVs compared to about 25% to 35% for FCEVs.[29]

The question of whether BEVs or FCEVs are the more economic option for LDHF therefore depends predominantly, but not exclusively,[30] on whether the payload and refuelling advantage FCEVs have

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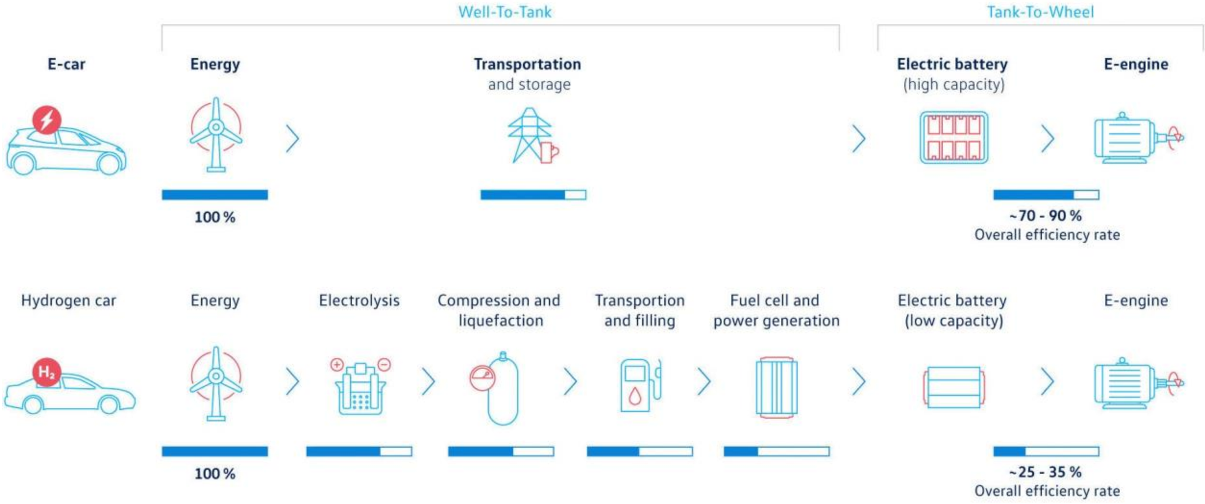
[29] Volkswagen. See Figure 1.1.

[30] For example, using hydrogen in place of freight is also argued to have additional benefits to the energy system by nature of its ability to more easily store large volumes of energy than is possible with batteries.

over BEVs offsets (and is expected to continue to offset) the electrical inefficiency of using electricity to produce hydrogen and power a FCEV.

Figure 1.1
Green hydrogen-powered FCEV vs. directly electrified BEV
Well-to-wheel efficiency comparison



Source: Volkswagen.

There are, of course, other options for decarbonising LDHF, such as blue hydrogen (hydrogen produced from hydrocarbons such as natural gas, with the carbon sequestered and permanently stored using carbon capture and storage (CCS) technology), biofuels, cleaner-burning fossil fuels, modal shift (rail and coastal shipping) or combinations of alternative fuels and modal shift.

In theory, if there are no market failures or coordination problems requiring government (or other) intervention or funding, market forces should determine whether a technology such as green hydrogen forms part of the least-cost path to decarbonisation. Indeed, the idea behind market-based approaches such as the New Zealand Emissions Trading Scheme (ETS) is that if a high enough price for carbon is signalled, then the role of government in determining what technologies should be adopted to decarbonise LDHF (or any other sector for that matter) is limited.

However, governments' decarbonisation objectives coincide with many low-emission technologies still being in nascent stages of adoption and commercialisation. At the same time, the current NZ ETS price is substantially lower than the prices required to achieve a material amount of decarbonisation activity in the near-term.[31] This means that centralised funding and decision making by governments and other bodies, rather than market forces, are influencing the decarbonisation path.

Although government action can help resolve coordination problems, when there is material uncertainty (as is the case for LDHF), this creates a risk of investing in technology that is subsequently overtaken by technology which progresses at a faster rate. This is particularly a risk for New Zealand, compared to major global players, as we are likely to be a "technology taker".[32] This could result in outcomes where New Zealand becomes locked into an inferior technology (and thus pays higher prices and/or receives lower quality in the long run) with the risk that assets could

[31] New Zealand Productivity Commission , *Low-emissions economy: Final report*, August 2018. (NZPC Low-emissions economy report)

[32] New Zealand is a very small market compared to major economies such as the United States and China, which have large markets and invest heavily in developing technologies. Any new technologies would be imported from overseas, and therefore New Zealand's investment will not influence any economies of scale achieved in these technologies.

eventually become stranded.[33] Another risk is that present investments may not be made to progress a particular technology, based on the assumption that a different technology will become more affordable at a later date. If this fails to occur, then decarbonisation targets may be missed or could be more costly to achieve if a sharper decarbonisation path is subsequently required.

Given these risks and that New Zealand is likely to be a technology taker, a prudent approach could be for government to adopt a diversified investment strategy and invest in numerous technologies. This would mean that when the uncertainty is resolved or reduced, New Zealand is well-positioned to efficiently progress those technologies that provide an economic means of decarbonising freight movements.

1.2. Scope of this project and report

To account for these risks and to reconcile the divergent views on the economics of using green hydrogen to help decarbonise LDHF, Ara Ake asked us to provide an independent review of the economics of green hydrogen in LDHF. This review has four potential stages:

- **Stage 1:** Review the existing literature on green hydrogen applied to LDHF in New Zealand;
- **Stage 2:** If gaps are identified in Stage 1 in answering the research question thoroughly, conduct our own modelling of the economics of green hydrogen in LDHF with a focus on filling those gaps;
- **Stage 3:** If green hydrogen appears to be economic, identify risks and potential impediments (funding, coordination/public good issues, externalities, market structure, business models, etc) that might impede the development of green hydrogen; and
- **Stage 4:** Identify potential solutions to issues identified in Stage 3.

This report covers Stage 1. We have reviewed all *publicly available* New Zealand-focused studies that discuss the potential role of green hydrogen for decarbonising LDHF.[34] We restrict our focus to studies which account for the nuances of the New Zealand economy and geographic nature of the freight task, although we have relied on international literature for support in our review where appropriate.

To review the existing body of evidence on this question, we developed a framework for assessing the economics of green hydrogen. This framework, referred to as the "**economic framework**", is how we think the research question should be answered. It **compares the net social benefit (i.e. total social benefit less total social costs) of each decarbonisation alternative examined**.[35] Note that "social" in this context means considering the economic costs and benefits from a national or economy-wide perspective, rather than assessing non-economic considerations such as equity and fairness.[36] The economic framework gives us a benchmark against which to assess the robustness of existing studies, while remaining "fuel agnostic". That is to say, while the motivation for the report is the recent increase in interest and investment in green hydrogen, our focus is on assessing the most economic path for decarbonising LDHF, regardless of the fuel (or indeed mode) used.

[33] This risk is, of course, a function of the level of investment required – the smaller the necessary investment, the less of a concern lock-in and stranding are.

[34] This is an important caveat to conclusions drawn from our Stage 1 review. Given the nascent application of the technologies we are discussing, information from public studies that are only a year or two old can quickly become out of date.

[35] Noting that the scope of this report is such that we examine only the alternatives considered by the studies reviewed. This is discussed further in section 3.5.

[36] See, e.g., New Zealand Treasury, *Guide to Social Cost Benefit Analysis*, July 2015, accessed 16/12/20 from: https://www.treasury.govt.nz/sites/default/files/2015-07/cba-guide-jul15.pdf. For example, a carbon tax is one way to create a "price" for a social cost which can be considered in an economic framework.

The economic framework forms part of the **"assessment framework"**, which involves assessing:

- Whether the studies apply the appropriate economic framework;
- Whether the studies adequately capture the relevant costs and benefits; and
- The robustness and transparency of any modelling that is conducted.

Of course, each past study had its own specific research question(s) and each presented its results in a different way to the ideal set out in our assessment framework. This is to be expected. The critiques in this report should therefore not necessarily be interpreted as an indication of the quality of the past work we have reviewed – it may simply indicate that the studies are answering a different question and have a different purpose.

That being said, transparency of any modelling is paramount to ensure that future funding and policy decisions are supported by complete and accurate information. Providing transparency around the assumptions used in the different studies and reconciling the different conclusions reached is one of the major purposes of the Stage 1 review.

As part of this first stage, we have engaged with numerous stakeholders in the transport and energy sectors in New Zealand to obtain feedback on the economic framework we have adopted and to ensure we are reviewing the right studies (i.e., a complete list of existing studies which examine the future of LDHF in New Zealand specifically including consideration of green hydrogen and FCEVs).

Table 1.1 sets out the public domain studies we have reviewed. The colour coding indicates whether the studies contain quantitative economic modelling of using green hydrogen for LDHF (blue shading) or are a qualitative review of LDHF alternatives including green hydrogen (green shading).

Table 1.1
New Zealand studies assessing the future of LDHF that consider green hydrogen

Study	Year	Depth
Modelling Hydrogen Pathways for MBIE, Castalia	2020	Economic analysis (model results)
Hydrogen in NZ, Concept Consulting for MBIE, Energy Efficiency & Conservation Authority (EECA), Contact, Meridian, Powerco, First Gas	2019	Economic analysis
H2 Taranaki Roadmap, Venture Taranaki/Hiringa Energy/New Plymouth District Council	2019	Review/Economic analysis
Gas Infrastructure Futures in a Net Zero New Zealand, Vivid Economics for First Gas and Powerco	2018	Economic analysis
Green Freight Strategic Working Paper and Background Paper, Ministry of Transport (MoT)	2020/ 2019	Review and qualitative discussion of costs and challenges
A vision for hydrogen in New Zealand: Green Paper, Ministry of Business, Innovation and Employment (MBIE)	2019	Review and qualitative discussion of costs and challenges
House View: Hydrogen, Z Energy	2019	Review and qualitative discussion of costs and challenges
Low Emissions Economy Report, New Zealand Productivity Commission (NZPC)	2018	Review and qualitative discussion of costs and challenges

The rest of this report is structured as follows:

- Section 2 provides an overview of LDHF in New Zealand;
- Section 3 summarises the technical characteristics of the different alternatives for decarbonising LDHF considered by the studies we reviewed;

- Section 4 set out the **economic framework** we consider should be used to evaluate the economics of green hydrogen and alternatives for decarbonising LDHF, as well as the **assessment framework** we use to review the studies;
- Section 5 provides a high-level summary of the studies we reviewed and their conclusions, with discussion split between studies that are a qualitative assessment and those that contain quantitative modelling (the focus of our review);
- Section 6 assesses the quantitative modelling, including comparing the cost outcomes and conclusions across the studies;
- Section 7 provides a qualitative assessment of aspects of using different fuels, including those that were not quantified in any of the studies; and
- Section 8 looks at areas identified for further investigation.

2. Overview of heavy freight in New Zealand

In this section we provide a brief overview of heavy freight in New Zealand and distinguish long-distance heavy freight from other heavy freight to the extent information is available. Table 2.1 provides an overview of heavy freight in New Zealand.

Table 2.1
Overview of heavy freight in New Zealand

Freight composition	In New Zealand in 2017/2018, 93% of total tonnes of freight was transported by road.[37] Intraregional freight makes up 77% of this road freight, 14% travels to an adjacent region and 2.2% travels between islands.[38] For shorter trips, road freight is more cost efficient than other options and New Zealand's road freight demand has been increasing over the last decade.[39]
Freight emissions	The heavy fleet carrying this freight contributed 26.7% of all transport emissions in 2017, but only constitutes 7% of total annual travel.[40] Each heavy vehicle over 10 tonnes emits 1,420 grams of CO_2 per kilometre,[41] and in 2017 heavy trucks in New Zealand emitted 3,115,000 tonnes of CO_2 to the atmosphere.[42] Over half the emissions from heavy freight comes from interregional travel,[43] which as noted above is just over 15% of freight moved.
Fleet composition	In 2019 there were over 160,000 heavy trucks on the roads in New Zealand,[44] increased from 144,000 in 2017.[45] More than 55% of heavy vehicles are part of a fleet of five vehicles or less.[46] We understand that heavy trucks in New Zealand have axle load restrictions that are lower than most other countries, requiring more multiple axle vehicles for a given freight task than elsewhere.[47] New Zealand is also one of few countries globally with right-hand drive.
Freight movement	Heavy trucks travel almost 3.5 billion kilometres annually as of 2019, increasing every year since 2013.[48] The heaviest trucks (gross weight over 20 tonnes) accounted for 36% of the truck fleet but 64% of the total kilometres travelled in 2017, with increasing weight of a vehicle directly correlating with increasing miles travelled.[49]

A major factor in comparing the economics of BEVs against other road freight alternatives is the route and kilometres travelled of the truck within a given driver shift (due to range limitations under current technology). Existing data on the routes driven by certain freight trucks is sparse and

[37] Another 5% was by rail and another 2% coastally. Ministry of Transport (2019), *The Green Freight Project – Background paper on reducing greenhouse gas emissions from road freight in New Zealand through the use of alternative fuels*, September 2019, pg.11. (MoT Background Paper)

[38] MoT Background Paper, p13.

[39] MoT Background Paper, p12; Ministry of Transport, *Annual fleet statistics 2019*, p15.

[40] Ministry of Transport, *Annual fleet statistics 2018*, p15.

[41] Ministry of Transport, *Green Freight – Strategic Working Paper*, 2020 (MoT Strategic Working Paper), Table 1.

[42] MoT Strategic Working Paper, Table 1.

[43] NZPC Low-emissions economy report, p 375.

[44] Ministry of Transport, *Annual fleet statistics 2019*, p15.

[45] MoT Background Paper, p12.

[46] MoT Background Paper, p13.

[47] Hiringa Energy, Venture Taranaki, New Plymouth District Council, *H2 Taranaki Roadmap – How hydrogen will play a key role in our new energy future*, March 2019, p37. (H2 Taranaki Roadmap)

[48] Ministry of Transport (2019), *Annual fleet statistics 2019*, p15.

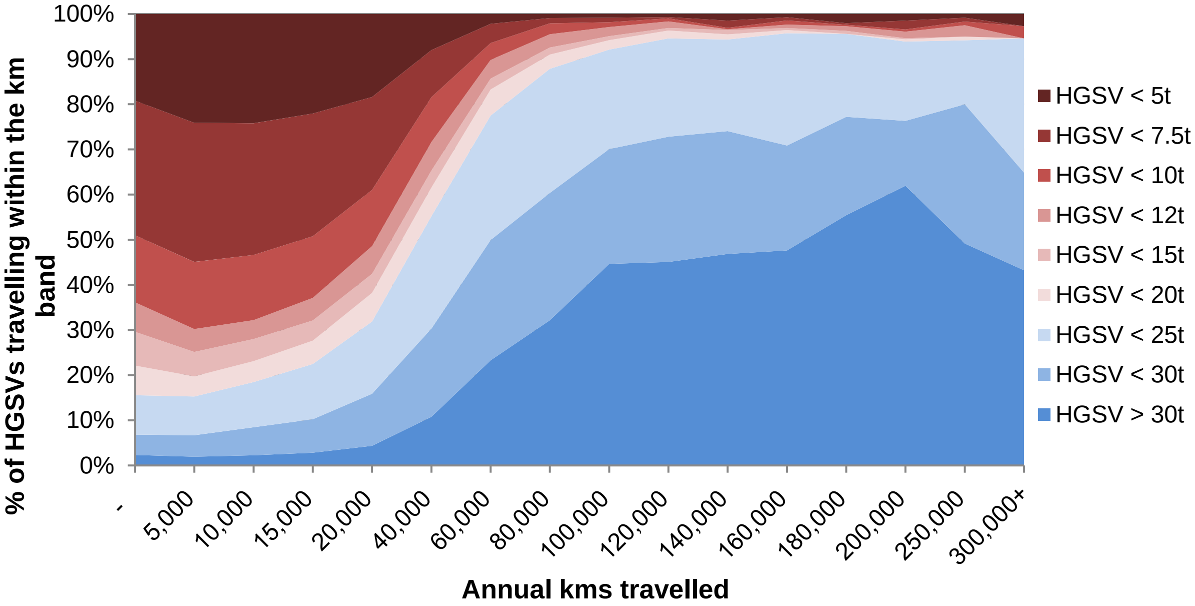
[49] MoT Background Paper, p12.

relatively aggregated, but understanding the driving patterns of the heavy fleet by weight in New Zealand is key to determining which alternative fuel may suit different parts of the freight task.

For example, a truck might travel a high amount of kilometres each day, but make multiple stops to load and unload during which a BEV could theoretically be charging.[50] A truck moving freight from Auckland to Tauranga, Tauranga to Hamilton, then Hamilton back to Auckland could, theoretically, have the opportunity to charge twice during its roughly 450km “shift”. In contrast, a truck taking freight from Auckland to Palmerston North would have a roughly 500km trip, giving no potential opportunity for a BEV to charge (without extra time costs) while covering a similar distance. The load of freight required in each example also influences the economics of the chosen vehicle or fuel. These examples illustrate the complexity of the heavy freight task; however, it is currently not apparent from public data which trucks follow which routes, and how frequently.

It does appear that on an annual basis, the heaviest trucks predominately travel the furthest each year. The chart below shows 2010 data from the MoT on heavy goods service vehicles (HGSVs) annual distance by gross vehicle mass (GVM) band. Recognising that this represents the state of things ten years ago, this chart shows that over 90% of all HGSVs that travelled more than 100,000 kms that year had a gross vehicle mass of over 20t. From this chart we can see that there are a variety of different truck weights from 20t to over 30t travelling anywhere between 100,000kms to more than 300,000kms. Although these would all be considered LDHF, there is still variation in their weight and driving patterns, which may result in different requirements of the freight truck.

Figure 2.1
Percent of HGSVs travelling within an annual kilometer band
By GVM band
2010



Source: NERA analysis of MoT data.

Similar data are available for HGSVs by annual kilometre band in 2019, but these data do not disaggregate by GVM band (and therefore we cannot tell what size truck is travelling in the distance band). Comparing the breakdown of HGSVs by kilometres travelled in 2010 to 2019 as a sense check on the validity of the 2010 data, 3.1% of all HGSVs in 2010 and 3.7% in 2019 (roughly 4,700 trucks in both years) travelled over 100,000kms.

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[50] The logistics of charging while loading/unloading are also relevant if a heavy BEV were to require special charging equipment.

3. Methods of decarbonising LDHF in studies reviewed

Each option considered as an alternative to the status quo has the potential to get the heavy freight sector to net zero carbon, in some cases by offsetting remaining carbon emissions with afforestation. The extent to which any alternative is considered in this section is dependent on their consideration by the studies we have reviewed. That is to say, there are potentially other ways to lower the emissions profile of moving freight around New Zealand, but the scope of this paper is to evaluate the approaches examined so far by the studies reviewed.

We describe each option from a technical perspective at a high level and set out the technological progress and relevant New Zealand projects we are aware of to date. The technical descriptions in this section are intended to be brief, serving as context for the following sections.[51]

3.1. Hydrogen (using FCEVs)

Hydrogen is not a primary energy source, like fossil fuels or wind, but instead stores potential energy, and must be converted from a primary energy source.[52] When combined with oxygen, hydrogen releases energy to be harnessed as fuel in a fuel cell with only water and heat as by-products.[53]

Although hydrogen does not release carbon emissions when used as a fuel downstream in a vehicle, the process to produce the hydrogen upstream may, depending on its primary energy source. Most hydrogen produced today is produced by steam methane reforming (SMR) using natural gas, and to a lesser extent partial oxidation using heavy oil and coal, therefore releasing carbon emissions in the production process. These are referred to as “grey” or “brown” hydrogen.[54] However, low- to zero-emission production methods are beginning to emerge with green and blue hydrogen (see sections 3.1.1 and 3.1.2, respectively).

Hydrogen after extraction does not have very high energy density, for example, compared to electric batteries.[55] Therefore, it is generally compressed to increase its energy density and reduce the physical space required to transport it. Compression requires energy, and therefore results in additional lost energy to get hydrogen to its final point of use.

The economics of supplying hydrogen fuel to vehicles at a refuelling station is significantly influenced by the proximity of the supply, as these different distribution methods have materially different costs. “Centralised” production of green hydrogen would be such that production takes place in a location near to a large renewable energy source and is then compressed and transported (either by truck or pipeline) to a refuelling location, which includes the costs of production, compression,

[51] Helpful and more in-depth technical descriptions can be found in Concept’s Research report, the MoT Green Freight Background Paper, and the H2 Taranaki Roadmap. Additionally, helpful technical diagrams of the inner workings of ICEVs, BEVs, and FCEVs can be found at https://afdc.energy.gov/vehicles/how-do-gasoline-cars-work.

[52] Despite being the most commonly occurring element on earth, hydrogen occurs in its pure form rarely in nature. Primary energy (such as natural gas, the sun, wind – any naturally occurring fuel source which can be used immediately and directly) must therefore be expended to extract the hydrogen from another compound. Therefore, we can think of expending energy to extract hydrogen as storing that energy in the form of hydrogen.

[53] Hydrogen, when burned directly for energy, will emit nitrogen oxides as an emission (see: Florida Solar Energy Center, “Hydrogen Basics – Internal Combustion Engines”, accessed 15/12/20 from: http://www.fsec.ucf.edu/en/consumer/hydrogen/basics/utilization-ice.htm.) However, when hydrogen is applied to generate electricity in a fuel cell these emissions are not created. H2 Taranaki Roadmap, p17; Connecticut Hydrogen-Fuel Cell Coalition, “Fuel cell Environmental Impact”, accessed 15/12/20 from: http://chfcc.org/resources/fuel-cell-environmental-impact/

[54] MBIE Green Paper, p40-41.

[55] Put another way, a tank of hydrogen with the same energy, with no compression, would take up much more space than a battery that stored the same volume of energy.

transportation and distribution.[56] "Decentralised" production of green hydrogen would be such that the production takes place on site of the refuelling location and is compressed and stored for use, including the cost of production, compression, and storage.[57] These two methods will have significantly different capital costs in their production given economies of scale and energy efficiency.[58]

In a "centralised" production model, hydrogen fuel must be transported from the site of production to a refuelling station. Hydrogen is generally transported as a gas through a pipeline (such as a natural gas pipeline, either blending with existing gas or retrofitting to accept pure hydrogen)[59] or as a compressed gas in a carbon fibre cylinder or tank by truck to its destination.[60] Technologies are developing, although not yet commercially available, around storing liquified hydrogen in cryogenic tanks.[61] This increases the density of the fuel and allows more to be carried in a smaller space, ultimately decreasing the cost. A final option is to bond hydrogen to a chemical carrier or convert into ammonia, which allows the highest density of hydrogen to be transported but requires conversion back to pure hydrogen at the final point, which uses additional energy.[62]

The refuelling infrastructure network proposed by Hiringa is such that both centralised and decentralised options would be established.[63] Additionally, Firstgas has received a Provincial Growth Fund grant to assess whether hydrogen can be transported via existing pipelines either as 100% hydrogen or blending with natural gas.[64] Firstgas and Hiringa have announced a collaboration agreement in November 2020 in which they plan to advise each other on each of these projects and potentially collaborate on other projects towards developing hydrogen pipeline infrastructure.[65]

From here, hydrogen fuel can be used within an FCEV. The basics of how a hydrogen fuel cell works are shown in Figure 3.1. The electricity generated by the fuel cell converting the hydrogen fuel continuously charges a smaller battery, which powers an electric motor (like a battery electric vehicle), making an FCEV a zero-emission vehicle.

[56] H2 Taranaki Roadmap, p34.

[57] H2 Taranaki Roadmap, p34.

[58] H2 Taranaki Roadmap, p34.

[59] Office of Energy Efficiency & Renewable Energy, "Hydrogen Pipelines", accessed 15/12/20 from: https://www.energy.gov/eere/fuelcells/hydrogen-pipelines

[60] Concept (2019), *Hydrogen in New Zealand Report 3 – Research*, 29 January 2019 (Concept Research Report), p10.

[61] Hydrogen Council (2020), *Path to Hydrogen Competitiveness – A cost perspective*, 20 January 2020, p39.

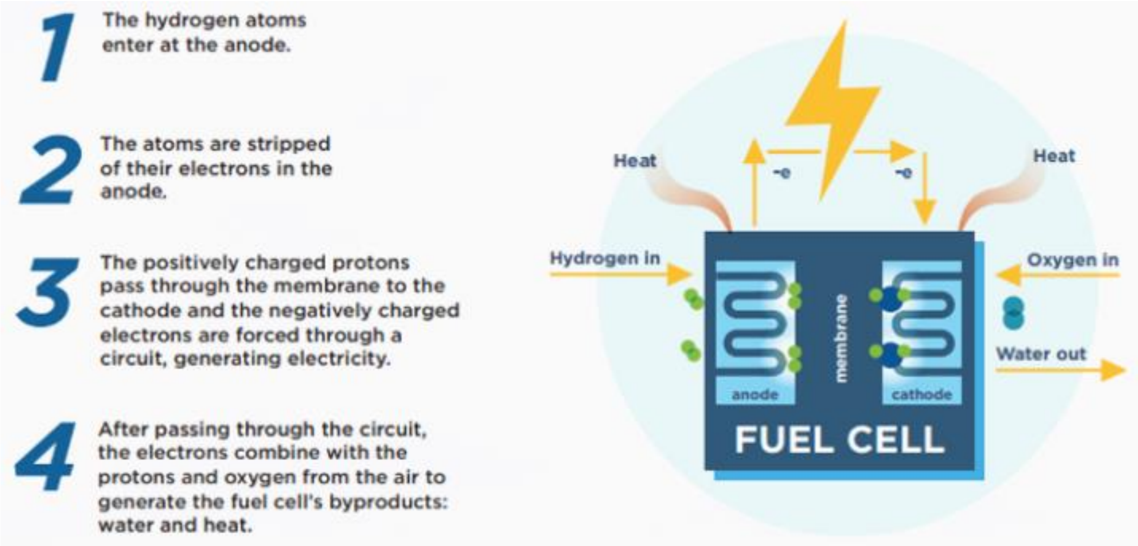
[62] Concept Research Report, p10.

[63] H2 Taranaki Roadmap, p33.

[64] First Gas, *Hydrogen pipeline project gets Government funding*, accessed 15/12/20 from: https://firstgas.co.nz/news/hydrogen-pipeline-project-gets-government-funding

[65] Hiringa Energy, *Firstgas and Hiringa Energy have sights set on advancing green hydrogen together*, accessed 15/12/20 from: https://www.hiringa.co.nz/post/firstgas-and-hiringa-energy-have-sights-set-on-advancing-green-hydrogen-together

Figure 3.1
How hydrogen fuel cells work



Source: Fuel Cell & Hydrogen Energy Association, at http://www.fchea.org/fuelcells.

An emerging issue with production of fuel cells at a large commercial scale is that platinum is used as a catalyst within the fuel cell, which is a high-cost precious metal with environmental concerns in its extraction.[66] This point does not appear to be a commercial issue yet, but could as the demand for hydrogen fuel cells grows with hydrogen use. The amount of platinum used is very small and platinum can be recycled at the end of its life in a fuel cell,[67] but there is limited platinum available to mine and recycle.[68] For context, platinum is also used in catalytic converters in traditional ICEVs in smaller amounts, and it is where the majority of recycled platinum is reclaimed from today.[69] Reduced-platinum and platinum-free replacements are underway to resolve this barrier.[70]

Presently, a number of new and existing auto companies are piloting hydrogen fuel cell heavy trucks including HYZON, Nikola, Daimler/Volvo, Toyota/Hino, and Hyundai. At this stage none of these trucks are available commercially, but most are in pilot stages.

Hiringa Energy has partnered with HYZON to secure FCEV heavy trucks for service in New Zealand beginning in 2021, with an initial group of 20 trucks and plans to roll out over 1,500 trucks by 2026.[71]

3.1.1. Green hydrogen

An alternative to SMR is water electrolysis, which uses electricity to separate water molecules to extract hydrogen. When electrolysis is performed by applying electricity from a renewable primary energy source, the resulting product is considered green hydrogen as there are zero carbon emissions

[66] Sulfur oxides are produced in the extraction of platinum. Deloitte (2020), *Powering the Future of Mobility – Hydrogen and fuel cell solutions for transportation*, 2020, p.81

[67] Deloitte (2020), *Powering the Future of Mobility – Hydrogen and fuel cell solutions for transportation*, 2020, p.81

[68] FuelCellsWorks, "Platinum in Fuel Cells: Too Precious for Clumping", 8 August 2019, accessed 15/12/20 from: https://fuelcellsworks.com/news/platinum-in-fuel-cells-too-precious-for-clumping/

[69] Johnson Matthey, *Pgm market report*, May 2020, from: http://www.platinum.matthey.com/documents/new-item/pgm%20market%20reports/pgm-market-report-may-2020.pdf, p26.

[70] Argonne National Laboratory, "Platinum-free catalysts could make cheaper hydrogen fuel cells", 20 May 2020, accessed 15/12/20 from: https://www.anl.gov/article/platinumfree-catalysts-could-make-cheaper-hydrogen-fuel-cells

[71] Hiringa Energy, "Hiringa Energy and HYZON Motors to Deploy Fuel Cell-Powered Heavy Trucks in New Zealand in 2021", 31 August 2020, accessed 15/12/20 from: https://www.hiringa.co.nz/post/hiringa-energy-and-hyzon-motors-to-deploy-fuel-cell-powered-heavy-trucks-in-new-zealand-in-2021

produced. This means that the use of electrolysis to produce hydrogen to power an FCEV creates a zero-emission life cycle.[72]

Currently, the most mature and common form of electrolysis is alkaline electrolysis, which has been used for over a century in industrial settings. Newer forms of electrolysis (polymer electrolyte membrane electrolysis and solid oxide electrolysis) are quickly developing which provide more efficient production of hydrogen.[73]

We also understand that converting biogas to methane, from which steam reformation is used to produce hydrogen is another form of green hydrogen.[74] This form of green hydrogen is not zero emission like electrolysis from renewable electricity but is instead carbon neutral. This is because the initial feedstock is made from plants (which absorb carbon), but the hydrogen production process releases carbon. A caveat which we return to in our discussion of biofuel is that if carbon-emitting agricultural processes are used to grow the initial feedstock (such as using nitrogen fertiliser), the production is no longer carbon neutral.

Hiringa Energy, in their FCEV fleet development, plans to implement a mix of centralised generation with distributed fuel, distributed (decentralised) generation and third-party generation with offtake to provide fuel to their refuelling station network.[75]

3.1.2. Blue hydrogen with CCS

One solution to reduce the emissions from traditional SMR-produced hydrogen is using a carbon capture and storage (CCS) process. SMR reacts methane, usually from natural gas, with high temperature steam (between 700°C and 1,000°C) in the presence of a metal catalyst, which produces hydrogen and carbon monoxide.[76] CCS technology extracts the carbon produced during the SMR process and transports it by pipeline to be pumped into a storage site, typically depleted fossil-fuel deposit sites.[77]

Recently fitted CCS projects have captured 90% of carbon emitted.[78] A developing technology called the Allam cycle captures 100% of carbon emissions,[79] but presently there is only a single test facility up and running employing this technology.[80] The geological soundness of the storage location is imperative to CCS remaining effective in the very long run.[81]

Aside from the SMR production process itself, the costs associated with blue hydrogen include the carbon price on the residual emissions and the CCS costs: carbon capture at the production site,

[72] Excluding the emissions created in the production and disposal of the vehicle, or the electrolysis plant.

[73] H2 Taranaki Roadmap, p25.

[74] H2 Taranaki Roadmap, p25; Minh, Doan Pham, Tan Ji Siang, Dai-Viet N. Vo, Thanh Son Phan, Cyrille Ridart, Ange Nzihou, and Didier Grouset (2018) "Hydrogen production from biogas reforming: An overview of steam reforming, dry reforming, dual reforming, and tri-reforming of methane", *Hydrogen Supply Chains*, pp. 111-166. Academic Press.

[75] Hiringa Energy, *Fueling* Network, accessed 15/12/20 from: https://www.hiringa.co.nz/refuelling-network

[76] Office of Energy Efficiency & Renewable Energy (2020), *Hydrogen Production: Natural Gas Reforming*, accessed 15/12/20 from: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

[77] Concept Research Report, p25.

[78] IEAGHG, “Toward Zero Emissions CCS from Power Stations using Higher Capture Rates of Biomass”, March 2019, pp 6-7.

[79] Allam, Rodney & Martin, Scott & Forrest, Brock & Fetvedt, Jeremy & lu, Xijia & Freed, David & Brown, Bill & Sasaki, Takashi & Itoh, Masao & Manning, James (2017) “Demonstration of the Allam Cycle: An Update on the Development Status of a High Efficiency Supercritical Carbon Dioxide Power Process Employing Full Carbon Capture.” *Energy Procedia*. 114. 5948-5966.

[80] Power, “300-MW Natural Gas Allam Cycle Power Plant Targeted for 2022”, 27 November 2019, accessed 15/12/20 from: https://www.powermag.com/300-mw-natural-gas-allam-cycle-power-plant-targeted-for-2022/

[81] Intergovernmental Panel on Climate Change (2005), *Carbon Dioxide Capture and Storage*, 2005, p.197

transportation of the gas to the storage location, and storing the carbon underground (compression, injection, and availability of suitable sites). These can vary widely depending on the specifics of the technology applied and infrastructure and storage site availability and proximity.[82]

The US-based start-up 8 Rivers, the developer of the Allam cycle,[83] through their New Zealand-based subsidiary Pouakai NZ, announced plans in 2018 to develop large-scale hydrogen, power, ammonia, and urea plant employing the Allam cycle using natural gas.[84] As of last year, Pouakai NZ was expecting to have this facility operational by 2024.[85]

3.2. Direct electrification (using BEVs)

A BEV uses an electric motor, like an FCEV. The electric motor in a BEV is instead powered solely by a battery, which is charged by an external power source. If entirely renewable electricity is used to charge the battery, the use of a BEV has a zero-emission life cycle.[86] If the vehicle is plugged into the grid to charge its battery, it is the mix of primary energy sources (i.e., renewable or non-renewable generation) being used to power the grid at the time of charging which determines the life-cycle emissions of running the vehicle. Given New Zealand's very high zero-carbon renewables penetration (averaging nearly 70% since 2014)[87], New Zealand is well positioned for BEVs to have zero emissions if they charge outside of peak demand hours when fossil-fuel peaking plants run. As this generation sector decarbonises in the future, the time of charging will become less of an issue from an emissions perspective.

Heavy BEVs will require special charging infrastructure which can accommodate a fleet of vehicles overnight. Unlike FCEVs, which refuel in a similar timeframe to ICEVs, BEVs take several hours to charge depending on the charger wattage. The technology to improve this in a meaningful way is only beginning to be established commercially.[88] Even with the expectation that the high-capacity charging requirements for heavy BEVs will be met, this could, depending on when charging happens and whether it does in fact need to be very high capacity,[89] have a significant impact on the electricity grid if the nation's fleet of LDHF vehicles were to be electrified.

The batteries in BEVs, given current technology, are large and make up a significant proportion of the weight of a vehicle in comparison to traditional ICEVs. Although this is not an issue for smaller passenger BEVs, it becomes an issue for LDHF where every tonne of weight added by a battery is a tonne of freight that cannot be taken in a trip by the heaviest vehicles due to road weight restrictions.

However, it is unclear to what extent this will be an issue for heavy BEVs. Although there is clear consensus that heavy BEVs will require enough batteries to begin diminishing payload capabilities compared to an ICEV, it is difficult to find reliable, public information demonstrating how significant

82 Concept Research Report, p26.

83 8 Rivers, "8 Rivers Hydrogen", accessed 15/12/20 from: https://8rivers.com/portfolio/8-rivers-hydrogen/

84 Stuff, "Taranaki hydrogen power project could cost $4b", 28 November 2018, accessed 15/12/20 from: https://www.stuff.co.nz/taranaki-daily-news/news/108888547/taranaki-gas-reserves-not-robust-as-billiondollar-project-looms

85 Stuff, "$3-4b Taranaki energy centre could be up and running in 2024", 1 July 2019, accessed 15/12/20 from: https://www.stuff.co.nz/taranaki-daily-news/news/113558410/34b-taranaki-energy-centre-could-be-up-and-running-in-2024

86 Excluding the emissions created in the production or disposal of the BEV, or the power station.

87 Note that geothermal generation is excluded from this statistic, as it is a renewable source but is not zero-carbon. MBIE, "Electricity Statistics", accessed 15/12/20 from: https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/electricity-statistics/

88 New Atlas, "World's fastest EV charger gives drivers 120 miles in 8 minutes", 26 April 2018, accessed 15/12/20 from: https://newatlas.com/abb-350kW-fast-charger/54377/

89 For example, the impact on the grid would be reduced if charging of trucks happened overnight using lower capacity charging infrastructure.

this issue will be in practice, given the limited number of existing heavy BEVs. Additionally, some groups have noted that BEVs (and therefore FCEVs) should theoretically have lighter powertrains than traditional ICEVs due to the omission of certain components required in an internal combustion engine which are unnecessary for electric motors,[90] which could also affect overall payload capabilities.[91]

The lithium-ion batteries used in BEVs are made of lithium and cobalt, which are rare earth metals requiring significant energy to extract.[92] The recent spikes in demand for these materials due to their use in a range of electric technologies has led to major concern about the future price and availability of the materials, and the existing ethics in the supply chain.[93] Some components in the batteries can be recycled, but it is costly and dangerous to do so.[94] Lithium-ion batteries contain toxic and flammable materials, and therefore recycling these batteries prevents these materials from degrading the environment and reduce reliance on mineral extraction and specific suppliers.[95] Research is being done in this area to find battery technologies which require less to none of these materials.[96]

ChargeNetNZ installed the first pair of publicly available 300kW chargers in August 2020.[97] Most light BEVs are not capable of charging at this level (established charging stations around New Zealand are generally 50kW[98]), but the installation is an example of the technology progression in motion around BEVs in New Zealand.

The vehicle manufacturers currently developing heavy duty BEVs include Daimler, Volvo, Volkswagen and Tesla, none of which are commercially available yet.[99] Elon Musk (Tesla's CEO) has stated in an interview in November 2020 that Tesla is expecting the Tesla Semi to have a range of 1000km and a payload reduction of "maybe" 1 tonne.[100] For reference, the original Tesla Semi estimates were two models with 500km and 800km expected ranges.[101]

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[90] NACFE, "Electric Trucks: Where they make sense", accessed 15/12/20 from: https://nacfe.org/emerging-technology/electric-trucks/

[91] Noting that, if this theory is true, FCEVs would benefit most from this in terms of increased payload capabilities compared to traditional ICEVs.

[92] Deloitte (2020), *Powering the Future of Mobility – Hydrogen and fuel cell solutions for transportation*, 2020, p.83.

[93] Recent price spikes have occurred in both materials, generating concern over long term availability. Although various continents have lithium mines, over 65% of cobalt production occurs in the Democratic Republic of Congo. There have been recent issues regarding cobalt mining from this country due to a lack of transparency in the material origins and supply disruptions. See McKinsey & Company, *Lithium and cobalt – a tale of two commodities*, June 2018.

[94] Beaudet et al (2020), "Key Challenges and Opportunities for Recycling Electric Vehicle Battery Materials", *Sustainability*, 12(14), p.583.

[95] Beaudet et al (2020), "Key Challenges and Opportunities for Recycling Electric Vehicle Battery Materials", *Sustainability*, 12(14), p.583.

[96] Reuters, "China's CATL is developing new EV battery with no nickel, cobalt, exec says", 15 August 2020, accessed 15/12/20 from: https://www.reuters.com/article/us-catl-batteries/chinas-catl-is-developing-new-ev-battery-with-no-nickel-cobalt-exec-says-idUSKCN25B0BA

[97] ChargeNet NZ, "ChargeNet NZ installs New Zealand's fastest Electric Vehicle chargers", 27 August 2020, accessed 15/12/20 from: https://charge.net.nz/chargenet-nz-installs-new-zealands-fastest-electric-vehicle-chargers/

[98] NZTA, "Electric vehicle charging stations list view", accessed 15/12/20 from: https://www.journeys.nzta.govt.nz/ev-chargers-list-view/

[99] Vox, "Big electric trucks and buses are coming – Here's how to speed up the transition", 19 November 2020, accessed 15/12/20 from: https://www.vox.com/energy-and-environment/2020/11/19/21571042/tesla-electric-cars-trucks-buses-daimler-volvo-vw-charging

[100] Inside EVs, "Elon Musk: Tesla Semi to get 1,000 km (621 miles) of range", 24 November 2020, accessed 15/12/20 from: https://insideevs.com/news/456354/elon-musk-tesla-semi-1000-km-range/

[101] Tesla, "Tesla Semi", accessed 15/12/20 from: https://www.tesla.com/semi

3.3. Advanced biofuel (using existing ICEVs)

Biofuels are made from plants and organic waste materials. Currently, there are two distinct categories of biofuels:

- **Conventional biofuels,** are biofuels that must be blended in low levels (up to about 7%) into fossil diesel to be compatible with existing diesel vehicles.[102]
- **Advanced biofuels**, specifically renewable diesel, can replace diesel completely as it is chemically the same as petroleum diesel.[103] This is considered a “drop-in” fuel, since it can be used in existing diesel-powered vehicles and distributed using existing diesel infrastructure.[104]

Renewable diesel is currently the only technology which can provide a net zero carbon outcome on its own, while the use of conventional biofuels as they stand today would leave a large gap to offsetting carbon emissions. For conventional biofuels to be a net-zero option, existing ICEVs would need to be retrofitted to allow for 100% conventional biofuel use.[105] This has not been explored in detail by the existing studies but could potentially be an avenue for decarbonisation. Therefore, we set aside conventional biofuels as a consideration as, without additional consideration of retrofitting or vehicles developed for use, this would largely put the costs considered into the same category as continued use of diesel with a separate carbon offset.

This is consistent with the analysis in the Ministry for the Environment (MfE) January 2020 marginal abatement cost curve (MACC) report, which considers that drop-in biofuels are the most prospective to displace fossil fuels from existing vehicles, rather than developing alternative or retrofitting vehicles to accommodate conventional biofuels.[106] They note this is in part because New Zealand is a technology-taker for transport, and global focus has turned towards the likes of electric vehicles rather than the development of biofuel-ready alternative vehicles.

Using a renewable diesel in an ICEV still creates emissions during combustion “at the tail pipe”, although its combustion is theoretically carbon neutral because carbon is offset through the life cycle of the fuel (being made from plants, which absorb carbon).[107] However, this fact is under scrutiny given the range of potential organic matter used and variance in production methods.[108] Renewable diesel can be produced from biomass materials such as crop residues, wood, sawdust and grasses.[109] However, scaling up is considered challenging by some as there are currently limited amounts of sustainable waste feedstock from non-food and non-feed sources.[110] Scion, in their *NZ Biofuel Roadmap*, suggest that producing drop-in fuels within New Zealand from lignocellulosic crops in the shorter-term and from trees grown on non-arable land in the longer-term may be attractive options to produce domestically.[111]

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[102] Scion (2018), *New Zealand Biofuels Roadmap Summary Report,* February 2018 (Scion Summary Report), p12.

[103] US Energy Information Administration, “Biofuels explained – biomass-based diesel fuels”, accessed 15/12/20 from: https://www.eia.gov/energyexplained/biofuels/biodiesel-in-depth.php

[104] Scion Summary Report, p12-13.

[105] For example, a heavy truck specifically designed by Fulton Hogan to run on 100% biofuel is in use in Christchurch. Fulton Hogan, “Fulton Hogan takes it to 100 percent”, accessed 15/12/20 from: https://www.fultonhogan.com/fulton-hogan-takes-it-to-100-percent/

[106] Ministry for the Environment, *Marginal abatement cost curves analysis for New Zealand*, January 2020 (MfE MACC), p84.

[107] NZPC Low-emissions economy report, p366.

[108] NZPC Low-emissions economy report, p366.

[109] US Energy Information Administration, “Biofuels explained – biomass-based diesel fuels”, accessed 15/12/20 from: https://www.eia.gov/energyexplained/biofuels/biodiesel-in-depth.php

[110] IRENA, *Advanced Biofuels: What holds them back?*. November 2019, p19.

[111] Scion (2018), *New Zealand Biofuels Roadmap Technical Report,* February 2018 (Scion Technical Report), p77 & 79.

While theoretically biofuels can be carbon neutral, supply chains must be meet sustainable standards, as biofuel production can create negative consequences for water and soil quality and fertilisers used in biofuel crop production may use nitrogen fertilisers (the production of which releases carbon).[112] Additionally, the land use change from biodiverse forest to cultivated land may reduce the carbon offsetting to such an extent that emissions exceed that of fossil fuels.[113]

Neste Corporation is the largest producer today of renewable diesel, with production facilities in Singapore and the Netherlands.[114] Neste suggests, after studies and field trials, that its renewable diesel also burns cleaner than traditional diesel, therefore also reducing emissions at the tailpipe.[115] There are various other refineries currently producing renewable diesel, but in recent years investment in biofuels has declined globally.[116]

3.4. Continued use of diesel with carbon offset (using existing ICEVs)

A net-zero carbon option is the status quo of diesel ICEVs while investing in a carbon offset through afforestation. This would mean status quo continuation of established importing of diesel fuel, distribution through pipelines, existing refuelling infrastructure and maintenance for each component. Section 2 discusses the state of carbon emissions of the LDHF fleet in New Zealand.

The route to achieving net zero carbon through this approach is by investing in land use change to forest in order to offset the carbon emitted by the combustion of diesel. However, many organisations and commercial contributors to carbon emissions have set goals to surpass the status quo and, as such, much of this report focuses on the alternatives described above.

3.5. Additional alternatives not considered

Along with the various methods of achieving net zero carbon for LDHF in New Zealand considered here, there are a number of other avenues which we do not explore further. We have limited the scope of our review to the options explored in the existing studies set out in Table 1.1. This does not mean that other potential alternatives are not without merit, but instead likely puts the option into a category of either achieving net zero (rather than zero) emissions or is based on a technology which is in too early a stage of development to consider seriously at this stage.

For example, the economics of converting the New Zealand LDHF fleet to FCEVs and using brown hydrogen could be evaluated, but this would require a carbon offset of some kind. Another alternative one could investigate is an emerging technology called methane cracking, which creates hydrogen by splitting methane with solid carbon, or graphite, as the other by-product (which can then be used commercially). However, this technology is still in pilot stages.[117] Additional options such as adopting

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[112] NZPC Low-emissions economy report, p366.

[113] Uusitalo, V., Väisänen, S., Havukainen, J., Havukainen, M., Soukka, R., & Luoranen, M. (2014) "Carbon footprint of renewable diesel from palm oil, jatropha oil and rapeseed oil". *Renewable Energy*, *69*, 103-113.

[114] IRENA, *Advanced Biofuels: What holds them back?*. November 2019, p19.

[115] NESTE, "Reduced emissions", accessed 15/12/20 from: https://www.neste.com/products/all-products/renewable-road-transport/reduced-emissions

[116] IRENA, *Advanced Biofuels: What holds them back?*. November 2019, pp 14 & 19.

[117] Hazer Group, "The Hazer Process", accessed 15/12/20 from: https://hazergroup.com.au/about/#hazerprocess; Ralf Dickel, "Blue hydrogen as an enabler of green hydrogen: the case of Germany", The Oxford Institute for Energy Studies, May 2020, p17.

vehicles powered by natural gas or methanol could be further alternatives, as the emissions profile of natural gas is lower than diesel.[118]

3.6. Summary of alternatives considered in studies reviewed

Table 3.1
Summary of decarbonisation alternatives considered in existing studies of green hydrogen for LDHF

	Green hydrogen / FCEVs	Blue hydrogen / FCEVs	Direct electrification / BEVs	Advanced biofuel / ICEVs	Diesel + carbon offset / ICEVs
Production method	Electrolysis using renewable electricity	SMR + CCS	Wind/Solar/Hydro generation	Refining grown organic feedstock or sourced organic waste	Refinery or importation of refined product
Distribution	Truck/pipeline for centralised production, none/little for decentralised production.	Truck/Pipeline	Electricity transmission / distribution network.	Truck/Pipeline	Truck/Pipeline
Method of storage on vehicle	Compressed fuel tank	Compressed fuel tank	Battery	Fuel tank	Fuel tank
Downstream method of energy conversion	Fuel cell + electric motor	Fuel cell + electric motor	Electric motor	Internal combustion engine	Internal combustion engine
Emissions profile	Zero emissions if electricity used for electrolysis is entirely carbon free	Residual emissions of roughly 10% under current technology	Zero emissions if renewable electricity is used. For grid connected recharging, emissions depend on time of charging	In theory, low net emissions over lifecycle; there are emissions at the tail pipe	Heavy trucks in NZ emit 1,420g of CO_2 per km[119]

[118] Hagos, D. A., & Ahlgren, E. O. (2018) "Well-to-wheel assessment of natural gas vehicles and their fuel supply infrastructures–Perspectives on gas in transport in Denmark", *Transportation Research Part D: Transport and Environment*, *65*, 14-35.

[119] MoT Strategic Working Paper, Table 1.

4. Our approach to reviewing the studies

The purpose of this study is to address the broad research question of "**what needs to be true for green hydrogen to be the most economic path for decarbonising LDHF in New Zealand?".** In this initial stage of the project, we have two broad tasks:

- Assessing the robustness of the studies identified for review, both in terms of their methodological soundness and the implementation of that methodology; and
- Analysing the outputs of studies to synthesise their conclusions on the economics of green hydrogen for LDHF in New Zealand, taking into account our views on the robustness of the studies.

In this chapter we describe our approach to the first task. To assess the robustness of the existing work on this question requires that we first define a framework on the appropriate methodology for answering the question. In our view, the most appropriate method of answering this question is **to compare the total societal costs of different methods of decarbonising LDHF.** Having defined a framework, we can then assess the existing studies against that framework, as well as consider more general issues around the transparency and robustness of assumptions, as well generic modelling issues.

In this section we:

- Define the appropriate economic framework for answering the question (section 4.1); and
- Set out the framework we apply when reviewing the robustness of the existing literature on this question (section 4.2).

4.1. Framework for assessing the economics of decarbonisation alternatives

We interpret "most economic" to coincide with the concept of economic efficiency. Through this lens, the most economic method of decarbonising LDHF is the method that achieves net zero emissions for LDHF with highest net societal benefits. In other words, the option that maximises the difference between total societal costs and total societal benefits. Note that societal costs and benefits, in this context, means that economic costs and benefits must be considered from a national or economy-wide perspective, as opposed to including non-economic considerations around equity and fairness.[120]

In the context of decarbonising LDHF, one could narrowly focus on minimising the societal costs of achieving that goal. However, different options may involve benefits besides reducing carbon emissions, which should also be taken into account. In the diagram below we set out the framework we consider should be applied to answer the question. Similarly, it is important that social costs and benefits, rather than simply private costs and benefits are considered. In the presence of unpriced externalities (such as air pollution), the option which is privately optimal (i.e., maximises profits for the freight operator), may not be the most socially optimal (i.e., maximises the wellbeing of broader society).

[120] See, e.g., Treasury (2015), *Guide to Social Cost Benefit Analysis*. For example, a carbon tax is one way to create a "price" for a social cost which can be considered in an economic framework.

Figure 4.1
Components for assessing net societal benefit of different methods of decarbonising LDHF

	Framework Component	Description
Social costs	Delivered cost of fuel	Delivered cost of fuel at the point of refueling (i.e., the capital and operating costs of fuel production, storage, transport and refueling), including energy losses
	Operational running costs	Per tonne-kilometre running costs costs based on relative technical efficiency of different fuels/technologies
	Ownership costs	Lifetime ownership costs, including purchase cost and maintenance over the expected life of the asset
Social benefits	Environmental impact/sustainability	• External environmental impact of fuel production, use in vehicle and parts used in both fuel and vehicle production • Vehicle disposal process and recyclability of parts • Future externalities if current production proves unsustainable • Emissions besides CO_2
	Other societal benefits	Different options may have other benefits such as resiliency/security of supply
Overlays to assessing costs/benefits	Timeframe for analysis	Over what period are benefits/costs being assessed? Given maturity of different technologies, the answer may differ depending on the timeframe assessed
	Cost curves/paths for costs/benefits	Consideration of how costs/benefits are expected to evolve in the future
	Risk and uncertainties	What are the risks/uncertainties associated with the costs/benefits? Just comparing expected values may lead to incorrect conclusions if certain options have much greater uncertainty/risk with the costs/benefits

At a high level, we therefore consider that the following steps should be taken to assess the most economic path to decarbonising LDHF in New Zealand:

1. Estimate the total social costs of using each alternative to decarbonise LDHF;
2. Overlay any additional benefits of the different options which may or may not be quantifiable, such as resiliency/security of supply; and
3. Consider the risks/uncertainties associated with the costs/benefits and timeframe over which decarbonisation is being assessed.

When calculating and comparing the total social costs of each option, one could make the comparisons in total dollar terms for the freight task or collapse these costs to an average metric such as dollars per kilometre or dollars per tonne-kilometre. Given the question at hand is to find the most economic method of decarbonising New Zealand’s LDHF freight movements, the amount of freight that is moved is a key component of the equation. Comparing the dollars *per kilometre* for two technology types where the trucks can carry different amounts of freight would give misleading results. Therefore, our preference would be to either compare the total costs in dollar terms for the entire LDHF task or collapse this down to dollars *per tonne-kilometre*. Where data are available, we will assess both dollars per kilometre and dollars per tonne-kilometre for comparison and transparency.

Regarding the non-quantifiability of certain benefits/costs, it is important that categories of benefits/costs which are difficult/impossible to quantify are not ignored in any analysis. In some sense the purpose of quantification is to inform decision makers “what you need to believe” about the magnitude of non-quantifiable costs/benefits, in order for one option to be preferred over another.

That is to say, if one option appears more expensive than another, but the "expensive" option has a number of unquantifiable benefits that the "cheaper" option doesn't, the analysis might actually suggest the more expensive option is more economic if the difference in quantifiable cost is marginal. A narrow focus on quantifiable costs/benefits might lead to the erroneous conclusion that that a lower-cost option was preferable.

The uncertainty point is particularly important in the current context, where zero or net zero-emission technologies for LDHF is at a nascent stage (as described in section 3) and governments and other centralised bodies are making decisions about future technology choices and providing funding. That is to say, if governments and policy makers are "picking winners" when there is considerable uncertainty, they may pick the wrong option. This could result in:

- New Zealand having stranded assets, if another technology proves lower cost in spite initial investment in another technology;[121] or
- Being locked into an inferior technology (and thus paying higher prices/receiving worse quality). This could occur if significant initial investment is made in a decarbonisation option which subsequently turns out to be technologically and/or economically inferior in the future. The initial investment could give this technology a cost advantage (in a forward-looking sense) over the technology that ultimately proves to be superior, but which hasn't received significant investment.[122]

If there is uncertainty, there may therefore be value in waiting for this uncertainty to be resolved. Real Options frameworks[123] or "least worst regret" (LWR) analysis[124] are techniques which can be used for this type of analysis. The key insight from both techniques is simply that the distribution of outcomes matters (and in the case LWR, the downside in particular), and therefore focusing on point estimates is inappropriate. Of course, while there may be value in waiting, one also needs to consider the costs of waiting. In the current context, given the long life of trucks, waiting may lock in existing technologies if new trucks are purchased in the interim.[125]

The timeframe is also an important consideration given:

- The existing fleet of diesel trucks in operation, which generally remain in the New Zealand fleet for an average of 24 years (from new);[126] and
- Some technologies may not be commercially viable right now but may be in the future.

Given an existing long-lived truck stock, making a material impact to emissions now would either require replacing the fleet at great cost or implementing decarbonisation options that use the existing fleet. In the medium/longer term, trucks will be retired and replaced, and thus changing to a new technology, in terms of the trucks, simply involves buying a different truck when it is time to replace the truck. This means that depending on the timeframe for decarbonisation, different options may be better in the short term (i.e., life of existing trucks) vs the medium/long term. Or put another way, the "path" may be different from the "end point".

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[121] This risk being a function of the level of investment required – the smaller the investment, the less of a concern stranding is, or indeed lock-in as set out in the next bullet.

[122] Put another way, if "sunk" investments are made now, and changing to a new technology would require duplicating those investments, it may be cheaper on a forward looking basis to stick with the existing technology, even if the alternative would be lower cost if no investments had been made in either technology.

[123] Real Options frameworks, generally used when considering investments, attempt to choose a "best" strategy across possible flexible strategies, accounting for a range of potential futures and adaptations of those futures.

[124] LWR analysis is a decision-making tool which recommends options or strategies which are expected to produce the least "regret" (i.e., cost) across all scenarios analysed even when the probabilities of outcomes are unknown.

[125] Noting that at the time of writing, there are no heavy e-trucks available commercially.

[126] MoT Background Paper, p13.

4.2. Framework for assessing the studies

Having defined the economic framework that appropriately answers the research question, we now set out the assessment framework we use when reviewing the studies. In effect, this is a set of questions we ask of each study. Our assessment framework is set out in Figure 4.2 below.

Figure 4.2
Assessment framework

Coherence of modelling framework
The purpose of these questions is to identify whether the underlying method seeks to estimate costs that could transpire given its underlying assumptions
Is the study addressing the same question?
To what extent is each alternative considered?
What policies or public funding does the modelling assume are in place to support hydrogen and/or other fuels?
Are the costs of alternative fuels analysed in a consistent way?

Completeness of cost components
Analysing whether green hydrogen is least-cost requires that cost estimates are complete. This set of questions is essentially whether the studies appropriately capture the costs identified in the economic framework above.
Are the total societal costs of each alternative appropriately captured (i.e. the cost items set out in the economic framework)?
Are non-quantifiable/hard-to-quantify factors accounted for?
What costs have been assumed for policies to support (or deter the use of) hydrogen and/or other fuels?
What allowance has the study made for the costs of transitioning to the green hydrogen or an alternative fuel? Has more than one fuel option been considered in their path to decarbonisation?
Has allowance been made for risk/option value of developing green hydrogen or alternative fuels?

Transparency and robustness of assumptions
The credibility of the results from a study will depend on whether the supporting assumptions are clearly explained, and the sensitivity of results explored.
Are the assumptions explicitly presented?
Are the assumptions externally verifiable?
Do the assumptions fall within range of external benchmarks and, if not, is the deviation justified?
Have critical assumptions been identified and the results sensitivity tested for these assumptions?
Are assumptions dependent on a certain scale being taken up, or reliant on other use cases being taken up? If so, what are they?

5. Overview of studies considered and their conclusions

In this section we provide an overview of the existing studies on the economics of decarbonising LDHF using green hydrogen in New Zealand. We split our discussion between:

- Studies with quantitative economic analyses of the different decarbonisation options for LDHF (section 5.1); and
- Studies that qualitatively discuss the opportunities and challenges across decarbonisation options (section 5.2).

5.1. Reviews with economic analyses of decarbonisation options

This set of studies reviewed perform quantitative modelling on the costs of future LDHF alternatives, and most additionally contain some level of qualitative discussions. An additional study, which is outside the direct scope of this report, is the January 2020 MfE report, *Marginal abatement cost curves analysis for New Zealand*. This study contains analysis of the marginal abatement cost for heavy BEVs against traditional ICEVs using diesel based on the total cost of ownership, and evaluate the potential break-even carbon price required for renewable diesel to supersede fossil fuel.[127] We have not included this study in our methodological review, as the study does not consider hydrogen in FCEVs for heavy trucks. However, we do reference the study's conclusions in sections 6.5.3 and 7.4 in this report where relevant.

5.1.1. New Zealand Green Hydrogen Modelling for MBIE, Castalia

Purpose

MBIE's exploration into green hydrogen's potential in New Zealand begins with the *Vision for Hydrogen* green paper, discussed in the prior section, and is intended to continue in a quantitative way with a "New Zealand Hydrogen Roadmap" as a next step.[128] This is currently targeted to be competed in the first half of 2021.[129]

At present, MBIE has released a dashboard relying on an underlying modelling tool on green hydrogen in New Zealand prepared by Castalia – this dashboard relies on the user to choose key inputs and only allows the user to review the specific dashboard outputs. Therefore, it is difficult for us to assess the approach taken or provide our own input on its economic framework, but we can review the model at a high level and extract some key information.

Review of model

The model allows the user to select electricity costs and annual electricity price change, the electrolyser utilisation, the annual change in FCEV and BEV capital costs, and the change in carbon price – therefore we can conclude that these assumptions are accounted for in each output of the model.

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[127] MfE MACC Report, p 41.

[128] MBIE, "A roadmap for hydrogen in New Zealand", accessed 15/12/20 from: https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-strategies-for-new-zealand/a-vision-for-hydrogen-in-new-zealand/roadmap-for-hydrogen-in-new-zealand

[129] MBIE, "New Zealand Hydrogen Strategy" presentation, 5 August 2020, accessed 15/12/20 from: https://www.bec.org.nz/__data/assets/pdf_file/0006/198744/Business-Energy-Council-Hydrogen-Presentation_MBIE.pdf

The model itself does not provide an answer to our main research question, instead looking at potential New Zealand-wide supply and demand for green hydrogen under various scenarios. The model provides output looking from 2020 to 2050 on:

- consumption of green hydrogen in New Zealand;
- CO_2 emissions reduction in New Zealand due to use of green hydrogen;
- levelised cost of green hydrogen (including international benchmarks); and
- composition of New Zealand heavy vehicle fleet (FCEVs, BEVs, and diesel).

However, a presentation provided by Castalia to the Business Energy Council provides further analyses including the modelled cost per kilometre for a "representative truck" across ICEVs, BEVs, and FCEVs. It provides in this presentation a high, low, and base case with a few underlying assumptions, such as:[130]

- the price of diesel increases at 3% per year from retail price (high case is 5% and low case is zero percent);
- hydrogen price begins at the "optimised 2020 New Zealand price" of USD$3.96/kg (the underlying calculations of the price are not presented);
- hydrogen capital costs decline at 5% annually and electrical capital costs decline at 3% annually.

We also assume that the "base case" presented here is the same as the base case assumptions presented on the dashboard (which includes a button to "reset to base case"), and will proceed under this assumption when evaluating the conclusions against the other quantitative studies.

Conclusions

The base case analysis in Castalia's presentation on the cost per kilometre for a "representative truck" across ICEVs, BEVs and FCEVs shows that although FCEVs are more expensive per kilometre than BEVs until after 2040, they should converge with BEVs before 2050. This scenario also finds that BEVs would be cheaper than diesel before 2030. This assumes a rising diesel price of 3% per year and a rising carbon price of 4.5% per year, and therefore puts ICEV cost per kilometre above a BEV before 2030 and above an FCEV before 2035. However, these results should be interpreted with caution as it is unclear what weight class of trucks within heavy trucks are modelled, and although we assume that the results for this analysis are presented in NZD, the hydrogen cost is presented in USD to present against international benchmarks and it is unclear what exchange rate is used.

The presentation does not include further conclusions and does not reveal some critical assumptions (such as capital cost of trucks), but notably the presentation discusses importing from Australia – it demonstrates that importing Australian-produced green hydrogen could compete with domestically produced green hydrogen from present through 2050. Additionally, the model (again under the assumption that the model base case is the same as the presentation analysis), assumes that as time progresses and costs for FCEVs and BEVs converge, adoption of both FCEVs and BEVs increase to the point that by 2050, the two e-trucks will have displaced roughly 50% of the diesel heavy vehicle fleet (albeit with BEVs making up roughly 75% of e-trucks).

[130] Castalia, "New Zealand Green Hydrogen Modelling Presentation to Business Energy Council", 5 August 2020 (Castalia Presentation), accessed 15/12/20 from: https://www.bec.org.nz/__data/assets/pdf_file/0005/198743/Business-Energy-Council-Hydrogen-Presentation_Castalia.pdf

5.1.2. *Hydrogen in NZ*, Concept Consulting

Purpose

Concept Consulting developed a three-volume study reviewing the economics of hydrogen for various use cases in 2019, sponsored by Contact, Meridian, Powerco, First Gas, MBIE, and EECA. The study provides a summary report, an analysis report, and a research report detailing Concept's process. The purpose of the study is to examine whether hydrogen (not only green hydrogen, but also blue and brown hydrogen) technologies are likely to be cost-effective in various use cases to decarbonise New Zealand's economy. This aligns closely with our own research question, and Concept provides detailed information about its assumptions. Although the study looks at other use cases, we focus on the hydrogen production cost assessment and heavy freight fuel comparison assessments. These assessments provide present and future cost conclusions, in 2020 and 2040 respectively.

Approach

Regarding the hydrogen production cost assessment, current and future costs assumptions are presented for electrolysers, operating costs, storage costs, wholesale electricity and electricity network costs, which are obtained from literature reviews the range of which is provided in an appendix.[131] Discount rate and useful life assumptions are given, and the final hydrogen price estimates are sensitivity tested against other international published estimates.[132] It notes that caution must be used comparing against international assumptions, as electricity input costs vary materially across countries.[133]

From here, blue hydrogen is considered, assuming that CCS could capture 75% of emissions from steam-methane reforming.[134] It notes that, therefore, the price of carbon drives the economics of blue hydrogen in New Zealand due to the remaining emissions gap.[135] It provides a cost model for very large-scale production of blue hydrogen with a supply chain of natural gas, capital costs and process losses of SMR+CCS, and carbon price.[136] It excludes storage costs, assuming it would be directly fed into a transmission pipeline – this seems to be where the study implicitly excludes applying blue hydrogen to heavy freight, as the study only looks at green hydrogen in this use case.[137]

Concept's approach to evaluating the total cost of ownership for heavy freight across diesel, BEVs and FCEVs begins with the total cost of ownership components for a diesel vehicle using a breakdown provided by a major freight operator.[138] Capital costs, maintenance costs, and fuel costs are the major components which are very specific to each vehicle type, but other general costs such as tyres and driver costs are assumed to be the same. The vehicle-specific costs are developed by component for each technology and include reductions in cost for the future scenario dependent on the component. Penalties are developed for the decreased payload and increased charging times of BEVs ("productivity penalties"), and RUCs are increased by an additional factor for BEVs to account for the fact that RUCs increase with the weight of a vehicle.[139] The combined penalties reduce for the future

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131 To be clear, the range of values obtained from Concept's literature review is provided in the appendix such that a reader can benchmark the assumptions. However, the literature underlying the review is not provided. Concept Analysis Report, p11.

132 Concept Analysis Report, p11-12.

133 Concept Analysis Report, p12.

134 Concept Analysis Report, p26.

135 Concept Analysis Report, p26.

136 Concept Analysis Report, p27.

137 Concept Summary Report, p.8.

138 Concept Analysis Report, p34.

139 Concept Analysis Report, p34 & 37-42.

scenario, assuming that battery technologies will continue to improve (range increase and battery density improvement).[140]

Vehicle efficiency, cost of delivered fuel, cost of refuelling infrastructure, and a refuelling model (i.e., at-base and away-from-base charging for BEVs) are considered to develop fuel costs for each vehicle type.[141] A "service station" model is developed to account for compression costs for a fuel tank and overhead costs for the service station itself for hydrogen refuelling, based on information from Z and sensitivity tested against hydrogen station delivered fuel costs in California.[142]

Finally, four scenarios are considered. First, two separate assumptions are applied about the annual kilometres driven each year by the heaviest class of freight vehicles in New Zealand – according to Concept, on average heavy vehicles drive roughly 75,000 kilometres per year, but newer vehicles (e.g., BEVs and FCEVs) are likely to drive much further than this and therefore a scenario at 150,000km/year is also considered.[143] Two separate hydrogen take-up scenarios are modelled. First, a small-scale scenario is presented where no additional renewable electricity generation is needed. This assumption means that electrolysers can produce opportunistically, meaning the electrolysers use off-peak electricity, and therefore can achieve lower costs.[144] A second large-scale hydrogen take-up scenario is considered, where hydrogen is not only used for other use cases, but globally it is adopted and therefore New Zealand is pushed into adopting hydrogen – this assumption means that hydrogen cost for fuel is higher due to the increased price of electricity stemming from increased demand, as larger scale production is needed, and the technology developments for batteries are reduced.

Conclusions

The conclusions find that BEVs are likely to be the least-cost option for the heavy freight fleet under the small-scale scenario. However, the sensitivity analysis of large-scale take up on vehicles traveling 150,000kms/year bring the FCEV total cost of ownership close to BEVs.

5.1.3. *H2 Taranaki Roadmap*, Venture Taranaki, Hiringa Energy and New Plymouth District Council

Purpose

The H2 Taranaki Roadmap was developed as a joint report between these groups on a broad range of applications for hydrogen in both Taranaki and more broadly in New Zealand. The report develops a roadmap for a series of projects for the energy industry in New Zealand to transition towards the use of hydrogen, including establishing a hydrogen refuelling network for vehicles and piloting hydrogen transport options.

Approach

The report discusses blue hydrogen as a transitional decarbonisation option for the industrial sector, but states that green hydrogen can be applied to the new hydrogen transport market.[145] It offers

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140 Concept Analysis Report, p41-42.

141 Concept Analysis Report, p42.

142 Concept Analysis Report, p13 and 43-44.

143 Concept Analysis Report, p41.

144 Note that here, Concept has modelled the efficient trade-off between electrolyser capex and opex with wholesale electricity prices, in which they find it most efficient to run electrolysers 85% of the time – in other words, avoiding the peak 15% of periods. Concept Analysis Report, p23.

145 H2 Taranaki Roadmap, p15.

comparisons to non-hydrogen alternatives to decarbonising the sectors of the economy it discusses, but approaches all business cases with a hydrogen-focused lens.

The report provides an overview of green and blue hydrogen production methods, storage and distribution and infrastructure descriptions. [146] Additionally, a qualitative assessment of FCEVs compared against ICEVs and BEVs is provided.[147]

Various opportunities for hydrogen to be used across a range of vehicle types is discussed at a qualitative level, but a brief analysis is provided for a quantified cost comparison of diesel, BEVs, and FCEVs for heavy freight from 2018 to 2030.[148] The analysis provides the estimated costs per tonne-kilometre for each vehicle/fuel (opposed to cost per kilometre), which accounts for the decreased payload and increased recharging times for BEVs. The assumptions for payload and annual kilometres are explicitly presented, while assumptions such as increases in diesel and grid electricity cost and decreases in hydrogen price and BEV/FCEV capital costs are stated as taken into account but without underlying assumptions being presented.

Conclusions

A chart is provided with the NZ$ per tonne-kilometre over time for the three vehicle types, with two separate scenarios presented for BEVs where a standard 50kW charger is used and 150kW fast charging. No carbon price appears to be applied on the diesel scenario or is at least not noted as included. The conclusions show that although diesel remains least cost in terms of tonne-kilometres until 2030, when it reaches price parity with FCEVs, FCEVs are least cost in each year modelled between the two zero-emission options.

5.1.4. *Gas Infrastructure Futures in a Net Zero New Zealand*, Vivid Economics

Purpose

This report was prepared by Vivid for First Gas and Powerco in order to assess potential paths forward for natural gas and its infrastructure in New Zealand, in light of the country's adopted decarbonisation targets.

Approach

Three core net-carbon scenarios are developed modelling the potential futures of natural gas and existing infrastructure across various sectors of the economy, two of which involve applying hydrogen to heavy freight (considered a "hard-to-treat" sector). One of these two scenarios, the Green Gas scenario, assumes that the gas transmission system is transitioned to carry hydrogen gas (then distributed to refuelling stations), while the other, the All Electric scenario, assumes the gas transmission lines are decommissioned and hydrogen is still the choice for decarbonising heavy freight where production and refuelling takes place either centrally or at depots and is transported by truck to a network of refuelling stations.[149]

Blue hydrogen is not considered as a viable alternative for any hydrogen application considered as "the feasibility of CCS in New Zealand is currently uncertain", and therefore hydrogen considered for fuel is assumed to be green hydrogen.[150] However, it notes that should CCS prove to be a feasible

[146] H2 Taranaki Roadmap, p25-35.

[147] Major points identified by this review are discussed in section 7. H2 Taranaki Roadmap, p16-17.

[148] H2 Taranaki Roadmap, p43-44.

[149] Vivid Report, p28 & 39-40.

[150] Vivid Report, p39.

option, the costs of applying hydrogen could be significantly lower. Additionally, BEVs are dismissed for heavy freight without further consideration, stating that they are not feasible due to the long distances demanded in this sector and the high cost and weight of batteries large enough to meet the requirements for the task.[151] Given these dismissals, the only option considered suitable for decarbonising heavy freight is green hydrogen (which it quantifies for the Green Gas scenario) and alternatively, in the third scenario, continuing to burn diesel and afforestation to offset the carbon emissions.[152]

The first scenario assumes continued use of fossil fuels and is based upon modelling performed in the NZPC report discussed in the prior section.[153] This does not directly consider heavy freight, but instead implicitly considers that low emissions technologies will not develop quickly enough for goals to be met, and instead policy action is taken increasing the carbon price to between $150 and $250/t CO_2e to achieve net-zero emissions.[154] Following this, Vivid's quantification of diesel heavy freight vehicle's price per kilometre includes a carbon price of $200/t CO_2e.[155]

Vivid notes at the outset of the scenario quantification that its estimates are simple and further work would be needed to apply detailed costing, due to the costs of potential solutions being technically and commercially immature and therefore poorly understood.[156] Of the two alternative scenarios in which FCEVs are solution to decarbonising the heavy freight sector, only the Green Gas scenario (where transmission lines are repurposed) is modelled quantitatively. It develops a low estimate and a high estimate for 2050 (the year of the Government's decarbonisation goal).

The delivered cost of hydrogen fuel estimates assume either a 10% (low) or 20% (high) increase in the costs of current gas transmission to account for costs of retrofitting pipelines.[157] To calculate the cost per kilometre of running a green hydrogen FCEV, assumptions differ across the "low" and "high" estimates generally such that high assumptions are based on cost estimates for 2030, assuming that technology and costs plateau around this point through 2050, and the low assumptions allow for continued cost reductions through 2050.[158]

We were able to recreate the values which Vivid finds for the cost per kilometre of FCEVs using a combination of the inputs presented plus our own independent research and testing the assumed specific energy of hydrogen.[159] There are issues with the underlying assumptions presented and a number of assumptions are not included in the modelled cost stack, as discussed in the following section.

Conclusions

The study concludes that there is a "high degree of uncertainty surrounding the least-cost approach" to decarbonising the identified hard-to-treat sectors.[160] Overall, the conclusions are such that there further investigation needed and greater certainty over the potential for hydrogen is needed before good policy decisions could be made.

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[151] Vivid Report, p16.

[152] Vivid Report, p24.

[153] Vivid Report, p24.

[154] Vivid Report, p38.

[155] Vivid Report, p44.

[156] Vivid Report, p29.

[157] Vivid Report, p42 & 52.

[158] Vivid Report, p38 & 39.

[159] Skai, "Hydrogen Details", accessed 15/12/20 from: https://www.skai.co/hydrogen-details

[160] Vivid Report, p48.

In regard to heavy freight, it concludes "only in heavy transport is there an unambiguous finding, as the use of electricity as a fuel in heavy transport does not appear feasible".[161] However, we note that no analysis is actually performed of BEV economics to support this statement. Additionally, it notes that although afforestation will likely be important in the transitional period to net zero emissions, alternative strategies will be needed past 2050.[162]

5.2. Reviews with qualitative discussions of opportunities and challenges across decarbonisation options

This set of studies reviewed does not perform quantitative modelling on the costs of future LDHF alternatives. The New Zealand Productivity Commission (NZPC) report does perform quantitative modelling, but not towards the research question, so this study is considered qualitative in regard to the scope of this paper.[163]

The summaries here discuss the studies to the extent that future fuel options for road freight are examined, although most of the papers have broader scope than this. Policy suggestions and examinations included in the papers are not discussed here, instead focusing on the assessments of the economics of fuels outside the scope of government interventions.

5.2.1. *Green Freight Strategic Working Paper* and *Background Paper*, Ministry of Transport

Purpose and approach

The Ministry of Transport (MoT) has prepared two separate papers for its Green Freight project:

- A background paper containing non-technical research on opportunities for the freight industry to reduce GHG emissions;[164] and
- A strategic working paper to provide the Government with a range of options to increase the uptake of "alternative green fuels", released to after receiving submissions and feedback on the background paper.[165]

The background paper's purpose is to answer the question "how could New Zealand best use alternative fuels to reduce GHG emissions from road freight?"[166] This question, although not quite the same as our research question, is closely aligned to ours and provides New Zealand-focused non-technical background research on options to decarbonise road freight. The scope is therefore slightly broader than ours, looking at road freight in general rather than LDHF specifically.

The paper establishes that the Government's existing emissions reduction mechanisms for the transport sector are not likely to be sufficient to achieve net zero carbon by 2050, and therefore alternative fuels must also be considered as part of the strategy to achieve this goal.[167] It therefore

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[161] Vivid Report, p45.

[162] Vivid Report, p14.

[163] Note that in our research, we also reviewed the Interim Climate Change Committee's report, *Accelerated Electrification*. The ICCC developed this report to provide advice to the Government on planning for the transition to 100% renewable electricity by 2035. This report, upon review, is outside the scope of our research question, as the report does discuss replacing fossil fuels in transport with electricity to reduce New Zealand's emissions but does not investigate heavy freight or hydrogen as a fuel for vehicles in detail.

[164] MoT Background Paper, p3.

[165] MoT Strategic Working Paper, p7.

[166] MoT Background Paper, p3.

[167] MoT Background Paper, p3.

examines the challenges and opportunities surrounding direct electrification, hydrogen, and biofuels as alternative options.

The strategic working paper sets out the same options explored in the background paper in terms of the options considered. This paper's goal, building on the research of the background paper, is to provide policy direction options to the Government to support the reduction of greenhouse gases in the transport sector.

Conclusions

Its research provides a range of potential avenues, but the overall conclusions on these technologies are such that:

- Significant improvement in battery energy density and fast charging infrastructure are essential for BEVs to play a significant role in reducing greenhouse gas emissions in road freight, but instead have applicability immediately in shorter-haul operations;[168]
- Hydrogen FCEVs are likely to be best suited to long-range heavy trucks to complement other alternative fuel types in other applications, but efficiency improvements and reductions in capital costs would have significant impact on price and competitiveness with alternatives;[169]
- Conventional biofuels only provide reduction in greenhouse gas emissions at the rate they can be blended into fossil fuels, which is low (roughly 5%) when used in conventional ICEVs, and are costly to produce given the large amounts of feedstock needed and significant up-front capital investment;[170] and
- Advanced (drop-in) biofuels have the ability to reduce greenhouse gas emissions by 85-90%, but at the time of writing were only beginning to be commercially produced internationally.

From these conclusions, the background paper suggests that good policy and investment decisions require a full life cycle analysis of each fuel to be compared fairly, and that the current state of each technology means none of the three technologies considered provides a clear solution.[171]

The strategic working paper conclusions remain the same as those in the background paper, with expanded scope suggesting policy direction given those conclusions.[172]

Main issues of note are that the choice of fuel is constrained by availability and cost:[173]

- Biofuels are available now and can be used across the wider transport system including in existing infrastructure;
- FCEVs are not readily available in New Zealand;
- The upfront high cost of new-technology vehicles is prohibitive; and
- Developing supporting infrastructure will be critical to enabling a transition to BEVs or FCEVs moving forward.

The paper notes that opportunities to shift road freight to rail and coastal shipping or changing freight operational models can also reduce greenhouse gas emission from the sector but is outside the scope

[168] MoT Background Paper, p26.

[169] MoT Background Paper, p34.

[170] MoT Background Paper, p41.

[171] MoT Background Paper, p6.

[172] MoT Strategic Working Paper, p19.

[173] MoT Strategic Working Paper, p25.

of the report.[174] It also adds that if the Government decides to pursue any of the options presented, that further analysis will need to be undertaken to fully understand the impacts.

5.2.2. *A vision for hydrogen in New Zealand: Green Paper*, MBIE

Purpose and approach

MBIE's green paper is the first stage in a larger project developing the Government's investigation into the application of hydrogen to the energy system and economy. Following this vision paper, MBIE is developing its roadmap for hydrogen.[175]

The intention of the green paper is to provide a high-level assessment of the potential applications of hydrogen across the economy, pulling on established research on the subject and generally providing a technical assessment of opportunities. The paper aims to identify "the possible applications, benefits and barriers to uptake for hydrogen in our energy, transport and export sectors".[176] As such, the paper does not provide many answers in service to our research question given its different focus, but does give a general overview of specific topics of interest. Hydrogen production strategies as well as application to transport and mobility are discussed in the paper.

Conclusions

The paper notes that although grey and blue hydrogen could play a transitional role, the Government considers that green hydrogen has a stronger opportunity in New Zealand given its renewable energy resources.[177] The paper discusses the energy losses sustained by hydrogen from well to wheel when applied in a FCEV, but states that efficiency can be largely a matter of economics if emissions are valued.[178]

In its discussion of hydrogen's place in transportation, the paper acknowledges that FCEVs and BEVs are likely to be complementary in the overall transition away from fossil fuels.[179] It finds that BEVs are more efficient for short distances and lighter vehicles, while FCEVs are suitable for heavy payloads traveling long ranges.[180] Safety has been noted as a concern applying hydrogen to road vehicles, but the study finds that FCEVs are as safe, and potentially safer, than traditional vehicles.[181]

Overall, the green paper's synthesis of prior research and case studies determines that green hydrogen is likely to have a role in the largest and longest distance transport sector, past LDHF to aviation, straddle carriers, and cargo ships, while other alternative fuels and continued use of fossil fuels may suit smaller and shorter-distance transport.[182]

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[174] MoT Strategic Working Paper, p6.

[175] MBIE, "A roadmap for hydrogen in New Zealand", accessed 15/12/20 from: https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-strategies-for-new-zealand/a-vision-for-hydrogen-in-new-zealand/roadmap-for-hydrogen-in-new-zealand

[176] MBIE Green Paper, p19.

[177] MBIE Green Paper, p11.

[178] MBIE Green Paper, p 23.

[179] MBIE Green Paper, p49.

[180] MBIE Green Paper, p48.

[181] MBIE Green Paper, p49.

[182] MBIE Green Paper, p50.

5.2.3. *House View: Hydrogen*, Z

Purpose and approach

Z's house view on hydrogen paper aims to discuss what Z believes (as of August 2019) about the potential for hydrogen as a fuel in New Zealand, both in transport and industrial uses. The paper does not set out to answer a research question, but instead sets out Z's own views formed on hydrogen given current projects, discussions with customers and sector participants and its own research.

Conclusions

Z finds that green hydrogen and blue hydrogen are the most likely pathways for hydrogen production in New Zealand but note the current high costs and energy losses of green hydrogen and that CCS has not yet proved to be a commercially viable process.[183] It sees blue hydrogen, if feasible, as a transitionary fuel while a market for hydrogen is established.[184] Z's discussions with customers indicate that it is interested and open to hydrogen as an alternative fuel, but indicated a strong interest in biofuels as a transitionary fuel due to the applicability in existing infrastructure and operating practices.[185]

Z finds that electrification is likely to be the dominant choice for light vehicles, but hydrogen and biofuels are preferred options for heavy transport vehicles.[186] However, it sees that heavy transport manufacturers are significantly behind light vehicle manufacturers in deployment of vehicles.[187]

It concludes that it is too soon to commit to hydrogen fully, and that there will not be a single "silver bullet" to decarbonisation. Therefore, it believes investigation into multiple options should continue with urgency.[188]

5.2.4. *Low Emissions Economy Report*, New Zealand Productivity Commission

Purpose and approach

The NZPC developed the Low Emissions Economy Report as an inquiry to identify options for how New Zealand could reduce its domestic greenhouse gas emissions, guided by two broad questions:

- "What opportunities exist for the New Zealand economy to maximise the benefits and minimise the cost that a transition to a lower net-emission economy offers, while continuing to grow incomes and wellbeing?"; and
- "How could New Zealand's regulatory, technological, financial and institutional systems, processes and practices help realise the benefits and minimise the costs and risks of a transition to a lower net emissions economy?"

Therefore, the scope of this paper is extremely broad when compared to our research question. However, Chapter 12 of this report is dedicated to emissions sources and opportunities in the transport sector.[189] Sections 12.5 and 12.6 address heavy freight and therefore these are the sections we will summarise. This section of the review states that the main opportunities for decarbonising heavy

[183] Z, *House View: Hydrogen*, August 2019 (Z House View), p4.

[184] Z House View, p5.

[185] Z House View, p5.

[186] Z House View, p6-7.

[187] Z House View, p13.

[188] Z House View, p15.

[189] Note also that hydrogen is not a focus in any other sections of the report.

transport are electrification, biofuels or biogas, and hydrogen-fuelled vehicles.[190] The paper provides a research-heavy review of these three options, citing to various New Zealand-centric and international studies to support the conclusions.

Conclusions

Like many others, it concludes that long-haul trucks are largely unsuitable for direct electrification under current technologies, given their limited travel range and weight of batteries.[191] However, it notes that Tesla is developing the Tesla Semi, suggesting that these barriers may be overcome.[192]

The study concludes that conventional biofuel's ability to reduce emissions is dependent on the portion of biofuel contained in the fuel source, since these are blended at low volumes into fossil fuels and therefore only result in a similar proportioned reduction in emissions.[193] However, it notes that advanced "drop-in" biofuels, such as renewable diesel, are rapidly developing and could be ready to deploy in New Zealand within five years (from time of publishing).[194] Currently, use and availability of biofuels are low and scaling up biofuel production in New Zealand has significant implications for land use, as drop-in biofuels from non-food feedstock appear to be the most suited to New Zealand.[195] Moreover, it is unlikely biofuels will be profitable without an increase in the carbon price, and therefore the price of diesel.[196]

The study states that hydrogen FCEVs are better suited to LDHF than BEVs due to their longer travel range and faster refuelling.[197] It notes that several submitters to the paper also suggested that FCEVs could play a useful role in decarbonising the heavy fleet.[198] The biggest challenge was considered to be the substantial investment needed to establish infrastructure for production, transportation, and distribution of the hydrogen fuel.[199] Additionally, the high cost of FCEVs is a barrier to uptake.[200]

The study also briefly discusses the opportunity for modal shift of some freight in New Zealand away from road freight and onto coastal and rail shipping.[201] Although these methods have lower emissions profiles per tonne-kilometre, the volume of freight which is suitable to switch to these alternative modes is limited. Inter-regional (i.e., long distance) freight which is not time sensitive is best suited to this modal shift.

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[190] NZPC Low-emissions economy report, p363.

[191] NZPC Low-emissions economy report, p363.

[192] NZPC Low-emissions economy report, p363.

[193] NZPC Low-emissions economy report, p365.

[194] NZPC Low-emissions economy report, p365

[195] NZPC Low-emissions economy report, p365.

[196] NZPC Low-emissions economy report, p365.

[197] NZPC Low-emissions economy report, p367.

[198] NZPC Low-emissions economy report, p367

[199] NZPC Low-emissions economy report, p367.

[200] NZPC Low-emissions economy report, p368.

[201] NZPC Low-emissions economy report, p374-375.

6. Assessment of modelling performed with cost outcomes across fuel sources

This section steps through the assessment framework as outlined in section 4.2, assessing each study against each framework question: we examine the coherence of modelling framework, completeness of cost categories included, and the transparency and robustness of assumptions. The studies assessed here are those which have performed quantitative economic modelling, as discussed in section 5.1 above:

- Castalia (where relevant and assuming that the "base case" described on its model dashboard is the same as the base case used in the presentation analysis)
- Concept
- H2 Taranaki Roadmap
- Vivid

Note that the purpose of sections 6.1 through 6.3 are to give an assessment of their modelling approach, while the actual conclusions of the modelling are then presented in section 6.5 once the rigour and robustness have been established.

The following sections point out many areas where the quantitative studies are lacking – this should be read generously under the pretence that: (1) the questions addressed are not always the same as the research question we are addressing and (2) the studies note in various places that areas where they are lacking need further research.

6.1. Coherence of modelling framework

The purpose of these questions is to identify whether the underlying method seeks to estimate costs that could transpire given its underlying assumptions.

6.1.1. Question addressed

Table 6.1 below sets out the question addressed, or the stated purpose of each study.

Table 6.1
Stated research question/purpose of studies with quantitative modelling

Study author	Stated research question/study purpose
Castalia	Modelling for MBIE roadmap for hydrogen
Concept	Examine whether hydrogen technologies are likely to be cost-effective in various use cases to decarbonise New Zealand's economy
H2 Taranaki Roadmap	Roadmap for a series of projects for the energy industry in Taranaki to help New Zealand to transition towards a hydrogen economy
Vivid	Assess potential paths forward for natural gas and its infrastructure in New Zealand in light of the country's adopted decarbonisation targets

Of the studies considered, the Concept study's aim aligns the most closely with ours. The purpose of the Concept study is to examine the role hydrogen technologies *may* have in decarbonising New Zealand's economy, approaching by comparing alternative means of decarbonisation. This includes an analysis focused on transport and more specifically, heavy freight. The Castalia model dashboard was developed in order to support MBIE's vision for hydrogen roadmap. Therefore, we can interpret the purpose of the modelling to be exploring to what extent, and under what circumstances, green hydrogen will be involved in the future New Zealand energy market. The H2 Taranaki Roadmap was developed to discuss how hydrogen *will* play a key role in decarbonisation in New Zealand. The purpose of the Vivid study is to determine the various paths for natural gas and its infrastructure in light of New Zealand's decarbonisation goals, and therefore heavy freight is considered under this lens, or put another way, decarbonising heavy freight is only considered to the extent that natural gas infrastructure might be involved.

Due to the varied purposes of these studies, it is to be expected that the presentation of assumptions and depth of analysis on the specific question of decarbonising LDHF will vary. Therefore, critiques of the studies made under our framework are not necessarily criticism of how well the studies addressed their intended purpose. Put another way, a good study addressing a different question may not meet the ideal we set out for our purpose.

6.1.2. Options considered

As described in the framework section, the choice set against which green hydrogen has been quantitatively evaluated against can impact the conclusions if potential alternatives are excluded. Table 6.2 below sets out the alternatives for decarbonising LDHF considered in each study.

Table 6.2
Alternatives to decarbonise LDHF quantitatively modelled in each study

	Castalia	Concept	H2 Taranaki Roadmap	Vivid
Green hydrogen / FCEVs	✓	✓	✓	✓
Blue hydrogen / FCEVs	✗	✗**	✗**	✗
Direct electrification / BEVs	✓	✓	✓	✗
Advanced biofuel / ICEVs	✗	✗	✗	✗
Diesel + carbon offset / ICEVs	✓	✓	✓*	✓
Modal shift to rail or coastal shipping	✗	✗	✗	✗

** These studies review blue hydrogen for other uses than LDHF.
* It is not clear that a carbon price is included in the assessment of diesel.

The Castalia, Concept, and H2 Taranaki Roadmap analyses each consider green hydrogen-powered FCEVs, BEVs, and diesel ICEVs. Concept analyses the potential cost of blue hydrogen but does not apply it to use for heavy freight and instead compares it as a replacement for natural gas uses, but do not explain why it should not be considered as a vehicle fuel. The H2 Taranaki Roadmap also discusses the use of blue hydrogen but considers it as a "transitional" fuel and assumes green hydrogen will be immediately preferable for transport use. The Vivid study, however, only considers green hydrogen-powered FCEVs and diesel, dismissing CCS for blue hydrogen and BEVs for heavy freight as unfeasible. No studies consider advanced biofuels in the modelling scenarios (or any conventional biofuel blending in the diesel assumptions), cleaner burning fossil fuels or modal shift.

6.1.3. Policy/public funding

The Concept study qualitatively discusses that both FCEV and BEV take up are likely to need significant public funding to overcome the chicken-or-egg issue of vehicle adoption and refuelling networks but does not include any public resources in its modelling. Both the Concept and Castalia analyses consider an increasing carbon price for the diesel vehicle option – which could in theory be the result of explicit government action, though this would be in a technology neutral manner. The H2 Taranaki Roadmap analysis does not explicitly state that it is considering a carbon price in its diesel modelling, so we are unable to tell whether/how this is considered. The Vivid analysis includes a carbon price in its diesel option modelling and considers, at a high level (not specific to heavy freight), that afforestation will be taken on to offset continued use of fossil fuels.

The H2 Taranaki Roadmap is the only study which includes an assumption that RUC charges will be dismissed for FCEV and BEVs early on, which it assumes will go on through 2025 (consistent with current, existing policy for BEVs).[202] The Concept study by contrast assumes no difference in the RUC treatment of FCEVs, BEVs and ICEVs in terms of exemptions. Note that if a study assumed BEVs and FCEVs do not attract RUC charges while ICEV trucks do, this is essentially a cross-subsidy from users of ICEV trucks to BEV/FCEV trucks. From the perspective of evaluating social costs, this therefore biases the assessment towards BEVs/FCEVs.

6.1.4. Consistency of comparisons

The Concept analysis applies the same wholesale electricity prices across the BEV and FCEV scenarios, includes infrastructure costs and provides scenarios in which technology advances for both vehicle types. Capital costs for vehicles are assumed from market information and are reduced in future scenarios by applying percentage reductions to specific vehicle body and engine components which set the two e-trucks apart from ICEVs; hydrogen vehicles are assumed to have greater potential for cost reductions than BEVs, which does not seem unreasonable given the current estimate for a Tesla battery electric semi is roughly NZ$230,000 and a Nikola hydrogen semi is roughly NZ$500,000 (which are the two company benchmarks used in the Concept study). Although neither are commercially available, there is more commercially advanced light vehicle technology for BEVs and therefore it is likely that vehicle battery components may already be further along to a shallower part of the cost curve. The Castalia modelling similarly assumes that hydrogen vehicles will decrease in cost more substantially than BEVs.

The H2 Taranaki Roadmap analysis does not provide most of its underlying assumptions, so it is difficult to interpret how cost stacks have been developed. However, it explicitly assumes the same mileage and payload for FCEVs and diesel vehicles, while decreasing these for BEVs, and applies RUC exemptions for both e-trucks through 2025.

The Vivid study only compares diesel to FCEVs, while BEVs are dismissed for the task.

[202] Road User Charges (Exemption Period for Heavy Electric RUC Vehicles) Order 2017.

6.1.5. Summary of coherence of modelling framework

Table 6.3
Summary of coherence of modelling framework

	Castalia	Concept	H2 Taranaki Roadmap	Vivid
Question addressed	Modelling for MBIE roadmap for hydrogen.	Examine whether hydrogen technologies are likely to be cost-effective in various use cases to decarbonise New Zealand's economy.	Roadmap for a series of projects for the energy industry in Taranaki to help New Zealand to transition towards a hydrogen economy.	Assess potential paths forward for natural gas and its infrastructure in New Zealand in light of the country's adopted decarbonisation targets.
Options considered	GH2/FCEV, Electric/BEV, Diesel/ICEV	GH2/FCEV, Electric/BEV, Diesel/ICEV	GH2/FCEV, Electric/BEV, Diesel/ICEV	GH2/FCEV, Diesel/ICEV
Policy/Public funding	Considers increasing carbon price. Unclear if RUCs/RUC exemptions are included.	Qualitative discussion of overcoming chicken/egg, but no inclusion in modelling. Considers increasing carbon price and applies RUC. No RUC exemption for e-trucks applied.	Exemption of RUC through 2025 for e-trucks. Unclear is carbon price is applied.	Carbon price applied, high level (non-specific to LDHF) assessment of afforestation requirements.
Consistency of comparisons	Assumes FCEVs will decrease in cost twice as quickly as BEVs from 2020 to 2050. Applies same underlying wholesale electricity price. Unclear how infrastructure cost is applied.	Assumes FCEVs decrease in cost more quickly than BEVs. Provides alternative scenario where BEVs do not decrease in cost assuming that hydrogen is taken up at a large scale. Capital cost changes for vehicles are based on components of the vehicle (i.e., assume that the parts which are the same as diesel vehicles do not change in price).	Unclear how cost stacks have been developed. Provides a "Fuel+RUC", "Labor", and "Truck costs" component for each option compared. Assumes RUC exemptions for both e-trucks for the same period.	Dismisses BEVs on the basis that current tech does not support it as a feasible option for heavy freight.

6.2. Completeness of cost components

Analysing whether hydrogen is least-cost requires that cost estimates are complete (in effect, the social cost components set out in section 4. As an overall note, we avoid drawing conclusions on the completeness of the Castalia modelling as the public information we have access to, its dashboard and its presentation, do not contain many underlying assumptions of the modelling. We have no reason to believe the costs included are incomplete, we simply cannot verify them.

6.2.1. Total cost of ownership

The total cost of ownership comprises the delivered cost of fuel (upstream and midstream costs) and operating and vehicle ownership costs (downstream costs). We discuss each studies' treatment of these costs in turn:

Delivered cost of fuel

For its green hydrogen fuel costing, the Concept analysis provides a breakdown of each cost to produce hydrogen including electrolyser capex and opex, network charges and losses, and storage. Additionally, it develops a "service station" delivered cost of hydrogen which accounts for compression losses and service station infrastructure overhead. It also develops "at-base" and "away-from-base" charging costs for BEVs, including infrastructure and service station overhead. Neither the H2 Taranaki nor Castalia modelling present a bottom-up costing of the delivered price of fuel, so it hard to form a view on whether the delivered fuel price is reasonable. The H2 Taranaki study notes that it includes "allowance for" increase in diesel and electricity grid costs and decrease in hydrogen price as infrastructure builds out. The Vivid study includes its costs of hydrogen production assumptions about electricity, and electrolyser capex and fuel transmission (including the cost of retrofitting pipelines) and distribution, but it does not include network charges for the cost of electricity, service station infrastructure costs, or costs involved with energy losses.

Operational running/ownership costs

Concept provides a breakdown of capital costs for each vehicle considered and estimates for assumed cost reductions over time based on the technological components of the vehicle. ICEVs are not assumed to see any price reduction, while BEVs are assumed to see reduction in battery and powertrain costs. FCEVs are assumed to see reduction in powertrain and storage tank costs. It assumes maintenance costs of repairs and servicing for BEVs and FCEVs are reduced from that of diesel maintenance costs due to less complex engines and lower running heat. To account for the reduced payload size and increased refuelling time of BEVs, penalties are developed based on each of these issues which are applied to scale up all non-fuel costs (i.e., less productivity per load would mean more drivers and more vehicles and maintenance on those vehicles). RUCs are assumed to be increased for BEVs due to their increased weight. The H2 Taranaki Roadmap provides a stacked bar chart as the output, which includes segments for "labor", "truck costs" and "fuel+RUC". Based on the available information we cannot determine how these have been accounted for. However, payload and annual kilometres driven are reduced for BEVs to account for their decreased payload capabilities and increased refuelling time. The Vivid study does not include costs for maintenance or consider RUCs.

6.2.2. Indirect societal costs

Each study approaches their analysis from the perspective of an individual operator and the costs it would face either presently or likely to face in the future given various vehicle and fuel options. Therefore, none of the studies appear to account for indirect societal costs, nor do they claim to. The Castalia model provides output of the estimated reduction in CO_2 emissions from the use of green hydrogen, but this output includes other sectors than LDHF.

An additional indirect societal cost is the emissions cost to health. Degraded air quality from emissions (like particulates and NO_x) can drive health issues in the population, leading to higher societal costs in both healthcare and decline in human capital. An example of this consideration is available in the MfE MACC analysis.[203]

6.2.3. Non-quantifiable/hard-to-quantify factors

Similar to indirect societal costs, non-quantifiable and difficult to quantify factors are not accounted for in any study's analysis. For example, environmental impacts of lithium batteries and limited resourcing of platinum for hydrogen fuel cells are not considered.

Additionally, there are societal benefits to shifting the supply of energy away from imports and towards domestic production (through applying renewable electricity either directly or through electrolysis) including security and resiliency which are not taken into consideration, which may be hard to quantify. Section 7 goes into the factors we have identified on this in more detail.

6.2.4. Policy costs

As described elsewhere, increasing carbon price is considered in the diesel component of both the Concept and Vivid analyses, but it is unclear whether the H2 Taranaki Roadmap considers this. Additionally, BEVs are currently exempt from RUCs through 2025 and it is not unreasonable to assume that FCEVs will be extended the same exemption if the exemptions are reviewed,[204] but the H2 Taranaki Roadmap is the only analysis which accounts for this.

6.2.5. Transition/path

As mentioned above, the Concept, Vivid, and H2 Taranaki Roadmap analyses look at the cost of heavy freight through the lens of a single operator at a given point in time, rather than a holistic view of the path forward for New Zealand's heavy freight industry and the costs incurred. The aim of these analyses is to determine what the likely cost of each individual option would be as time progresses.

The Castalia dashboard does provide modelling of the estimated composition of New Zealand's heavy vehicle fleet between now and 2050, given the assumptions selected on the dashboard. This does provide a broader scope of the expectations of fleet changes in the future. However, we note that without knowing the underlying assumptions, it would not be reasonable for us to draw conclusions on the relevance to our research question. For example, it may include trucks travelling shorter distances, and therefore may include more BEVs than if only LDHF were being considered.

6.2.6. Approach to dealing with uncertainty

As a generalisation, the studies provide scenario analysis but don't explicitly grapple with the uncertainty associated with the costs for different options in the future and what that means for policy decision today. The Vivid study does not model both the scenarios it sets out for the potential future of hydrogen/FCEVs, but it does qualitatively address two potential outcomes (high levels of hydrogen uptake or low levels of hydrogen uptake). The Concept report also considers, and quantifies, the potential for high global hydrogen uptake and low hydrogen uptake. The H2 Taranaki Roadmap only provides two potential charging scenarios for BEVs but is static otherwise. The provision of a model, rather than output values, by Castalia allows for a large number of uncertain outcomes to be tested.

Vivid do however qualitatively note that there is a high degree of uncertainty around each assumption that it makes and conclude further that there remains a high degree of uncertainty around the least-cost approach to reducing greenhouse gas emissions in heavy freight.[205]

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203 MfE MACC, "MACC tool spreadsheet", January 2020, accessed 12/15/20 from: https://www.mfe.govt.nz/sites/default/files/macc-tool.xlsm

204 Road User Charges (Exemption Period for Heavy Electric RUC Vehicles) Order 2017.

205 Vivid Report, p48.

6.2.7. Summary of completeness of cost components

Table 6.4
Summary of completeness of cost components

	Castalia	Concept	H2 Taranaki Roadmap	Vivid
TCO				
Delivered cost of fuel	Cost assumptions mostly are not publicly available.	Provides detailed breakdown of costs to produce hydrogen including electrolyser capex/opex, network charges, storage, network/compression losses, and service station overhead. Develops bottom-up "at-base" and "away-from-base" charging infrastructure costs for BEVs.	Cost assumptions in "fuel" component of cost per tonne-kilometre are not publicly available. States, qualitatively, that allowance for increasing diesel/electricity costs and decreasing hydrogen costs have been considered.	Includes costs of hydrogen production including electrolysers and cost of electricity. Includes cost of transmission through retrofitted gas transmission lines plus distribution. It does not include in the cost stack service station infrastructure, costs from energy losses, or network charges.
Operational running / ownership costs	Cost assumptions are not publicly available.	Provides breakdown of capital costs for each vehicle and generates estimates for cost reductions over time based on each vehicle component. Includes maintenance. BEV payload and refuelling issues are addressed with penalties which scale up non-fuel costs (vehicle + labour). RUCs are assumed to be higher for BEVs.	Cost assumptions and components in “truck costs” (e.g., maintenance) are unavailable. RUC are bundled with fuel in output, so not possible to parse from fuel costs. Payload and annual kilometres are explicitly stated and scaled down for BEVs.	Only compares FCEVs and ICEVs, and therefore no reason to consider payload or labour cost issues. Includes capital costs of FCEVs decreasing over time but does not provide ICEV capital cost assumptions. No inclusion of maintenance costs or RUCs.
Indirect societal costs	Analysis of cost per kilometre is at individual operator level, and therefore does not appear to include indirect societal costs. Other areas of model provide estimated emissions reduction from application of GH2, but this includes other uses than LDHF.	Because this analysis is at the individual operator level, indirect societal costs beyond carbon emissions are not included.	Because this analysis is at the individual operator level, indirect societal costs beyond carbon emissions are not included.	Because this analysis is at the individual operator level, indirect societal costs beyond carbon emissions are not included.

Table 6.4 (continued)
Summary of completeness of cost components

	Castalia	Concept	H2 Taranaki Roadmap	Vivid
Non-quantifiable / hard-to-quantify factors	No apparent inclusion of these factors (e.g., environmental impacts of resourcing precious materials).	No apparent inclusion of these factors (e.g., environmental impacts of resourcing precious materials).	No apparent inclusion of these factors (e.g., environmental impacts of resourcing precious materials).	No apparent inclusion of these factors (e.g., environmental impacts of resourcing precious materials).
Policy costs	Increasing carbon price considered in diesel option.	Increasing carbon price considered in diesel option and RUC considered.	RUC exemptions included through 2025 for e-trucks. Unclear if increasing carbon price is considered.	None considered.
Transition / path	Provides analysis at individual operator level in terms of cost. However, model dashboard displays calculated heavy fleet composition in NZ through 2050.	Provides analysis at individual operator level in terms of cost at a given time.	Provides analysis at individual operator level in terms of cost at a given time.	Provides analysis at individual operator level in terms of cost at a given time.
Approach to dealing with uncertainty	The provision of a model, rather than output in values, allows for large number of uncertain outcomes to be modelled.	Considers, and quantifies, the potential for high global hydrogen uptake and low hydrogen uptake.	Considers two possible charging capabilities for BEVs.	Qualitatively addresses two potential outcomes for FCEVs, high hydrogen uptake and low hydrogen uptake.

6.3. Transparency and robustness of assumptions

The credibility of the results from a study will depend on whether the supporting assumptions are clearly explained, and the sensitivity of results explored. As in the last section, we note that we do not draw conclusions on the Castalia modelling at this point, given the accompanying hydrogen roadmap is not yet released and the model underlying the publicly released dashboard is not available, meaning that the inner workings and assumptions are not public information. It provides a disclaimer stating that the base case scenario is based on "actual capital and operating cost evidence from commercial projects, current literature and other authority".[206] Not knowing the underlying assumptions applied limits the usefulness of the modelling for public policy debates. We discuss each factor from our assessment framework related to the transparency and robustness of assumptions in turn before summarising.

6.3.1. Assumptions presented and verifiable

The Concept report explicitly provides values for its assumptions and provides a number of references to where it has pulled assumptions from. There are a few exceptions to this, but generally the critical assumptions are presented with referencing to source material. Notably, its assumptions for payload capabilities are not referenced.

The H2 Taranaki Roadmap only provides the critical assumptions of mileage and payload but does not provide other underlying cost assumptions nor referencing for the assumptions it does provide. Additionally, it provides its output as a stacked bar graph including general categories of "labor", "truck costs", and "fuel+RUC" with no labelling of values. The combination of the fuel and RUC components makes it such that even a rough estimate would be difficult to back out,[207] and the conclusions for the 50kW charging scenario for BEVs are an additional stacked piece on top of the 150kW bar – meaning none of the components for the 50kW scenario are able to be parsed apart.

As noted above, Vivid appears to be missing certain costs, but the costs included are presented and referenced. It does not explicitly provide a payload assumption as it is unnecessary in the analysis (given it does not compare against BEVs) but becomes relevant for our analysis of the results. Thankfully, given Vivid's transparent referencing, we are able to find the payload assumptions from the source material it has used.

6.3.2. External benchmarking

Here we test the critical assumptions made in each analysis against external sources and critique the authority of the assumptions made when reference is provided.

Electrolyser

Concept assumes $1,400/kW currently and $700/kW in 2040, Vivid assumes $1,294/kW its high scenario, based on costs in 2030, and $665/kW in the 2050 high scenario. These assumptions align with each other in that when placed on a timeline, it shows the cost of electrolysis dropping consistently. Concept's literature review plots current costs between $1,400 and $1,600 per kW, while the future costs from its literature review span from above $1,600 to below $600 – so it has selected values at the low end of the literature review. Vivid pulls the assumptions from a 2017 paper published in the International Journal of Hydrogen Energy in which 10 experts project the costs of electrolysis and a market presentation from a hydrogen producer NEL.

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[206] MBIE & Castalia, "A roadmap for hydrogen in New Zealand: Online modelling tool dashboard", accessed 12/15/20 from: https://www.mbie.govt.nz/assets/Data-Files/Energy/hydrogen-supply-and-demand-dashboard.xlsm

[207] In other words, the data are presented such that the final value for this "fuel+RUC" component is aggregated.

Benchmarking against a 2018 study on hydrogen from the International Renewable Energy Agency (IRENA), this study estimates the 2017 cost per kW to roughly $1,300/kW and 2025 to roughly $800/kW (converted to NZD from EUR).[208] A separate study from Frontier Economics for Germany's Agora Energiewende and Agora Verkehrswende in 2018 found a range of expected electrolysis costs, ranging from roughly $1,200-$1,500 in 2020, $1,000-$1,300 in 2030, and $800-$1,000 in 2050 (converted to NZD from EUR).[209]

Overall, these assumptions are aligned with one another and relatively reasonable considering their sourcing and external benchmarking, although there appears to be a somewhat wide range for capital costs.

Electricity

Concept assumes a current cost of wholesale electricity to be $75/MWh and unchanged for the future small-scale scenario, increased to $82/MWh[210] for the large-scale scenario. The value for the current wholesale electricity price is based on average baseload contract prices for grid-connected electricity. The future value for small-scale hydrogen production is based on separate Concept modelling, which assumes future cost reductions in renewable electricity technologies factored by increased prices based on system increase and development of progressively less favourable sites. The large-scale scenario reflects the cost that building additional power stations would add to the overall price of electricity, as hydrogen requires significantly more renewable energy to produce than directly electrifying processes. Vivid assumes costs of $90/MWh as a "low estimate of current costs", from an MBIE 2016 report, $70/MWh as the low estimate of future wind generation, from the New Zealand Wind Energy Association. Castalia provides a $61/MWh current cost of electricity which appears to be based on captive wind-only generation, assuming a reduction at 0.25% per year. We note that it is generally assumed that BEVs and FCEVs face the same electricity price, we discuss this issue further in Table 7.4.

These estimates are largely consistent with other benchmarks for dedicated wind or consuming off-peak generation:

- MBIE EDGS wind reference long run marginal costs are $66-$81 in 2020, and $62-$73 in 2040[211]
- Historic average wholesale prices from 2010 through 2019 are $81[212]
- Within-day pricing over the last 10 years is shown in Figure 6.1

[208] Using 2018 average EUR to NZD, €750 * 1.707 = $1,280.25, €480 * 1.707 = $819.36. IRENA, *Hydrogen from Renewable Power*, September 2018, p20.

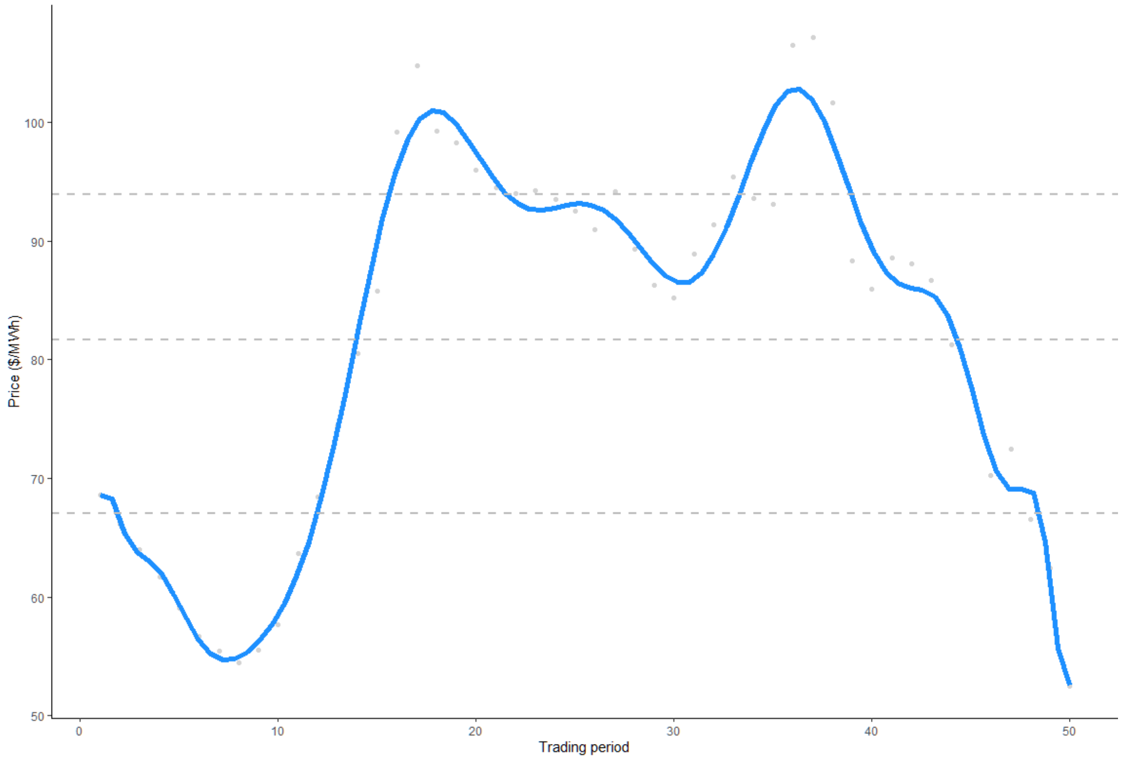
[209] Using 2018 average EUR to NZD, $1.00 = $1.707. Frontier Economics, "The Future Cost of Electricity-Base Synthetic Fuels", September 2018, p64.

[210] This is derived from Concept's statement that their large-scale scenario projects average wholesale prices "almost 10% higher" in their large-scale scenario than the small-scale scenario. $75 * 1.1 = $82.50. Concept Analysis Report, p25.

[211] MBIE, "Electricity demand and generation scenarios (EDGS)", accessed 15/12/20 from: https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-modelling/electricity-demand-and-generation-scenarios/

[212] Data accessed 15/12/20 from: www.emi.ea.govt.nz

Figure 6.1
Historic intra-day spot prices at OTA node
2010-2020



Source: NERA analysis of EA EMI dataset. Dashed lines represent the upper quartile, average and lower quartile of intra-day prices.

Infrastructure

A report from the International Energy Agency (IEA) on the future of hydrogen provides an overview of the costs of refuelling network infrastructure. Although the cost of building a refuelling network will vary considerably internationally, verifying cost estimates generally is difficult as currently there are very few hydrogen refuelling stations and generally the data are not disclosed.[213]

The Concept report is the only study which transparently shares the estimated hydrogen refuelling infrastructure costs – which it assumes are the same as Z's petrol stations on a $/GJ basis, plus the cost of energy losses. However, it is clear from international studies as well as New Zealand literature that initial investment in a hydrogen refuelling network will be substantial, requiring new and expensive parts and necessary at the same time as any FCEV take up.[214] Moreover, the IEA report discusses the issue that the cost of refuelling infrastructure depends greatly on economies of scale, which will take time to develop.[215] This suggests that the initial costs will be much higher than current service station overhead, although this could level out over the long run if FCEVs refuelling networks achieve similar scale to the current diesel refuelling network.

The Concept report is also the only study which transparently accounts for the cost of charging infrastructure, which it states is based on existing published prices for commercial fast chargers for the "at-base" estimate and use the same $/GJ service station overhead for the "away-from-base"

[213] IEA, *The Future of Hydrogen*, June 2019, p132.

[214] Hydrogen Council, *Hydrogen: Scaling up*, November 2017, p40; IEA, *The Future of Hydrogen*, June 2019, p132-133; Deloitte, *Fueling the Future of Mobility – Hydrogen and fuel cell solutions for transportation*, 2020, p38; MoT Strategic Working Paper, p24.

[215] IEA, *The Future of Hydrogen*, June 2019, p132.

charging estimates as that applied to hydrogen. However, specialised charging equipment will be needed for a battery electric truck fleet,[216] and therefore will likely incur over-and-above basic petrol station overhead costs to build out, in particular since it is based on nascent technology. There is the additional consideration for a large BEV fleet of optimising charging due to its high demands and the need to charge every night – this will likely add additional cost, plus network costs if the generation is not dedicated on site.[217] Similar to FCEVs, the initial costs are likely to be much higher than current service station overhead, but may level out in the long run if BEV charging networks achieve similar scale to the current diesel refuelling network.

Vivid does not include assumptions around infrastructure in its hydrogen fuel cost stack, while it is unclear how the H2 Taranaki Roadmap has done this.

Therefore, there are likely additional near-term costs of refuelling/charging infrastructure for both FCEVs and BEVs unaccounted for in at least Concept's and Vivid's analyses.

Vehicle capital costs

Concept's capital costs for FCEVs and BEVs are both based on the current estimated price for a Nikola hydrogen-powered semi-truck and the Tesla Semi. These costs appear to be the best public source available, given the lack of commercially available vehicles from other manufacturers.[218] Additionally, Concept assumes a 50% reduction in battery costs based on a study from IRENA and 25% reduction in powertrain costs by 2040. For FCEVs, it assumes a 75% cost reduction in hydrogen powertrains and 50% cost reduction in hydrogen storage tanks. It notes that these assumptions rely on large-scale manufacturing and a faster rate of uptake than EVs.

These assumptions are slightly optimistic in comparison to estimates by the IEA, which estimate that in the "long run", both batteries and fuel cells as a component in heavy trucks are likely to decrease in price by roughly 30%.[219] Although batteries are further along commercially and therefore less likely to see as steep a price decrease due to increased demand, they are likely to see more substantial increases in efficiency since the demand for improvements is at the forefront of the BEV space.[220]

Moreover, given the time which has passed since the writing of the report and the fact that these vehicles are not on the road yet, the cost reductions for both vehicle types may be optimistic.

Vivid's capital costs for FCEVs appear, in relative terms, much more aggressive – it is under NZ$200,000 in 2030 and roughly $165,000 in 2050, based on a UK paper from 2012 which was pulling from bottom up prices developed in 2010. Nikola had released its initial price estimates by the time the paper was released (at US$375,000), so it is unclear why it has applied this value.[221]

Concept's forward-looking capital costs for both FCEVs and BEVs may be somewhat optimistic, but its present costs are accurate based on publicly available information. Vivid's assumptions are less than half the currently available market price stated for a heavy-duty FCEV and therefore likely skewing the results downward.

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[216] MoT Background Paper, p20.

[217] MoT Background Paper, p20.

[218] Though we note that benchmarks such as these should be treated with caution when the vehicles are not commercially available yet.

[219] IEA, *The Future of Hydrogen*, June 2019, p137.

[220] Forbes, "Tesla 'Battery Day' Promises 56% Reduction In Battery Cost And Much More", 22 September 2020, accessed 15/12/20 from: https://www.forbes.com/sites/bradtempleton/2020/09/22/tesla-battery-day-promises-56-reduction-in-battery-cost-and-much-more/?sh=ac642926253f

[221] Green Car Reports, "Nikola One hydrogen range-extended electric tuck to be unveiled tonight", 1 December 2016, accessed 15/12/20 from: https://www.greencarreports.com/news/1107560_nikola-one-hydrogen-range-extended-electric-truck-to-be-unveiled-tonight

Vehicle capabilities and technology advancement assumptions

Vivid does not require a payload assumption in the modelling, as it does not model BEVs, but for reference, the diesel truck they reference for estimated mileage is assumed to have payload capabilities of 26t.

The Concept report, looking at the heaviest vehicles, estimates a 30t payload capability in its modelling of FCEVs and diesel trucks. It assumes that the battery electric powertrain weighs twice as much as a diesel powertrain with a full tank of gas, at 5t rather than 2.5t.[222] Therefore, the assumption for a BEV's payload capability is 27.5t. This results in a 9% payload penalty. The H2 Taranaki Roadmap assumes a 13t payload for BEVs and 20t payload for diesel and FCEVs, a payload penalty of 35%.

Neither of these analyses present references for their reductions in payload for BEVs. A study from 2017 in *Energies* journal found that batteries would only reduce the payload from a usual long-haul diesel vehicle (on German roads) by 20%.[223] As noted in section 3.2, it is difficult to find reliable public information on how significant the payload reduction will be for heavy BEVs.

Additionally, the H2 Taranaki payloads are both lower than the maximum vehicle weight restrictions in New Zealand, with the largest trucks carrying payloads of roughly 24t on average[224] and therefore there is not a clear reason to reduce the payload capabilities of the BEV at this weight. This lower weight choice is somewhat inconsistent with other discussion in the report, given it notes that heavy trucks such as those hauling liquid bulk and forestry products (requiring the heaviest trucks) would be the best application.

Regarding technology assumptions, Concept assumes a one third weight reduction in battery size in its small-scale scenario which allows for BEV technology to improve, therefore reducing the payload penalty further to only 6%. The H2 Taranaki Roadmap assumes the same weight through 2030. As mentioned above, this is unlikely to be realistic due to the high global interest in improving vehicle battery technology.

The H2 Taranaki Report provides two charging capability scenarios, affecting the overall mileage capability of a BEV in a year. It assumes a standard 50kW charging scenario as is available currently[225] and a fast-charging scenario where 150kW chargers are used, both of which apply to the entire time period. Concept's approach is different than the H2 Taranaki Roadmap, instead applying a 120kW used in the present and advancing to 1MW in the future. Concept indicates that the assumptions here are conservative given the rapidly increasing capability of chargers. At the time of writing, it noted that 350kW chargers had already developed overseas, and we note that very recently 300kW chargers have now been installed in Auckland.[226]

Therefore, the Concept estimates potentially skew results to an optimistically lower price for BEVs regarding vehicle capability assumptions, with a potentially overgenerous payload

[222] It does not explicitly state that the batteries themselves are included in the powertrain, but it is inferred given the increased weight and the inclusion of the diesel tank for the ICEV. In theory, this could account for the electric motor being lighter than the diesel engine.

[223] Mareev, I., Becker, J., & Sauer, D. U, 2018, "Battery dimensioning and life cycle costs analysis for a heavy-duty truck considering the requirements of long-haul transportation". *Energies*, 11(1), 55.

[224] Stimpson and Co., "Monitoring, Evaluation and Review of the Vehicle Dimensions and Mass Rule implementation", 6 May 2014, accessed 15/12/20 from: https://www.nzta.govt.nz/assets/Commercial-Driving/docs/Monitoring-evaluation-and-review-of-the-Vehicle-Dimensions-and-Mass-Rule-30-April-2013.pdf

[225] NZTA, "Electric vehicle charging stations list view", accessed 15/12/20 from: https://www.journeys.nzta.govt.nz/ev-chargers-list-view/

[226] However, these are currently quite expensive. ChargeNet NZ, "ChargeNet NZ installs New Zealand's fastest Electric Vehicle Chargers", 27 August 2020, accessed 15/12/20 from: https://charge.net.nz/chargenet-nz-installs-new-zealands-fastest-electric-vehicle-chargers/

reduction, while the H2 Taranaki Roadmap estimates what is likely an overly restrictive payload penalty to the BEV estimate. However, Concept's assumptions on charging capabilities of BEVs are potentially more realistic given current technology advancements, while the H2 Taranaki Roadmap's charging assumptions already may be out of date. These results illustrate the difficulty in predicting the future evolution of technologies that currently have nascent adoption.

6.3.3. Sensitivity testing

The Concept analysis provides "sense checks" throughout the report, testing the conclusions against external sources. Moreover, they provide four different scenarios testing the effects of the level of hydrogen uptake, the advancements of new vehicle technologies, and the kilometres being driven each year by these vehicles.

Concept provides an alternative scenario in which hydrogen is taken up at a large scale, and in this scenario, it assumes that battery technology does not progress. Although it is interesting to test this case, it creates results which are not likely to play out in reality; battery technology will almost surely progress, due to the fact that although they may currently be less efficient for heavy-duty trucks, they are clearly the ideal choice in the light fleet according to each of the studies reviewed here. Therefore, it is highly likely that batteries will continue to see substantial increases in efficiency and density regardless of their applicability in LDHF. In addition, as described in section 3.2, there is commercial interest in solving this issue for freight and effort is being applied to do so, above interest for light vehicles.

The H2 Taranaki Roadmap provides only one feature to sensitivity test its conclusions, by providing scenarios with a standard 50kW charger for BEVs and an advanced 150kW charger. The Vivid analysis provides a high and low estimate for 2050 in which it assumes technology costs either plateau in 2030 or continue to decrease through 2050, but the fact that this analysis only looks at a single point quite far in the future diminishes the usefulness of these conclusions when so much uncertainty remains in the interim.

6.3.4. Scale and use case dependence

As noted in regard to sensitivity testing, the Concept report allows for scenarios in which hydrogen is taken up at a small scale and a large scale. The small-scale scenario assumes that hydrogen is likely only used for a single use case, and therefore electrolysers can run during off-peak periods and battery technology likely outpaces hydrogen technology. In the large-scale scenario, it is assumed that additional renewable generation is needed to be built and electrolysers must be run more frequently, such that the cost of electricity increases. Additionally, it is assumed that globally hydrogen is the technology "winner" and therefore battery technology does not advance further. The other studies do not appear to account for scale or use case dependence in quantitative analysis.

It should be noted that this could be a significant factor in TCO with either e-truck's mass adoption, as mentioned in other sections of the report. High levels of adoption could mean that electrolysers must run at times when they cannot take advantage of off-peak pricing, or BEVs may have to charge at off-peak hours due to charging optimisation strategies.[227] Moreover, grid and generation expansion could increase electricity prices under either technology. Relatedly, if hydrogen is used for purposes besides LDHF, and there are material economics of scale in hydrogen production,[228] then assuming multiple use cases could reduce the delivered cost of hydrogen.

[227] The most efficient use of specialised charging infrastructure may call for staggering truck charging, requiring some trucks to charge off peak.

[228] Office of Energy Efficiency & Renewable Energy, "Central Versus Distributed Hydrogen Production", accessed 15/12/20 from: https://www.energy.gov/eere/fuelcells/central-versus-distributed-hydrogen-production

6.3.5. Summary of transparency and robustness of assumptions

Table 6.5
Transparency and robustness of assumptions

	Castalia	Concept	H2 Taranaki Roadmap	Vivid
Assumptions presented and verifiable	N/A	Explicitly provides values for assumptions and provide a number of references. Some exceptions, but generally critical assumptions are verifiable.	Provides critical assumptions of payload and annual mileage, no referencing of sources. Other assumptions are impossible to back out from conclusions.	Missing certain costs, but costs included are presented and referenced.
External benchmarking				
Electrolyser	N/A	In line with external benchmarks.	N/A	In line with external benchmarks.
Electricity	Somewhat low, appears consistent with off-peak pricing.	In line with external benchmarks.		In line with external benchmarks.
Infrastructure	N/A	Likely missing relevant higher costs of developing infrastructure in the near-term.	N/A	N/A
Vehicle capital cost and technology advancement	N/A	Present assumptions are accurate given publicly available information, but forward-looking assumptions may be optimistic.	N/A	Assumptions for FCEV capital cost are outdated/low, although more recent market info was available at the time of the study.
Vehicle capabilities	N/A	Potentially over-optimistic assumptions about BEV payload capabilities.	Likely over-pessimistic about BEV payload capabilities.	N/A
Sensitivity testing	Provides a high scenario and low scenario aside from the base case assumption, increasing/decreasing diesel price inflation and FCEV capital cost.	Provides "sense checks" throughout, testing conclusions against external sources. Provides four separate scenarios flexing H2 uptake, technology progress, and vehicle mileage.	Provides estimates for BEVs using a 50kW charger and 150kW charger.	Provides "high" and "low" estimates assuming technology/costs plateau around 2030 or continue to decrease through 2050.
Scale and use case dependence	N/A	Sensitivity testing includes scenarios flexing hydrogen uptake and likely tech progression under the assumption hydrogen is/is not globally adopted.	None addressed.	None modelled. Scenario addressed but no analysis performed.

6.4. Summary of methodological review of modelling

Table 6.6
Summary of assessment framework application to quantitative studies

Study author	Coherence of modelling framework	Completeness of cost components	Transparency and robustness of assumptions
Castalia	▪ **Purpose:** Provides modelling for MBIE's hydrogen roadmap. ▪ **Modelling methodology:** Much of the underlying modelling is not public so unable to draw conclusions on methodology. ▪ **Options considered:** Diesel/ICEV, hydrogen/FCEV, and electricity/BEV.	▪ **Component completeness:** Appear to include appropriate cost categories where available. A number of cost categories are not presented but may be included. ▪ **Cost component detail:** Other areas of modelling include societal-cost focused components but appear to include non-LDHF areas of the economy.	▪ **Transparency:** Most assumptions to underlying modelling are unavailable. ▪ **Robustness:** Model itself allows user to test many potential scenarios. High, low, and base case results provided in presentation.
Concept	▪ **Purpose:** Examines whether hydrogen technologies are likely to be cost effective in various use cases to decarbonise New Zealand's economy. ▪ **Modelling methodology:** Estimates total cost of ownership in 2020 and 2040. Modelling documented and internally consistent. ▪ **Options considered:** Diesel/ICEV, hydrogen/FCEV, and electricity/BEV.	▪ **Component completeness:** Provides detailed breakdown of cost assumptions which generally are thoroughly reported. ▪ **Cost component detail:** Indirect societal costs or hard-to-quantify factors are not included.	▪ **Transparency:** Nearly all quantifiable underlying costs considered, discussed and generally referenced. ▪ **Robustness:** Assumptions generally stand up to external benchmarking and provides various sensitivity scenarios. However, payload assumptions are potentially over-optimistic towards BEV capability.
H2 Taranaki roadmap	▪ **Purpose:** Roadmap for a series of projects for the energy industry in Taranaki to help New Zealand transition towards a hydrogen economy. ▪ **Modelling methodology:** TCO for 2018, 2020, 2025, and 2030. Quantitative analysis is a minor component of the overall paper and details on the underlying modelling are partially unavailable. ▪ **Options considered:** Diesel/ICEV, hydrogen/FCEV, and electricity/BEV.	▪ **Component completeness:** General cost categories are included in the analysis but some are aggregated to a high level. ▪ **Cost component detail:** Indirect societal costs or hard-to-quantify factors are not included.	▪ **Transparency:** Most assumptions to underlying modelling are unavailable except for critical assumptions on payload and annual kms travelled. ▪ **Robustness:** The payload restrictions for BEVs are likely overly restrictive, skewing BEV TCO estimates upward. Two BEV charging capability scenarios are tested.
Vivid	▪ **Purpose:** Assess potential paths forward for natural gas and its infrastructure. ▪ **Modelling methodology:** TCO in 2050. Analysis minor component of overall report. ▪ **Options considered:** Diesel/ICEV and hydrogen/FCEV.	▪ **Component completeness:** Some major cost components are missing from the analysis. ▪ **Cost component detail:** Indirect societal costs or hard-to-quantify factors are not included.	▪ **Transparency:** Very transparent assumptions for hydrogen/FCEV, assumptions unavailable for diesel. ▪ **Robustness:** Assumptions included in model generally stand up to external benchmarking but for capital cost of FCEV, which are quite low.

6.5. Modelling conclusion analysis

6.5.1. Summary of quantitative analyses

Here we set out the final conclusions drawn from the quantitative modelling, comparing the conclusions against one another given the assessment of the methodologies used.

As discussed in the summaries of each study, at a high level the results of the modelling in each of the quantitative studies conclude:

Table 6.7
Summary of quantitative findings in New Zealand studies of using green hydrogen for LDHF

Study author	Commissioned by	Quantitative conclusions
Castalia	MBIE	The base case finds that FCEVs are more expensive per kilometre than BEVs until after 2040 but converge with BEVs before 2050. ICEV cost per kilometre passes above a BEV before 2030 and above a FCEV before 2035. However, vehicle weights and payloads are not provided and could have significant influence on results (e.g., lighter trucks).
Concept	MBIE, EECA, Contact, Meridian, Powerco, First Gas	Across all scenarios, BEVs are likely to be the least-cost option per kilometre and per tonne-kilometre for heavy vehicles, although both e-trucks are likely to become less expensive than ICEV use by 2040. FCEVs only begin to be competitively priced in the long term with BEVs in the scenario where battery technology is not assumed to improve.
H2 Taranaki Roadmap	Venture Taranaki, Hiringa Energy, New Plymouth District Council	The single scenario modelled finds that per tonne-kilometre, FCEVs are immediately less expensive than BEVs, even using a fast charger, and become competitively priced with ICEVs using diesel by 2030.
Vivid	First Gas and Powerco	Vivid only models diesel ICEVs against a high and low FCEV scenario in 2050, which is quite distant. Vivid's conclusion is by 2050, FCEVs are likely to be roughly the same price per kilometre as diesel ICEVs *before* applying a carbon price for the heaviest class of freight vehicles.

6.5.2. Analysis of quantitative conclusions across studies and scenarios

The full set of conclusions across all scenarios in each study are displayed in in Figure 6.2 and Figure 6.3 below. A full set of assumptions across each scenario in each study can be found in Appendix A.

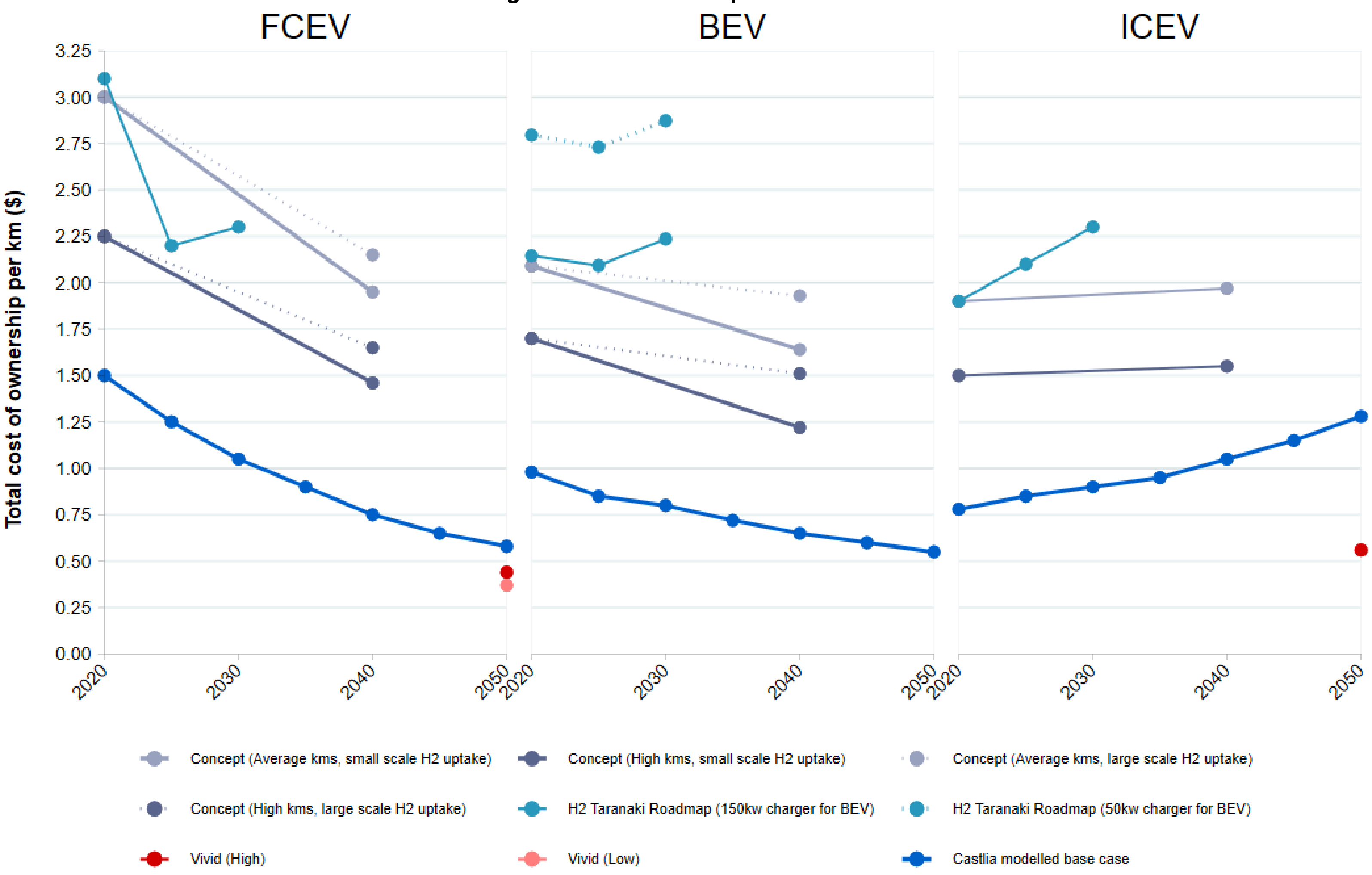
We review the TCO conclusions in two forms:

- TCO in dollars per kilometre ($/km); and
- TCO in dollars per tonne-kilometre ($/tkm).

The studies provide their conclusions in both of these metrics – the H2 Taranaki Roadmap provides its conclusions in $/tkm, while all other studies provide conclusions in $/km. We agree with the H2 Taranaki Roadmap methodology in that it is a more useful metric to know the cost per tonne of freight rather than the cost per payload, given the differences in capabilities of the different technologies. Moreover, this metric allows for future work to more easily compare these results against analyses of freight movement in modes other than ground transport.

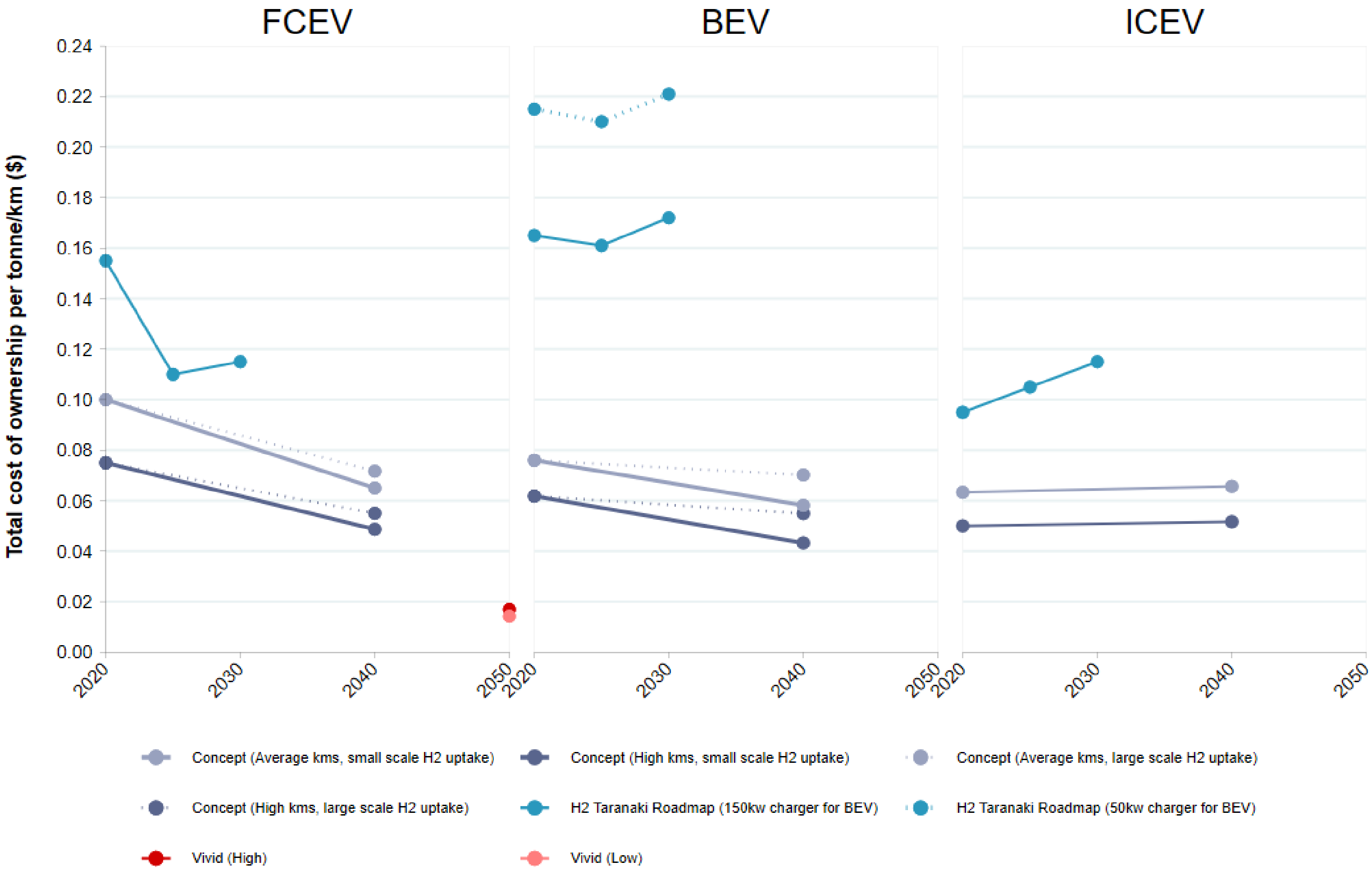
We have provided both metrics where available, meaning that in the instances the assumed payload is not available (for Castalia and the diesel/ICEV for Vivid) we have not provided values in $/tkm. Additionally, the payload assumption for the FCEV scenario is not explicitly stated in Vivid's analysis but is available in the referencing material – this has been sourced and applied to develop the $/tkm amount.

Figure 6.2
Comparison of quantitative study conclusions across considered fuels
Freight cost in dollars per *kilometre*[229]



[229] ICEV denotes diesel fuel with carbon offset. The H2 Taranaki Roadmap results are multiplied by payload assumptions to determine $/km for the given truck.

Figure 6.3
Comparison of available quantitative study conclusions across considered fuels
Freight cost in dollars per *tonne/kilometre* using payload assumptions[230]



[230] ICEV denotes diesel fuel with carbon offset. The Concept results are divided by payload assumptions to determine $/tkm. Castalia's payload assumptions and Vivid's diesel payload assumption are not available and therefore excluded here.

6.5.3. Discussion of compared outcomes

Only focusing on the Concept and Castalia results, when reviewing the $/km it looks clear that BEVs are the least-cost option in the long term across all Concept scenarios and the Castalia base case. However, when applying the payload to find $/tkm, the Concept results find that the cost of freight per tonne-kilometre is generally competitive in price across all vehicle types analysed.[231]

Note that the Concept large-scale scenarios show that BEV costs do not change much over time – as noted earlier, this is due to the assumption that given large-scale hydrogen take up, battery technology does not improve. It also causes the wholesale electricity price to increase for all users due to increased generation requirements, therefore effecting BEV charging prices as well. The only significant difference for FCEVs in this scenario from the small-scale scenarios is the price of delivered fuel increases based on the electricity cost.

Looking at the H2 Taranaki Roadmap results, on a $/km basis BEVs are less per trip if we assume 150kW chargers are used, but this would be overlooking the fact that there is only a 13t payload applied for BEVs (which is why it is appropriate to provide results in tonne-kilometre instead). It therefore makes more sense to focus on $/tkm, where we see that they conclude FCEVs should become competitive with diesel by 2030 but BEVs remain more expensive than both FCEVs and diesel ICEVs through the modelled range.

However, as noted in our modelling assessment, the payload difference between BEVs and FCEV/ICEVs is likely greater than the real world and therefore may be producing overly pessimistic results about BEV prices. This is also true for Concept's payload assumptions for BEVs, which could be producing overly optimistic results about BEV TCOs.

Another notable difference between scenarios is the comparatively large gap in the estimates for the BEV scenarios from the H2 Taranaki Roadmap, which highlights the impact that charging capability and payload assumptions have on BEVs' ability to compete. Given our assessment that the charging capability assumptions are lower than what we are likely to see in practice and the payload penalty appears aggressive (considering available information), the BEV estimates in the H2 Taranaki Roadmap analysis may not show the same conclusion against FCEVs if the charging capabilities were updated or a lower payload penalty was applied.

Given our analysis of the underlying methodology and assumptions (low capital cost of FCEVs and missing components from cost stack), it is unsurprising that the Vivid conclusions are so low.

Castalia's assumption for wholesale electricity costs are $14/MWh lower than Concept's in 2020 at $61/MWh, which appears to be based on captive wind-only generation[232] (i.e., not pulling from the grid) while Concept's is based on grid-connected prices.[233] Castalia assumes that electricity costs decrease by 0.25% each year while Concept's remain static (and even increase in the large-scale scenario) – this explains at least in part why Castalia's results for FCEVs and BEVs are so much lower than Concept's. Castalia also assumes a rising diesel cost each year, while Concept does not change the diesel cost over time.

Lastly, for additional context, the analysis of BEVs against diesel in ICEVs in the MfE MACC report finds that by 2030, there is a net public benefit by switching all new heavy vehicles on the road to BEVs. Put another way, it will be cost effective for new heavy trucks entering the fleet to be BEVs rather than ICEVs by 2030.[234]

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[231] As mentioned above, Castalia's payload assumptions and Vivid's diesel payload assumptions are unavailable and therefore we cannot deduce the $/tkm.

[232] Castalia Presentation, p. 21-22.

[233] Concept Analysis Report, p. 8-9.

[234] MfE MACC Report, p47-48.

6.6. Findings based on quantitative studies

All existing quantitative modelling we have reviewed focus on estimating only the private costs of using different fuels for a given truck. Private costs represent only one component of a potentially broader question that looks at the socially optimal[235] method of reaching net zero carbon emissions for LDHF, noting that if there were no market failures or externalities, these would be the same thing. The studies do not, and were not scoped to, look holistically at the heavy freight fleet in New Zealand and its fuel use and mode of transport, including:

- The ability of owner-operators *en masse* to purchase new-technology vehicles;
- What happens in the interim "waiting period" before the commercial availability of technology becomes widespread and its total cost of ownership becomes competitive with conventional options;
- Modal shift – the shifting of some freight to rail and coastal shipping would reduce total emissions, with other benefits including less traffic congestion and less wear and tear on the roads; and
- A full life cycle analysis of alternative options with a New Zealand lens, taking into account impacts on the environment, emissions concerning the construction and disposal of trucks, human health and supply-chain economic impacts (e.g., transitional costs due to job dissolution and creation).

The quantitative studies to date define an "end point" under their various assumptions, being a comparison of the total cost of ownership (TCO) for different vehicles and fuels at some point in the future. They do not reach conclusions on the cost of a transitional path with the points above in mind. These studies also almost exclusively analyse green hydrogen FCEVs and BEVs against diesel ICEVs.

Each of these studies reaches different conclusions due to the fact that each analysis applies differing inputs and assumptions in terms of both the costs included and the level/path for each cost. Through our review, we have found that the factors set out in Table 6.8 appear to have a large influence on the study conclusions about the competitiveness of FCEVs and BEVs.

As already noted, the quantifications in these studies focus on the end point and do not consider whether alternatives such as biofuels, blue hydrogen, cleaner-burning fossil fuels (e.g., methanol) or modal shift might form part of either the immediate path or longer term end point of decarbonisation in this sector. Therefore, we find that existing studies and the relevant analyses within have not provided a thorough answer to the most economic method (or methods) of decarbonising LDHF in New Zealand.

[235] Note that by socially optimal, we mean this in an economic sense, i.e., considering economy wide costs and benefits.

Table 6.8
Influential factors driving conclusions in quantitative studies comparing FCEVs and BEVs

Factor	Discussion
Speed of underlying technology cost reductions will likely determine which e-truck has a lower TCO.	Even allowing for the reduced capability of BEVs to carry large payloads presently, the capital cost of FCEVs and electrolysis would need to reduce more quickly than costs for battery technology. The Concept, Castalia and H2 Taranaki Roadmap analyses each show that the longer term TCO of FCEVs using green hydrogen depend on costs dropping more quickly for this alternative than for BEVs.
Battery recharging and weight issues persisting into the future will disadvantage BEVs for LDHF in the longer term.	If the disadvantages faced by BEVs in terms of reduced payload and the need to stop and recharge during a long-distance freight trip persist into the future, BEVs will be unlikely to compete with FCEVs in LDHF. Both Concept and the H2 Taranaki Roadmap modelling demonstrate that BEVs' TCO is highly impacted by these issues.
A substantially higher carbon price is needed to disincentivise continued diesel use.	As an indicative price reference, Concept applies a \$100/t CO_2e in 2040, finding that e-trucks would be cheaper than diesel in ICEVs by that point in time. Castalia does not disclose its carbon price assumption, but its analysis implies the price would need to rise to at least \$75/t CO_2e by 2035 for FCEVs to outcompete diesel. If restrictions on diesel imports are imposed, this would also likely increase the TCO of diesel.
Off-peak production (or dedicated renewable generation) is needed for green hydrogen to take advantage of lower electricity prices.	The Concept and Castalia modelling demonstrate that the assumed cost of electricity has a significant impact on the cost of producing green hydrogen. Because hydrogen is essentially a method of storing energy, it breaks the link between the time electricity is generated and when the vehicle needs to be refuelled (unlike present BEV charging). This means production of hydrogen can occur largely outside of peak hours (if grid connected) or by direct connection to embedded renewable generation. Green hydrogen can thus take advantage of non-peak electricity prices or the low cost of intermittent renewable generating capacity while still providing refuelling outside of the hours it is producing. If electrolysers were impeded from taking advantage of this lower cost of electricity, it would increase the barriers for hydrogen FCEVs to become economic by orders of magnitude due to green hydrogen fuel's greater (relative to BEV) demand for renewable energy. The Concept analysis and Castalia modelling assume the same underlying electricity pricing for BEVs and FCEVs; however BEVs may not be able to achieve the same price in practice (see Table 7.4).
Road User Charge (RUC) exemptions on e-trucks don't appear to be needed in the longer term for FCEVs or BEVs to become competitive with ICEVs.	RUC exemptions, which currently only exist for BEVs, don't appear to be needed in the longer term for e-trucks to be competitive with ICEVs if the other factors in this table hold. For example, the Concept modelling includes no RUC exemptions and finds that BEVs and FCEVs will become competitive with diesel ICEVs. The H2 Taranaki Roadmap modelling has RUC exemption initially and then removes it. This analysis demonstrates that RUC exemptions appear to have a significant effect on the cost per tonne-kilometre.

7. Qualitative assessment of non-quantified issues and opportunities

Some key things are missing from all modelling exercises described in the prior section, which are generally discussed in the qualitative studies summarised in section 5.2:

- Some more difficult to quantify aspects of the costs and benefits of the fuel sources and vehicles modelled are not included in the modelling;[236]
- Biofuels, blue hydrogen, cleaner burning fossil fuels and alternative modal options for freight are not modelled; and
- The analyses only take into account the total cost of ownership for an *individual*, rather than the total *societal* cost if these technologies are to be taken up at mass-scale.

This section summarises the issues and opportunities surrounding these which are discussed in the qualitative studies, as well as additional outside material we have reviewed and been provided by stakeholders to inform our own views on these options.[237]

Having summarised the issues and opportunities in each table, we note:

- Which points are economic issues (the subject of this stage of our review); and
- Which points relate to barriers to uptake (and therefore are the subject of our stage 3 review).

We additionally identify the potential materiality of each point – in other words, we determine whether the point is something that could significantly affect the economics of the option or is not likely to carry enough weight to materially change the economics of the option. We identify these points as:

- High = high impact and no mitigants
- Medium = low impact no mitigants or high impact with mitigants
- Low = low impact and mitigants likely

We then conclude each section by qualitatively summarising the likelihood of the economic issues which could alter the conclusions of the quantitative analyses.

7.1. Green hydrogen using FCEVs

The quantitative analysis in section 6 suggests that FCEVs are likely to be much higher in cost than BEVs in the shorter term. Whether and at what point FCEVs are competitive with BEVs in price in the longer term depends on the pace of battery technology. The following issues set out in Table 7.1 will also have an impact on the economics of FCEVs and green hydrogen.

[236] Some aspects are discussed qualitatively in the studies which have quantitative modelling, and some of these points have been referenced in this section.

[237] Note that the H2 Taranaki Roadmap also contains a substantial qualitative review and some of these issues are discussed as well.

Table 7.1
Qualitative assessment of non-quantified issues with using green hydrogen and FCEVs

Issue	Barrier or economics	Potential Materiality	Discussion	Potential mitigants
Platinum is required for fuel cells but is a scarce material.[238]	Barrier and economics	Medium - High	Alternatives to platinum are in development using more abundant metals.[239] Scarcity of platinum will impact both economics and feasibility. Currently, FCEVs are a relatively niche vehicle and it is not clear whether there is sufficient platinum, given current technology, to support a wide commercial market for FCEVs.	Research into replacements for and reductions of platinum in fuel cells[240] and more efficient recycling methods[241] is progressing. Scarcity, if material, will increase price which will ration FCEVs to the sectors where the use case is most compelling.
Cost of fuel very dependent on centralised or decentralised method of production/delivery[242]	Economics	Low	A centralised model would likely require transportation via the gas transmission network, which may require modification[243] Tube trailers can also be used to distribute hydrogen from a centralised facility to refuelling stations. Price competitiveness between the two options is dependent on quantity and distance.[244]	A decentralised model, while not having the same economies of scale as a centralised model, would have offsetting cost savings of lower transport costs and lower electricity costs due to being able to produce opportunistically.[245] Trade-offs in terms of cost exist in both scenarios, but even if transmission lines were used, this does not cover the South Island.[246]

[238] FuelCellsWorks, “Platinum in Fuel Cells: Too Precious for Clumping”, 8 August 2019, accessed 15/12/20 from: https://fuelcellsworks.com/news/platinum-in-fuel-cells-too-precious-for-clumping/

[239] Argonne National Laboratory, “Platinum-free catalysts could make cheaper hydrogen fuel cells”, 20 May 2020, accessed 15/12/2020 from: https://www.anl.gov/article/platinumfree-catalysts-could-make-cheaper-hydrogen-fuel-cells

[240] Princeton University, “For hydrogen fuel cells, mundane materials might be almost as good as pricey platinum”, 17 June 2019, accessed 16/12/20 from: https://www.princeton.edu/news/2019/06/17/hydrogen-fuel-cells-mundane-materials-might-be-almost-good-pricey-platinum

[241] Green Car Congress, “Fraunhofer IWKS starts project BReCycle on efficient recycling of fuel cells”, 9 April 2020, accessed 16/12/20 from: https://www.greencarcongress.com/2020/04/20200409-brecycle.html

[242] MBIE Green Paper, p25; MoT Background Paper, p42

[243] If converted to hydrogen use, exclusively, but would not need significant modification if hydrogen were blended with natural gas in the existing lines. See section 3.1 for discussion.

[244] Xianming Jimmy Li, Jeffrey D Allen, Jerad A Stager, Anthony Y Ku (2020), “Paths to low-cost hydrogen energy at a scale for transportation applications in the USA and China via liquid-hydrogen distribution networks”, *Clean Energy*, 4(1), 26-47.

[245] Office of Energy Efficiency & Renewable Energy, “Central Versus Distributed Hydrogen Production”, accessed 15/12/20 from: https://www.energy.gov/eere/fuelcells/central-versus-distributed-hydrogen-production

[246] Concept Analysis Report, p52.

Issue	Barrier or economics	Potential Materiality	Discussion	Potential mitigants
Large-scale storage technology	Economics	Low - Medium	According to MBIE technology for low cost, low-loss, high-volume storage does not exist presently[247] Research and development on this is in progress.[248]	Whether this is a problem depends on the production model (centralised vs distributed) and how widespread hydrogen adoption is: If hydrogen is a niche use case for LDHF and produced via a distributed model, mass storage is less likely to be a concern.
Highly dependent on cost of electricity and economics may rely on off-peak pricing for electricity and grid access.[249]	Barrier and economics	Medium - High	Peak/off-peak differential could diminish in the future as more storage comes online.[250] Off-peak pricing relies on onsite storage and also decreases electrolyser utilisation. Large scale production may increase demand and narrow the gap between peak and off-peak. Change to transmission pricing methodology (TPM) may remove transmission charge benefit of off-peak consumption. Distributed model may also involve gas to power (G2P) opportunistic electricity generation.[251] This increases profitability of H2 retailing, but also potentially re-links H2 value to wholesale electricity price.	Trucking and use of gas network can supplement onsite storage. If distributed generation occurs at fuelling sites, prices for retail customers could be de-linked from wholesale electricity price via contracts. BEV economics also depend on wholesale electricity price.
Chicken/egg problem of trucks/refuelling/production.[252]	Barrier	Medium	Producers will not invest if there is no demand for hydrogen and freight operators will not invest in trucks if there is no reliable supply and refuelling network.	The Hiringa business model explicitly addresses this issue by vertically integrating into production fuelling and truck ownership. Government action can also help resolve coordination problems. However, when there is material uncertainty this creates a risk of investing in a technology which is subsequently out-progressed.

[247] MBIE Green Paper, p40

[248] FuelCellWorks, "New and Large Scale Hydrogen Hub to Support Denmark's Green Transition", 1 December 2020, accessed 16/12/2020 from: https://fuelcellsworks.com/news/new-and-large-scale-hydrogen-hub-to-support-denmarks-green-transition/

[249] MoT Strategic Working Paper, p21

[250] In the extreme, projects such as the proposed pumped hydro scheme at Lake Onslow could largely eliminate any peak/off-peak price differential, though this is currently a subject of debate.

[251] In other words, an onsite fuel cell could convert hydrogen to electricity and inject power back into the grid at peak times.

[252] MBIE Green Paper, p51; NZPC Low-emissions economy report, p367

Issue	Barrier or economics	Potential Materiality	Discussion	Potential mitigants
FCEV trucks do not currently exist for purchase.	Barrier	Medium - High	Hydrogen FCEVs are not yet commercially available in New Zealand and the timeline within which they will be is unclear.	Current unavailability does not mean trucks will not be available in the future if the economics stack up. Toyota has had trucks in pilot programs for the last 3 years, and multiple manufacturers are developing and releasing hydrogen trucks.[253] Ultimately, New Zealand's scale means we are likely to be a technology taker and availability of trucks will be reliant on adoption of FCEV trucks in other markets.
NZ-specific requirements create hurdle for truck availability[254]	Barrier and economics	Medium - High	In addition to being one of the few RHD markets in the world, New Zealand also has specific requirements for heavy freight in relation to axle weight.[255] This may impact truck availability or increase costs.	New Zealand's specific requirements may limit the number of suppliers willing to supply New Zealand, but ultimately, this is likely to mainly be an issue around price. Hiringa has entered into a partnership with Hyzon and TR group to aggregate demand for an initial order of 20 trucks, with more planned to be introduced incrementally.[256] This issue also exists for BEVs.
Cost issue of owner-operators not being able to adopt tech	Barrier	Low	If FCEVs are significantly more expensive to purchase than diesel ICEVs and BEVs (and stay that way), owner-operators may be unable to finance them even if FCEVs are the more economic option in the long term.	A number of ownership models exist in the freight sector, including company-owned trucks. If the market transitions to FCEVs because it is privately profitable to do so and upfront purchase costs are a barrier to owner-operators, then the market will likely transition to more corporate ownership or alternative financing arrangements, such as Hiringa's and Nikola's lease model.[257]

[253] Aside from Nikola and Toyota, Hyundai and Daimler each have FCEV trucks in stages of release and piloting.

Forbes, "Toyota, Hino Plan U.S. Hydrogen Big Rig As Upstart Nikola Tries To Stay On Course", 5 October 2020, accessed 16/12/20 from: https://www.forbes.com/sites/alanohnsman/2020/10/05/toyota-hino-plan-us-hydrogen-big-rig-as-upstart-nikola-tries-to-stay-on-course

Hyundai Hydrogen Mobility, "Hyundai Motor's Delivery of XCIENT Fuel Cell Trucks in Europe Heralds Its Commercial Truck Expansion to Global Markets", 7 October 2020, accessed 16/12/20 from: https://hyundai-hm.com/en/2020/10/07/hyundai-motors-delivery-of-xcient-fuel-cell-trucks-in-europe-heralds-its-commercial-truck-expansion-to-global-markets/

Forbes, "Daimler Shows Off Long-Range Hydrogen Semi, New Battery Truck Amid Nikola Uproar", 16 September 2020, accessed 16/12/20 from: https://www.forbes.com/sites/alanohnsman/2020/09/16/daimler-shows-off-long-range-hydrogen-semi-new-battery-truck-amid-nikola-uproar

[254] MoT Strategic Working Paper, p22-23; MoT Background Paper, p24.

[255] H2 Taranaki Roadmap, p37.

[256] Hiringa Energy, "Hiringa Energy and HYZON Motors to Deploy Fuel Cell-Powered Heavy Trucks in New Zealand in 2021", 31 August 2020, accessed 15/12/20 from: https://www.hiringa.co.nz/post/hiringa-energy-and-hyzon-motors-to-deploy-fuel-cell-powered-heavy-trucks-in-new-zealand-in-2021

[257] Hiringa Energy, "TR Group & Hiringa announce partnership to jointly introduce Heavy Fuel Cell Electric Trucks into NZ", 8 July 2020, accessed 15/12/20 from: https://www.hiringa.co.nz/post/tr-group-hiringa-announce-partnership-to-jointly-introduce-heavy-fuel-cell-electric-trucks-into-nz; Nikola, "Leasing", accessed 16/12/20 from: https://nikolamotor.com/two

As this table demonstrates, the key ***non-quantified*** issues regarding the economics of using hydrogen in FCEVs for LDHF appear to be:

- The pricing and availability of platinum allowing for large-scale commercial FCEV markets and whether viable alternative catalysts are developed for use in fuel cells;
- The cost of electricity, including whether peak/off-peak differentials persist in the future and if proposed changes to the TPM increase the cost of drawing power off-peak; and
- The availability and pricing of FCEV heavy trucks suitable for the New Zealand market.

By contrast, the opportunities associated with green hydrogen FCEVs that were not quantified are set out below in Table 7.2 below.

Table 7.2
Qualitative assessment of non-quantified opportunities with using green hydrogen and FCEVs

Opportunity	Barrier or economics	Potential materiality	Discussion	Potential mitigants
Fuel cells have a longer life than batteries and need to be replaced less often[258]	Economics	Medium - High	The performance of batteries and fuel cells degrade over time and therefore batteries and fuel cells may need to be replaced during the life of the truck, although degrade more quickly. This may be exacerbated for high-usage vehicles like LDHF trucks, if ultra-fast charging is required to close charge time disadvantage for BEV trucks and this results in more frequent recharging.[259]	Battery technology will not stand still, so hydrogen's advantage may dissipate in the future.
Energy security/ independence and resiliency, particularly with distributed production	Economics	Low - High	Domestic and distributed protection provides an insurance value of sorts. Local production of fuel reduces reliance on overseas supply chains for fuel, relative to liquid alternatives which may be increasingly imported if plans to scale back production at Marsden Point are implemented.[260] Decentralised production (and storage) will also mitigate the impacts of local supply disruptions.	The benefits of domestic production would also apply to BEVs, as all electricity is generated domestically. Both BEVs and FCEVs would be impacted by an outage to the grid, as hydrogen requires electricity for production. However, local storage at refuelling sites would provide an insurance benefit over and above that provided by using electricity, unless installing batteries at BEV fuelling stations is economic. Still reliant on overseas supply chains for equipment, though fuel would be locally produced.

[258] MoT Background Paper, p28

[259] H2 Taranaki Roadmap, p16.

[260] The Northern Advocate, "Refining NZ to scale down its Marsden Point operation from next year", 5 October 2020, accessed 16/12/20 from: https://www.nzherald.co.nz/northern-advocate/news/refining-nz-to-scale-down-its-marsden-point-operation-from-next-year/W5M6FTGU4TSGOIVOGKOR3NINYE/

Opportunity	Barrier or economics	Potential materiality	Discussion	Potential mitigants
Noise pollution reduction compared to ICEVs[261]	Economics	Low	Vehicles with electric motors are much quieter than ICEVs.	LDHF spends most of its time on highways where noise pollution may be less of a concern. Freight pick up and drop off for LDHF is generally at logistics centres, which are located in industrial areas where noise may be less of a concern. Similarly, movements of heavy freight trucks in populated areas already face restrictions to minimise the impact.

The key unmodelled opportunities, are therefore:

- Fuel cells carry a longer-life advantage to batteries, which under present technology is exacerbated by fast charging; and
- Increased energy security if green hydrogen is produced locally, with further potential benefits if it is produced in a distributed manner.

7.2. Blue hydrogen using FCEVs

Many of the issues and opportunities with using blue hydrogen are common with green hydrogen in terms of their end use in an FCEV. The key unmodeled issues unique to blue hydrogen are the price of delivered fuel for FCEVs produced by SMR+CCS.

For context, Concept did in fact model a price of blue hydrogen against green hydrogen, but not in the context of use as a fuel for FCEVs and therefore used substantially different inputs. In this analysis of the power-to-gas use case which assumes using the gas transmission lines and large-scale hydrogen production facilities, Concept estimated blue hydrogen to be half the price green hydrogen per NZ$/GJ.[262]

The issues with blue hydrogen which we can qualitatively assess are set out in the table below.

[261] H2 Taranaki Roadmap, p16.

[262] Concept Analysis Report, p27-28.

Table 7.3
Qualitative assessment of non-quantified issues with using blue hydrogen FCEVs

Issue	Barrier or economics	Potential Materiality	Discussion	Potential mitigants
Technology maturity for CCS[263]	Barrier and economics	Medium - High	There are still remaining emissions using CCS presently. A new process which can be used to create hydrogen, the Allam Cycle, is stated to capture 100% of carbon but is still not a proven technology at large scale.[264] Uncertainty around technology progression and residual emissions (i.e., increased social cost) may hinder use case.	Technology doesn't stand still and CCS may improve within timeline that blue hydrogen could be adopted. Currently, an existing project to implement CCS in hydrogen production using the Allam cycle is slated to be established by Pouakai/8 Rivers in Taranaki.[265]
Geographic concentration of potential storage in Taranaki	Barrier and economics	Low - Medium	Geological soundness is paramount to CCS effectiveness. Taranaki is the only place identified in New Zealand that could potentially be used for CCS. This may require concentration of production in Taranaki.[266]	The gas transmission network already connects to Taranaki, so transport would not be an issue (subject to the transport concerns identified above). The majority of New Zealand's gas is in Taranaki,[267] so it's likely that blue hydrogen production would locate here anyways if a centralised production model was adopted.
Blue hydrogen is only a transitional fuel,[268] yet the infrastructure costs could be significant	Economics	Medium - High	Could result in stranded assets if blue hydrogen is displaced by another fuel in the future and production/storage facilities have no alternative use.	Less of an issue if cost recovery for initial investment occurs within timeframe that transition is expected to occur. CCS facilities may have applicability to other carbon-producing industrial processes, reducing the risk of stranded assets.[269]

The key non-quantified issues with respect to the economics of blue hydrogen are therefore that:

- CCS technology, if/when it matures, still could result in residual emissions; and
- Another fuel becomes more economic than blue hydrogen (for example, because CCS still results in residual emissions) before the initial investments are recovered, and these assets become stranded.

263 Concept Research Report, p26.

264 Power, "300-MW Natural Gas Allam Cycle Power Plant Targeted for 2022", 27 November 2019, accessed 15/12/20 from: https://www.powermag.com/300-mw-natural-gas-allam-cycle-power-plant-targeted-for-2022/

265 H2 Taranaki Roadmap, p26-27; NZ Herald, "8 Rivers 'clean energy' project breaks cover in push for $20m in funding", 26 November 2018, accessed 16/12/20 from: https://www.nzherald.co.nz/business/8-rivers-clean-energy-project-breaks-cover-in-push-for-20m-in-funding/633F72QPIHWOV74ZVXPSTRWLVA/

266 Concept Research Report, p26.

267 MBIE, "Gas statistics", accessed 156/12/20 from: https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/gas-statistics/

268 H2 Taranaki Roadmap, p15; Ralf Dickel, "Blue hydrogen as an enabler of green hydrogen: the case of Germany", The Oxford Institute for Energy Studies, May 2020.

269 Global CCS Institute, *Introduction to Industrial Carbon Capture and Storage*, June 2016.

The key economic opportunity is that blue hydrogen may be cheaper to produce than green hydrogen in the event hydrogen is taken up for other use cases.[270] Even if one believes that blue hydrogen is not a long-term solution because it uses fossil fuels as an input, it may provide a lower-cost transition fuel if one believes that green hydrogen is the end point.

7.3. Direct electrification using BEVs

The existing quantitative analyses suggest that BEVs suffer from payload and recharging issues currently, but still may be less expensive zero-emission vehicle than FCEVs in the near-term for LDHF under certain circumstances. The following additional issues and opportunities have been raised in the studies we have examined, through our own research and stakeholder discussions, but not quantified.

Table 7.4
Qualitative assessment of non-quantified issues with using direct electrification with BEVs

Issue	Barrier or economics	Potential Materiality	Discussion	Potential mitigants
Sustainability of lithium-ion batteries[271]	Barrier and economics	Medium - High	Concerns have been raised about the environmental impact of lithium and cobalt extraction and battery disposal/recyclability.[272] Additionally, increased demand for lithium and cobalt have raised concerns about longer-term availability.[273]	This is a global technological problem and research is being done towards developing various battery alternatives which rely on more abundant/safer materials.[274]
BEV trucks are just coming to the market.	Barrier	Medium - High	BEVs are just beginning to become commercially available for purchase in New Zealand and the timeline withing which they will be widely available is unclear.	Alsco has just released a BEV heavy truck in New Zealand, but it is unclear what its payload capabilities are.[275] Foodstuffs and EECA have recently partnered to develop a single EV refrigerated truck, which is driving on the South Island.[276] Scania recently launched a commercially available BEV truck in Europe[277]

[270] Vivid Report, p40; Concept Analysis Report, p28.

[271] MoT Strategic Working Paper, p23.

[272] MoT Background Paper, p18, 19, 21; MoT Strategic Working Paper, p23

[273] McKinsey & Company, *Lithium and cobalt – a tale of two commodities*, June 2018.

[274] Borah, R., Hughson, F. R., Johnston, J., & Nann, T. (2020), "On battery materials and methods", *Materials Today Advances*, 6, 100046.

[275] Alsco, "New Zealand's first long-haul EV road freighter", accessed 16/12/20 from: https://www.stories.alsco.co.nz/ev-freighter

[276] Foodstuffs, "Foodstuffs and EECA partner up to build NZ's first 100% electric refrigerated logistics truck", 26 June 2020, accessed 16/12/20 from: https://www.foodstuffs.co.nz/media-centre/news-media/foodstuffs-and-eeca-partner-up-to-build-nz%E2%80%99s-first-100-electric-refrigerated-logistics-truck/

[277] Electrive, "Scania launches BEV & PHEV truck series"., 27 November 2020, accessed 16/12/20 from: https://www.electrive.com/2020/11/27/scania-announces-market-launch-of-bev-phev-trucks/

Issue	Barrier or economics	Potential Materiality	Discussion	Potential mitigants
NZ-specific requirements create hurdle for truck availability[278]	Barrier and economics	Medium - High	In addition to being one of the few RHD markets in the world, New Zealand also has specific requirements for heavy freight in relation to axle weight.[279] This may impact truck availability or increase costs.	New Zealand's specific requirements may limit the number of suppliers willing to supply New Zealand, but ultimately, this is likely to mainly be an issue around price. This is equally true for FCEVs.
Fast charging may result in battery degradation, shortening battery life[280]	Economics	Medium - High	Performance degradation and battery replacement accelerated by using ultra-fast charging could increase costs.	Battery swapping schemes would avoid the need for fast charging, but this could increase costs (as more batteries would be need), though may not result in material net increase in batteries used (batteries would be used in parallel rather than sequentially)[281]
Generation/Grid constraints	Barrier and economics	Low - Medium	Fast charging during peak hours and charging in less developed areas of the grid could result in constraints on ability to charge.[282] Largely an issue of price (i.e., facing peak pricing or funding transmission upgrades), but this will affect the economics of using BEVs.	Battery swapping or smart charging (if possible for LDHF) could mitigate impacts of charging at peak.[283] More general, economy-wide initiatives to flatten demand (demand response, distributed energy resources and large-scale storage) could mitigate issues around peak pricing.

The main additional issues therefore appear to be the:

- Cost and availability of BEV trucks suitable for New Zealand (which is also an issue for FCEVs);
- Sustainability issues with continued use of lithium-ion batteries; and
- The impacts of fast charging on both network infrastructure and battery life and performance of the truck.

[278] MoT Strategic Working Paper, p.22-23; MoT Background Paper, p24.

[279] H2 Taranaki Roadmap, p37.

[280] H2 Taranaki Roadmap, p16.

[281] MoT Background Paper, p22.

[282] MoT Background Paper, p22; MoT Strategic Working Paper, p21/22

[283] MoT Background Paper, p22.

Table 7.5
Qualitative assessment of non-quantified opportunities with using direct electrification with BEVs

Opportunity	Barrier or economics	Potential materiality	Discussion	Potential mitigants
Energy security / independence	Economics	Low - High	Local production of electricity reduces reliance on overseas supply chains for fuel, relative to liquid alternatives which may be increasingly imported if plans to scale back production at Marsden point are implemented.[284]	Benefits of local fuel production equally apply to FCEVs, unless hydrogen is imported. Both BEVs and FCEVs would be impacted by an outage to the grid, as hydrogen requires electricity for production. Still reliant on overseas supply chains for equipment, though fuel would be locally produced.
Noise pollution reduction vs ICEV	Economics	Low - Medium	Vehicles with electric motors are much quieter than ICEVs.[285]	LDHF spends most of its time on highways where noise pollution may be less of a concern. Freight pick up and drop off for LDHF is generally at logistics centres, which are located in industrial areas, where, noise may be less of a concern. Similarly, movements of heavy freight trucks in populated areas already face restrictions to minimise the impact.

The key potential additional unquantified benefit of BEVs, relative to the status quo, is therefore security of supply and resiliency.

7.4. Advanced biofuel using ICEVs

As already discussed, biofuel of any type was not explicitly considered as an alternative in any of the quantitative analyses of green hydrogen. As mentioned in section 3, the advanced biofuel renewable diesel appears to be the only biofuel option at present which offers a realistic net zero carbon option (as conventional biofuels can only be blended with diesel at low rates without vehicle modification).

Table 7.6
Qualitative assessment of issues with using advanced biofuel with ICEVs

Issue	Barrier or economics	Potential Materiality	Discussion	Potential mitigants
Transparency of supply chain	Barrier and economics	Medium	Different organic materials can be used to produce renewable diesel and it's not clear that production is necessarily net zero. For example, if nitrogen fertiliser is used, this could increase emissions.[286]	Certification schemes for biofuel which guarantee lifetime emissions could be implemented, though this would impose additional costs. If lifetime emissions can't be verified, this would pose a barrier to biofuel uptake.

[284] The Northern Advocate, "Refining NZ to scale down its Marsden Point operation from next year", 5 October 2020, accessed 16/12/20 from: https://www.nzherald.co.nz/northern-advocate/news/refining-nz-to-scale-down-its-marsden-point-operation-from-next-year/W5M6FTGU4TSGOIVOGKOR3NINYE/

[285] H2 Taranaki Roadmap, p16.

[286] MoT Background Paper, p21, NZPC Low-emissions economy report, p366.

Issue	Barrier or economics	Potential Materiality	Discussion	Potential mitigants
Tail pipe emissions	Barrier	Medium - High	While biofuels can theoretically be net zero emission over their lifetime, there are still emissions at the tail pipe. This could raise concerns about localised air quality and pose a barrier to adoption for organisations committed to zero (as opposed net zero emissions).	Limited, unless biofuels have lower tail pipe emission than conventional diesel. Neste has shown that its renewable diesel burns cleaner than traditional diesel.[287]
Land and resource availability	Barrier and economics	Low - Medium	Biofuel production requires large amounts of feedstock.[288] The amount land required to grow the required crops would be substantial. Biomass, which also can be used, is also used by other industries and there would therefore be competition for resources.[289]	Scion modelling suggests that while significant there is sufficient non-arable land to grow enough trees to produce the renewable diesel required for LDHF.[290]
Unequal government support vs other low emissions options	Economics	Medium - High	ICEVs currently attract RUC while BEVs do not. This distorts choice towards BEVs (and potentially FCEVs), even though renewable diesel might also be low/net zero emission.	Govt policy could be changed to more directly promote zero/low emissions fuels in a technology neutral manner – for example, use a low emissions fuel standard (which targets emissions) instead of the RUC (which are weight-based charged designed to fund road maintenance).
Technological immaturity	Barrier and economics	Low - Medium	Production of renewable diesel is not yet occurring in large commercial quantities.[291]	This is a global problem and commercial applications are beginning to emerge overseas.[292] In addition, this option would use existing trucks so technological development is only required in production, unlike BEVs and FCEVs where trucks are also an issue.

The key economic issues are availability and a non-technology agnostic approach to promoting low-emission fuels in New Zealand, placing biofuels at an economic disadvantage.

Regarding the opportunities, these are set out in Table 7.7 below.

287 NESTE, "Reduced emissions", accessed 15/12/20 from: https://www.neste.com/products/all-products/renewable-road-transport/reduced-emissions

288 MoT Background Paper, p36.

289 US Department of Energy Alternative Fuels Data Center, "Renewable Hydrocarbon Biofuels", accessed 16/12/20 from: https://afdc.energy.gov/fuels/emerging_hydrocarbon.html

290 Scion Technical Report, p4.

291 Scion Summary Report, p20.

292 IRENA, *Advanced Biofuels: What holds them back?*. November 2019, p19.

Table 7.7
Qualitative assessment of non-quantified opportunities with using advanced biofuel with ICEVs

Opportunity	Barrier or economics	Potential materiality	Discussion	Potential mitigants
New trucks are not required, and existing trucks have a long life	Barrier and economics	Low - High	Advanced or "2nd generation" biofuels are a drop in substitute for diesel, therefore fuel substitution does not also require vehicle substitution. Long life of trucks (over 20 years across various uses) also means investment now can have lasting impact on emissions.	Trucks need to be replaced over time, so this is primarily a benefit within the usable lifetime of the current truck fleet. Whether this is a benefit therefore depends on the timeframe – for a more short-term timeframe the benefit would be substantial, whereas for a long-term analysis the benefit disappears.
Relatively immediate application	Barrier and economics	Medium - High	Given the nearer-term commerciality of biofuels and compatibility with the existing fleet, renewable diesel could provide a more immediate option for widespread emissions reductions,[293] even if it is not the most economic long-term method.	Commerciality of alternatives (BEVs and FCEVs) may progress more rapidly than some anticipate. If we continue to purchase new ICEVs in the short run, the long life of ICEVs may slow transition to alternative fuels in the future.

The key economic opportunities are therefore the more immediate application and the lack of an incremental vehicle cost, both of which are driven by the ability of advanced biofuels to be used as a drop-in substitute for diesel in existing vehicles.

Additionally, we note that the MfE MACC analysis finds that, assuming oil prices of US$62/bbl and NZ$80/tonne for logs delivered to a biorefinery, the carbon price is estimated to need to be NZ$240/t CO_2 for renewable diesel to supersede fossil diesel.[294] This price would go down if the price of oil were higher, or the price of feedstock were lower. It notes that if the price of diesel increased to above US$90/bbl (keeping constant the cost of feedstock), renewable diesel would become a very prospective option for decarbonising heavy road freight in New Zealand.[295]

7.5. Modal shift

Like biofuels, none of the quantitative analyses consider modal freight shift as an option for decarbonising LDHF. This is also not discussed as extensively in the qualitative studies we have examined (e.g., it was specifically out of scope for the Ministry of Transport's green freight project[296]).

As discussed in section 5.2.4 on the NZPC report, coastal and rail shipping have lower emissions profiles per tonne-kilometre. The volume of freight which is suitable to switch to these alternative modes is limited, likely to inter-regional freight which is not time sensitive is best suited to this modal

[293] MoT Background Paper, p37; MoT Strategic Working Paper, p22.

[294] Note that this cost is reported for marine and rail use, but the diesel is the same as what would be used in a heavy truck. MfE MACC Report, p45 & 88.

[295] MfE MACC Report, p86.

[296] MoT Strategic Working Paper, p8.

shift, or put another way, freight trips over long distances. This segment of the freight task overlaps significantly with that of the LDHF task.

Looking outside the transition to lower emissions fuels, modal shift could reduce emissions using existing technologies and fossil fuels. This is because trains and coastal shipping achieve economies of scale, and therefore are much more efficient on a pure $/tkm basis and emissions per tkm basis. Moreover, shifting freight away from roads would mean less congestion and required maintenance on New Zealand's highways.

The key issue deterring modal shift is that road freight offers flexibility and speed. Road freight is therefore more ideal in particular for shorter trips and to destinations that would not be hubs for freight or rail. By shifting freight which would need to be loaded back onto trucks for the first and final legs of the trip, an additional cost is added for time and labour to move the freight.

Modal shift could, theoretically, be combined with a complementary fuel shift by updating to electric (or hydrogen) trains. However, the North Island Main Trunk Line (NIMT) is not currently electrified between Hamilton and Auckland. As a result, in December 2016 KiwiRail replaced the NIMT fleet with diesel locomotives, as this was cheaper than the ~$1B cost of electrifying the rest of the NIMT.[297]

Given the flexibility offered by road, rail and coastal shipping will only be a substitute for road freight if it is superior in some or all of cost, reliability and speed.[298] This means the opportunity for modal shift is most likely to be LDHF.

It is a significant point to note that the part of the freight task where modal shift offers the most opportunity is also the same area where it is being suggested green hydrogen FCEVs have the most promise. This suggests the current lack of analysis of rail as an alternative for LDHF is an important omission.

Moreover, the MfE MACC analysis investigates the carbon price needed for battery electric trains to supersede diesel, finding that if the battery is sized to allow overnight charging, then a negative carbon price may be possible. This indicates electrified rail becoming more economically competitive in the future.[299]

Hydrogen may also provide additional opportunities for modal shift given it is a method for decarbonising ocean freight and hybrid electric and hydrogen trains could potentially be a cheaper option than electrifying the remainder of the NIMT.

This discussion illustrates that freight mode consideration should be given to:

- The potential benefits of electrifying the NIMT and making other investments to improve the speed and reliability of rail for LDHF, including the incidental reduced maintenance stemming from freight shifted off roads;
- The necessary price/quality improvement required for road freight customers to shift to different modes; and
- Whether the transition to lower emissions fuels could also facilitate the transition to different modes (e.g., the economics of using hydrogen fuel cell trains in New Zealand).

We note that the MoT Background Paper states that the ministry is conducting investigations in the benefits of shifting freight to rail and coastal shipping.[300] Our suggestion is therefore that this work should be integrated with work that more narrowly focuses on fuel choice for trucking. That is to say,

[297] NZPC Low-emissions economy report, p363; RNZ, "KiwiRail to scrap electric on main trunk line", 21 December 2016, accessed 16/12/20 from: https://www.rnz.co.nz/news/national/320956/kiwirail-to-scrap-electric-on-main-trunk-line

[298] A similar point is made by MoT Background Paper, p15.

[299] MfE MACC Report, p46.

[300] MoT Background Paper, p15.

any assessment should be both mode and fuel agnostic to get the most complete view on what is the most economic method of decarbonising LDHF.

In terms of our research question, this discussion suggests that for green hydrogen FCEVs to be the most economic path to decarbonising LDHF:

- Rail and coastal shipping cannot offer a service that is fast, reliable or cheap enough for substitution to occur; or
- The necessary investment required to decarbonise the rail or coastal shipping sector in the long term would be cost prohibitive.

7.6. Findings on unquantified issues and opportunities

In sum, our review identified a number of factors that were not explicitly quantified in the analyses of green hydrogen FCEVs, BEVs and diesel ICEVs and considerations around the other unquantified alternatives that in our view would have a material impact on the factors that need to be true for green hydrogen to be the most economic method of decarbonising LDHF. These are summarised in Table 7.8.

Table 7.8
Material non-quantified issues and opportunities using alternative decarbonisation methods for LDHF

Alternative	Non-quantified issues	Non-quantified opportunities
Green hydrogen / FCEVs	▪ The platinum problem, including sourcing and recycling.[301] ▪ Availability and pricing of FCEVs suitable for NZ conditions. ▪ Opportunistic production when electricity prices are low may not be viable if peak/off-peak differentials reduce and TPM pricing increases charges for off-peak use.	▪ Longer life of fuel cells vs batteries reduces lifetime costs of FCEVs compared to BEVs. ▪ Increased energy security/resiliency if produced locally. Additional benefit from decentralised production.
Blue hydrogen / FCEVs	▪ Same platinum and FCEV issues as per green hydrogen. ▪ CCS technology is developing but not yet widely established. ▪ If only a transition fuel, stranding risk if zero-emission alternatives become commercial earlier than anticipated.	▪ Blue hydrogen may initially be much cheaper to produce than green hydrogen.

[301] Platinum is a critical component to fuel cells (under current technology), and platinum is a rare and expensive metal. Therefore, large-scale adoption of FCEVs globally will likely require a substitute for platinum to be developed or technological advances that reduce the amount of platinum required to run an FCEV. Additionally, recycling platinum at the end of the life of the fuel cell is costly. As we discuss in section 3.1, research is already underway to find alternatives to platinum as a fuel cell catalyst.

Alternative	Non-quantified issues	Non-quantified opportunities
Direct electrification / BEVs	▪ The lithium and cobalt problems, including sourcing and recycling.[302] ▪ As per FCEVs, availability and pricing of BEV trucks meeting NZ specifications. ▪ Use of ultra-fast chargers could reduce battery life and performance. ▪ If ultra-fast charging leads to charging during peak demand periods, could result in increased grid costs and therefore increase BEV running costs.	▪ Resiliency/security of supply, vs imported fuels, of domestic energy production.
Advanced biofuel / ICEVs	▪ Road user charge (RUC) exemptions for BEV (and potentially FCEV) distort decisions away from biofuels. ▪ Supply constraints due to demand from other industries could strain mass adoption.	▪ More immediate use than FCEVs/BEVs. ▪ Use of existing ICEV fleet means existing fleet does not need to be replaced in near term.
Modal shift to rail or coastal shipping	▪ Less flexible than road freight, and cost and emissions savings still may not be enough to offset this. ▪ Investment will likely also be required to update infrastructure for these modes.	▪ More efficient from both a cost and an emissions perspective. ▪ Hydrogen FCEV trains could be cheaper than electrifying the remainder of the North Island Main Trunk Rail line. ▪ LDHF, promoted as most amenable to using FCEVs, may also be the portion of the freight task most amenable to modal shift, given distances involved.

Our key observation upon review of these studies is that there are significant factors outside the private costs borne by a freight operator which must be taken into account to determine the total societal cost of adopting any or each of the above alternatives in LDHF in New Zealand. Significant issues for BEVs and FCEVs are scaling up these technologies while relying on rare earth metals (platinum, cobalt and lithium) and the immediate issue of the legacy fleet of ICEVs in the "waiting period" until either e-truck becomes widely commercially available. Moreover, the continuous advances in battery and fuel cell technology leave significant uncertainty over the next decade in terms of private costs.

Additionally, from a total societal cost standpoint, applying RUC on some vehicles but not others is essentially a cross-subsidy. Presently, RUC exemptions only exist for BEVs, but moving forward this is likely to evolve to include other low- and zero-emission options. The RUC in part funds road maintenance, charged as a function of weight, not fuel choice. There is therefore a risk that applying RUC exemptions to promote decarbonisation in a way that is not technology-neutral could inefficiently distort fuel and vehicle choice away from other decarbonisation alternatives. This risk is particularly important given the uncertainty and technological immaturity of decarbonisation options for LDHF.

Our analysis also highlights that quantitative analyses comparing the TCO of green hydrogen-powered FCEVs against advanced biofuels or blue hydrogen have not yet been performed, although they have been qualitatively considered. Additionally, the TCO for conventional biofuels and other

[302] Lithium and cobalt are both critical components to lithium ion batteries (which run BEVs under current technology). These are both rare and expensive metals, and cobalt mines in particular are extremely concentrated geographically. The recent spikes in demand for these materials due to their use in a range of electric technologies has led to major concern about future price and availability, and current ethics in the supply chain. Therefore, continued adoption of BEVs at larger scale will likely require substitutes for, or major reductions of, these materials moving forward. Additionally, recycling these materials from batteries at the end of life is costly. As we discuss in section 3.2, research is underway to find alternatives to lithium and cobalt in batteries for electric vehicles.

lower-emission options (e.g. methanol and LNG) have not been quantified, although these could also potentially be effective as more immediate transitional fuels.[303]

Looking outside the more narrow lens of what fuel should be used in trucks, modal shift to rail and/or coastal shipping could potentially result in material cost and emissions savings across the transport sector, as well as other benefits including a substantial reduction in truck movements, road congestion and highway maintenance. We consider that modal shift should be further explored.

Our overall conclusion from our review of these studies is that there remains uncertainty as to what is the least-cost path to decarbonising LDHF in New Zealand, particularly where “path” is defined to include goals for both short-term and longer-term emissions reduction as the answers to each question might be different.

[303] Noting that this is not considered at length by any of the studies reviewed.

8. Areas for further investigation

The key gaps we have identified after reviewing the existing studies are:

- Existing studies focus on comparing green hydrogen FCEVs and BEVs with ICEVs, but do not consider broader alternatives for decarbonising LDHF such as biofuels, blue hydrogen, cleaner burning fossil fuels or modal shift;
- Relatedly, the studies focus on long-run economics (the “end point”) but do not consider in detail the economics of more immediate options to decarbonising (the “path”);
- The studies were often completed with a different purpose to ours, and therefore the modelling and assumptions are not available in a way that the findings can be rigorously tested and updated to account for future technology and cost changes; and
- The public data that exists on the LDHF task in New Zealand is relatively sparse and aggregated, which makes it difficult to define what LDHF means in a New Zealand context.

Our review suggests that the public policy debate surrounding both the “end point” and the more immediate-term “path” for decarbonising LDHF would benefit from a publicly available TCO model, with overlays for social costs and benefits. This would ideally compare the full identified range of options against each other and allow comparisons to be made both in the longer and more immediate terms. Such a model would facilitate answering a more holistic question such as “**what economic options exist to decarbonise LDHF in both the immediate and long term?”**

This model would allow assumptions to be transparently tested, updated and challenged. Much of the analysis that would go into a modelling exercise like the described public TCO model already exists but is contained in disparate reports and models which focus on a subset of the options.

Similarly, a more disaggregated and detailed public data set on truck movements would make such a model more useful and progress the policy discussion more generally. In particular, a better understanding of how far trucks travel in a day, how much freight they carry and how many trucks fit into different bands of daily tonne-kilometres would enable better identification of the segments of the LDHF task that are amenable to different decarbonisation options. This is particularly the case with respect to BEVs where the current trade-off between range, payload and charging time may not yet economically support the needs of LDHF.

Appendix A. Critical assumptions in each quantitative modelling scenario

The following tables display critical underlying assumptions for each scenario provided by each study. Note the following:

- Grey cells indicate the category isn't relevant to the vehicle type, while *n/a* indicates that the information is not available for the scenario and category.
- The H2 Taranaki Roadmap also includes assumptions for 2018, which is omitted from Figure 6.2, Figure 6.3 and this appendix, and 2025, which is omitted from the appendix due to repetition.
- Due to the sparse availability of the Castalia assumptions, only the available assumptions for 2020 and 2040 are presented for brevity.
- FCEV indicates green hydrogen-fueled FCEVs and ICEV indicates diesel-fueled ICEVs.

Table A.1
Concept assumptions[304]
Average kms

Vehicle	FCEV	BEV	ICEV	FCEV	BEV	FCEV	BEV	ICEV
Year	2020	2020	2020	2040	2040	2040	2040	2040
Scenario description	Base, average kms	Base, average kms	Base, average kms	Small-scale H2 uptake, average kms	Small-scale H2 uptake, average kms	Large-scale H2 uptake, average kms	Large-scale H2 uptake, average kms	Average kms
Upstream								
Electrolyser capex ($/kW)	$1,400			$700		$700		
Electrolyser utilisation	85%			85%		n/a		
Electricity ($/MWh)	$75	$75		$75	$75	$82	$82	
Off-peak	Y	Y		Y	Y	N	N	
Midstream								
Charging capability		120kW			1MW		120kW	
Delivered H2 ($/kg)	$11.30			$6.55		$9.11		
Diesel pump price ($/l)			$1.40					$1.40
Downstream								
Vehicle capital cost	$500,000	$250,000	$175,000	$250,000	$195,000	$250,000	$195,000	$175,000
Payload capacity (t)	30	27.5	30	30	28.2	30	28.2	30
Annual kms	75,000	75,000	75,000	75,000	75,000	75,000	75,000	75,000
Carbon price ($)			$20.75					$100.00
Fuel cost per km ($)	$1.01	$0.32	$0.57	$0.49	$0.16	$0.68	$0.19	$0.63
TCO $/km	**$3.00**	**$2.09**	**$1.90**	**$1.95**	**$1.64**	**$2.15**	**$1.93**	**$1.97**
TCO $/tkm	**$0.100**	**$0.076**	**$0.060**	**$0.065**	**$0.060**	**$0.072**	**$0.070**	**$0.066**

304 Assumptions and TCO can be found throughout Concept Analysis Report (for example, pp 11, 25, 33-50).

Table A.2
Concept assumptions
High kms

Vehicle	FCEV	BEV	ICEV	FCEV	BEV	FCEV	BEV	ICEV
Year	2020	2020	2020	2040	2040	2040	2040	2040
Scenario description	Base, high kms	Base, high kms	Base, high kms	Small-scale H2 uptake, high kms	Small-scale H2 uptake, high kms	Large-scale H2 uptake, high kms	Large-scale H2 uptake, high kms	High kms
Upstream								
Electrolyser capex ($/kW)	$1,400			$700		$700		
Electrolyser utilisation	85%			85%		n/a		
Electricity ($/MWh)	$75	$75		$75	$75	$82	$82	
Off-peak	Y	Y		Y	Y	N	N	
Midstream								
Charging capability		120kW			1MW		120kW	
Delivered H2 ($/kg)	$11.30			$6.55		$9.11		
Diesel pump price ($/l)			$1.40					$1.40
Downstream								
Vehicle capital cost	$500,000	$250,000	$175,000	$250,000	$195,000	$250,000	$195,000	$175,000
Payload capacity (t)	30	27.5	30	30	28.2	30	28.2	30
Annual kms	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000
Carbon price ($)			$20.75					$100.00
Fuel cost per km ($)	$1.01	$0.42	$0.57	$0.49	$0.19	$0.68	$0.26	$0.63
TCO $/km	**$2.25**	**$1.70**	**$1.50**	**$1.46**	**$1.22**	**$1.65**	**$1.51**	**$1.55**
TCO $/tkm	**$0.075**	**$0.062**	**$0.050**	**$0.049**	**$0.044**	**$0.550**	**$0.055**	**$0.052**

Table A.3
H2 Taranaki Roadmap assumptions[305]

Vehicle	FCEV	BEV	BEV	ICEV	FCEV	BEV	BEV	ICEV
Year	2020	2020	2020	2020	2030	2030	2030	2030
Scenario description	Base	Standard charging	Fast charging	Base	Base	Standard charging	Fast charging	Base
Upstream								
Electrolyser capex ($/kW)	n/a				n/a			
Electrolyser utilisation	n/a				n/a			
Electricity ($/MWh)	n/a	n/a	n/a		n/a	n/a	n/a	
Off-peak	n/a	n/a	n/a		n/a	n/a	n/a	
Midstream								
Charging capability		50kW	150kW			50kW	150kW	
Delivered H2 ($/kg)	n/a				n/a			
Diesel pump price ($/l)				n/a				n/a
Downstream								
Vehicle capital cost	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Payload capacity (t)	20	13	13	20	20	13	13	20
Annual kms	208,000	120,000	203,000	208,000	208,000	120,000	203,000	208,000
Carbon price ($)				n/a				n/a
Fuel cost per km ($)[306]	$1.66	n/a	$0.43	n/a	n/a	n/a	n/a	n/a
TCO $/km	**$3.10**	**$2.80**	**$2.15**	**$1.90**	**$2.30**	**$2.87**	**$2.24**	**$2.30**
TCO $/tkm	**$0.155**	**$0.215**	**$0.165**	**$0.095**	**$0.115**	**$0.221**	**$0.172**	**$0.115**

305 Assumptions and TCO can be found at H2 Taranaki Roadmap, pp 43 & 44.

306 The fuel cost per kilometer in 2020 is derived from the H2 Taranaki Roadmap TCO figure. Because RUC exemptions are applied to BEVs and FCEVs in 2020, the "Fuel+RUC" component of the stacked bar only includes fuel. We have therefore estimated the fuel cost per km in 2020 for FCEVs and 150kW-charging BEVs by extracting this value and multiplying by the payload (FCEV=.083*20=$1.66) (BEV 150kW=.033*13=$0.43). Note that the 50kW-charging BEV scenario is not able to be parsed apart as it is included as an additional stack piece to the 150kW bar.

Table A.4
Vivid assumptions[307]

Vehicle	FCEV	FCEV	ICEV
Year	2050	2050	2050
Scenario description	Low	High	Base
Upstream			
Electrolyser capex ($/kW)	$665	$1,294	
Electrolyser utilisation	50%	50%	
Electricity ($/MWh)	$70	$90	
Off-peak	n/a	n/a	
Midstream			
Delivered H2 ($/kg)	$6.15	$7.40	
Diesel pump price ($/l)			n/a
Downstream			
Vehicle capital cost	$164,814	$190,542	n/a
Payload capacity (t)	26	26	n/a
Annual kms	79,269	79,269	n/a
Carbon price ($)			$200.00
Fuel cost per km ($)	$0.17	$0.20	$0.39
TCO $/km	**$0.37**	**$0.44**	**$0.56**
TCO $/tkm	**$0.014**	**$0.017**	**n/a**

307 Assumptions and TCO can be found at Vivid Report, p 42, 44, 52 and 53.

Table A.5
Castalia assumptions[308]

Vehicle	FCEV	BEV	ICEV	FCEV	BEV	ICEV
Year	2020	2020	2020	2040	2040	2040
Scenario description	Base	Base	Base	Base	Base	Base
Upstream						
Electrolyser capex ($/kW)	n/a			n/a		
Electrolyser utilisation	41.5%			41.5%		
Electricity ($/MWh)	$61	$61		$58	$58	
Off-peak	n/a	n/a		n/a	n/a	
Midstream						
Charging capability		n/a			n/a	
Delivered H2 ($/kg)	n/a			n/a		
Diesel pump price ($/l)			n/a			n/a
Downstream						
Vehicle capital cost	n/a	n/a	n/a	n/a	n/a	n/a
Payload capacity (t)	n/a	n/a	n/a	n/a	n/a	n/a
Annual kms	n/a	n/a	n/a	n/a	n/a	n/a
Carbon price ($)			n/a			n/a
Fuel cost per km ($)	n/a	n/a	n/a	n/a	n/a	n/a
TCO $/km	**$1.50**	**$0.98**	**$0.78**	**$0.75**	**$0.65**	**$1.05**
TCO $/tkm	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**

308 Assumptions and TCO can be found on the Castalia model dashboard and at Castalia Presentation, p 7.

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