REPORT ON THE DECARBONISATION OF NEW ZEALAND'S FREIGHT RAILWAY

MAY 2024

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Abbreviation	Full Name
1C	Charging a battery at a rate that moves it from empty to full in 1 hour
AC	Alternating current
ARM	Active Risk Manager (software)
BAU	Business as usual
CBAx	A NZ Treasury Cost-Benefit Analysis tool
CCRA	Climate Change Response Act 2002
CERF	Climate Emergency Response Fund
CIPA	Climate Implications of Policy Assessment
COVID-19	Coronavirus disease 2019
CLC	Climate Leaders Coalition
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
CPAD	Capital Projects and Asset Development
DC	Direct current
DBC	Detailed Business Case
DFT	KiwiRail medium power, medium axleload legacy diesel locomotive.
DL Gen 1	First 20 DL diesel locomotives entering service 2011.
DL Gen 2	Second batch of 20 DL diesel locomotives entering service 2013.
DL Gen 2	Third batch of 8 DL diesel locomotives entering service 2015.
DL Gen 2.3	Fourth batch of 15 in 2018. First DL with modern brake systems.
DL Gen 2.3 (ii)	Fifth batch of 10. Equivalent to 2.3.
DM	New high power diesel locomotive on order from Stadler. 57 locomotives by 2026.
DTCC	MOT Domestic Transport Costs and Charges study
ECI	Early contractor involvement
EMD	Electro-motive Diesel (formerly General Motors, now Progress Rail)
EPA	Environmental Protection Authority
ESS	Energy Storage System
ETS	Emissions Trading Scheme
EY	Ernst and Young
FY	Financial year
GHG	Greenhouse Gas
HCV	Heavy Commercial Vehicle
HCV2b	A 9-axle HPMV, the most common HPMV, with access to most of the road network
HPMV	High Productivity Motor Vehicle
HPHE	High Performance High Engagement – model for engaging with workforce
HV	High Voltage
H2T	Hamilton to Tauranga (or Te Maunga) electrification
IBC	Indicative Business Case
IC, ICE	Internal combustion, internal combustion engine
ILM	Investment logic map

Abbreviation	Full Name
ILUC	Indirect Land Use Change
IMC	In-motion charging
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
IREX	Interisland Resilience Programme (new KiwiRail ferries)
$ktCO_2$-e	1000 tonnes carbon dioxide equivalent
kV	Kilovolt
kWh	Kilowatt hour
MBCM	Waka Kotahi's Monetised Benefits and Costs Manual
MBIE	Ministry of Business, Innovation and Employment
MCA	Multi-criteria analysis
MFE	Ministry for the Environment
MOT	Ministry of Transport
MW, MWh	Megawatt, Megawatt hours
NFDS	National Freight Demand Study (MOT)
NOx	Oxides of nitrogen (atmospheric pollutant)
NTK, ntk	Net Tonne Kilometre
NZ	New Zealand
NZTA	New Zealand Transport Agency, Waka Kotahi
NZTE	New Zealand Trade and Enterprise
OEM	Original Equipment Manufacturer
OLE	Overhead line electrification
P2H	Pukekohe to Hamilton electrification
PBC	Programme Business Case
PGB	Programme Governance Board
PM10	Atmospheric particulate pollutant size
RWF	Recommended Way Forward
SAF	Sustainable Aviation Fuel
SFC	Static frequency converter
SOE	State Owned Enterprise
STK	Single track kilometre
TOC	Total Ownership Costs
TSS	Traction substation
V	volt
VoR	Ministry of Transport's Value of Rail study (by Ernst and Young)
X-64	Conceptual battery locomotive, 4 powered axles
X-66	Conceptual battery locomotive, 6 powered axles
ZGHG	Zero Greenhouse Gas

REVISION HISTORY

Rev.	Revision Date	Details	Edited By
Preliminary Issue 1	19/05/23	Preliminary for KR Review	9(2)(a) - Privacy [redacted]
Issue 1.1	11th August 2023	First full Issue	[redacted]
Issue 1.2	28th May 2024	Feedback from peer review Updated economic analysis to align with Board approved locomotive strategy associated with existing fleet and updates to benefit rates from Waka Kotahi MBCM dated April 2023	[redacted]

APPROVAL FOR ISSUE

Role	Name	Organisation	Signature	Date
Project Director, Future Rail	9(2)(a) - Privacy [redacted]	KiwiRail	MM	19/05/2023
Project Director, Future Rail	[redacted]	KiwRail	MM	10/08/2023
Programme Director, North Island Investments	[redacted]	KiwiRail	WR	28/5/2024

1. Executive summary

1.1. Introduction and context

Rail transport is a lower carbon emitter than road transport per tonne kilometre now and likely will be in the future. If rail can achieve a higher freight mode share, this alone will lower supply chain emissions for New Zealand and enable KiwiRail to contribute to the Government's Emissions Reduction Plan freight target of a 35% reduction by 2035, even with the continued use of diesel locomotives.

But this would still leave rail creating GHG emissions, albeit fewer per unit of work than road. Rail's full contribution can be achieved only by full decarbonisation of its locomotives.

The objective of this report is to develop a credible and robust plan to reduce the carbon emissions produced by KiwiRail's main line locomotives in performing its freight task. Decarbonising rail freight locomotives will contribute to the country's target to reach net zero carbon emissions by 2050, which is required by the Climate Change Response Act 2002 ("CCRA").

Rail is fortunate in offering an immediate option, in the form of overhead line electrification, to begin decarbonising without waiting for other technologies or fuels to be developed.

Evaluating decarbonisation strategies for locomotives involves the integration of three significant analyses, the traffic levels to be carried in future, the technical choices that can be made on fuel and motive power, and the economic evaluation of these in conjunction with a practical plan for delivery.

Accordingly this study includes:

- A number of freight traffic scenarios and analysis of their impact on the railway's freight task. The most likely scenarios, apart from business as usual (BAU), involve removing current constraints to enable more traffic to be carried (5.5 billion ntkm, compared with BAU 4.1 billion), and the impact of assuming Ports of Auckland is not closed but rather constrained to its current level of activity (6 billion ntkm).
- A detailed evaluation of the potential fuel choices and motive power types, including the impact of future traffic scenarios on them, and a feasibility analysis of the most likely types.
- A discounted cash flow model of the preferred options under selected traffic scenarios, including the relative costs of the options, and their benefits from a national viewpoint (encompassing social and environmental benefits).
- A practical way forward towards transforming the railway and contributing to reducing the country's emissions

While aimed at the KiwiRail Executive and Board, to ensure rigor and meet the expectations of viewing agencies, the report follows the format of a Treasury Better Business Case Indicative Business Case (IBC) and has been tested against the Waka Kotahi framework. It covers how the investment will be procured, funded and managed, and the risks, both technical and process.

The report assumes that decarbonisation will be complete by 2050, in line with the CCRA, and focusses on the technology to do so. It does however propose accelerating this to 2040. Diesel performs well, despite not achieving ZGHG, but the focus of the report is on alternative technologies that do deliver ZGHG and it implicitly assumes that the government will take measures to ensure that ZGHG energy is economic relative to continued use of fossil fuels.

Of the broad range of options considered for zero carbon motive power, the two assessed as most likely to succeed are battery electric, and a mix of battery electric and overhead line electrification (OLE). A further three options, biofuels, hydrogen and system-wide OLE were considered alongside these but are not preferred. Neither were hybrid (electric – diesel) locomotives found to warrant further consideration. All of these options are analysed in depth.

1.2. Biofuel

The modelling ranks biofuels as financially the most competitive option for the next few decades (assuming mineral diesel is not in the mix). A key factor is the model assumes a standard duty cycle which needs two medium battery locomotives to replace one driven by liquid fuels[1], increasing costs. A second is that official curves are used for the future price of biofuel and there are considerations which are not yet reflected in these curves.

The study concluded that it will be very difficult to establish adequate local or imported supplies of acceptable 2nd generation or better biofuel from sustainable sources. The land use is significant, the technology is still developing and EROI is poor. If rail has other options, it is preferable to leave the limited biofuel supply to users who do not. Moreover biofuels remain an internal combustion fuel, and still create GHG emissions, albeit no net emissions. They also lack the transformative nature of a move to electrification.

Nevertheless the conclusion is that biofuels should remain for deeper consideration at later stages of the study, as a fall back against failure of the favoured options and to further reduce the emissions of any modern diesel locomotives retained until 2040.

1.3. Hydrogen

Hydrogen fuel cells had the lowest net benefit apart from OLE for all main lines and hydrogen is not proposed to be taken forward at this time. It has a lower energy density than diesel, so large quantities have to be carried on board (or more frequent refuelling is needed). It also requires very special provision and care in storage and handling, including on board the locomotive. The locomotive technology is complex and a long way from being developed. Internationally, it is being considered for freight routes much longer than those in New Zealand. These are routes that would be beyond the storage capacity of battery locomotives, and not warranting investment in OLE. A second decision window opens in the late 2030's, as today's new generation diesel locomotives come due for replacement or repowering. If the feasibility and economics of hydrogen has advanced there is the opportunity for reconsideration.

1.4. Electricity

Where possible, using electricity directly is preferred because it delivers three times the usable energy than using hydrogen produced by that electricity. The conclusion of this study is that NZ rail routes do not require an intermediate energy carrier like hydrogen. It appears viable to use electricity in locomotives directly thus electricity is the preferred means of powering future locomotives.

As well as being zero carbon, to the extent that the grid supply is renewable, using electricity will have a transformational impact on the railway, which internally combusted ZGHG fuels will not have.

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[1] A consequence of the lower energy density of batteries.

These include eliminating local air quality emissions, which have significant health impacts, reduced use of lubricating oil, reduced maintenance and the ability to minimise or avoid turn around servicing.

Electricity could reduce the railway's carbon emissions from main line locomotives, currently 112,000 t CO_2-e in 2022, to near zero by 2040.

1.5. Battery – electric locomotives

Overhead Line Electrification (OLE) is a known technology with few risks, and KiwiRail has a long experience with it. But as a national solution, the high capital cost of the required infrastructure makes it not viable as a system-wide solution for the relatively low density of traffic in New Zealand.

Battery locomotives on the other hand do not need such an investment, other than a more modest investment in chargers and the batteries themselves. The projected advances in battery locomotive technology are a game changer for lower density networks like New Zealand's, making electrification viable.

Battery locomotives are relatively simple technology, but so far not fully developed. The report assumes that there will be considerable technical progress in battery capacity, together with price reductions, that the electricity grid will support charging at locations that KR needs, and that manufacturers will have a high capacity locomotive available by 2028 for pilot operation, and more generally by the 2030s. It is not unreasonable to expect these issues to be solved but there is an element of risk in this selection requiring effort to resolve and, more importantly, time for the industry to evolve from prototype to production.

1.6. Conventional OLE

While system wide OLE is unaffordable and economically counterproductive, overhead electrification of key routes is not.

Infill OLE on the route sections Pukekohe to Hamilton (P2H) and Hamilton to Tauranga (H2T) delivers a continuous conventional electrified network Auckland – Hamilton – Palmerston North and Hamilton – Tauranga[2].

This solution, with battery on the rest of the network, was dearer than battery alone, although all three best options were reasonably close within the precision of the analysis.

But this cost analysis excluded the risks of and delay with battery technology, the imperative for early action and the opportunity offered to avoid investment in the existing legacy diesel locomotive fleet.

The segments recommended for OLE are key strategic routes carrying 46% of New Zealand rail freight traffic. Nearly half of New Zealand rail freight traffic would become directly powered by electricity, using conventional low risk technology. Under the studied growth scenarios up to 60% of all NZ rail freight could end up running on this wired network.

This could be achieved quickly, by around the end of this decade, while time was being allowed for battery technology to advance and for KiwiRail to gain experience in battery operation through a pilot scheme. This would also allow a locomotive fleet redeployment that removes some legacy diesel locomotives from service rather than investing in expensive life extension refurbishment. The

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[2] Hamilton to Pukekohe only 83 route km and Hamilton to Tauranga only 104 route km.

next stages of the business case will further explore the strategic case for extending OLE to these routes.

Most importantly, early progress would be made with shifting a significant proportion of the New Zealand rail freight task to ZGHG.

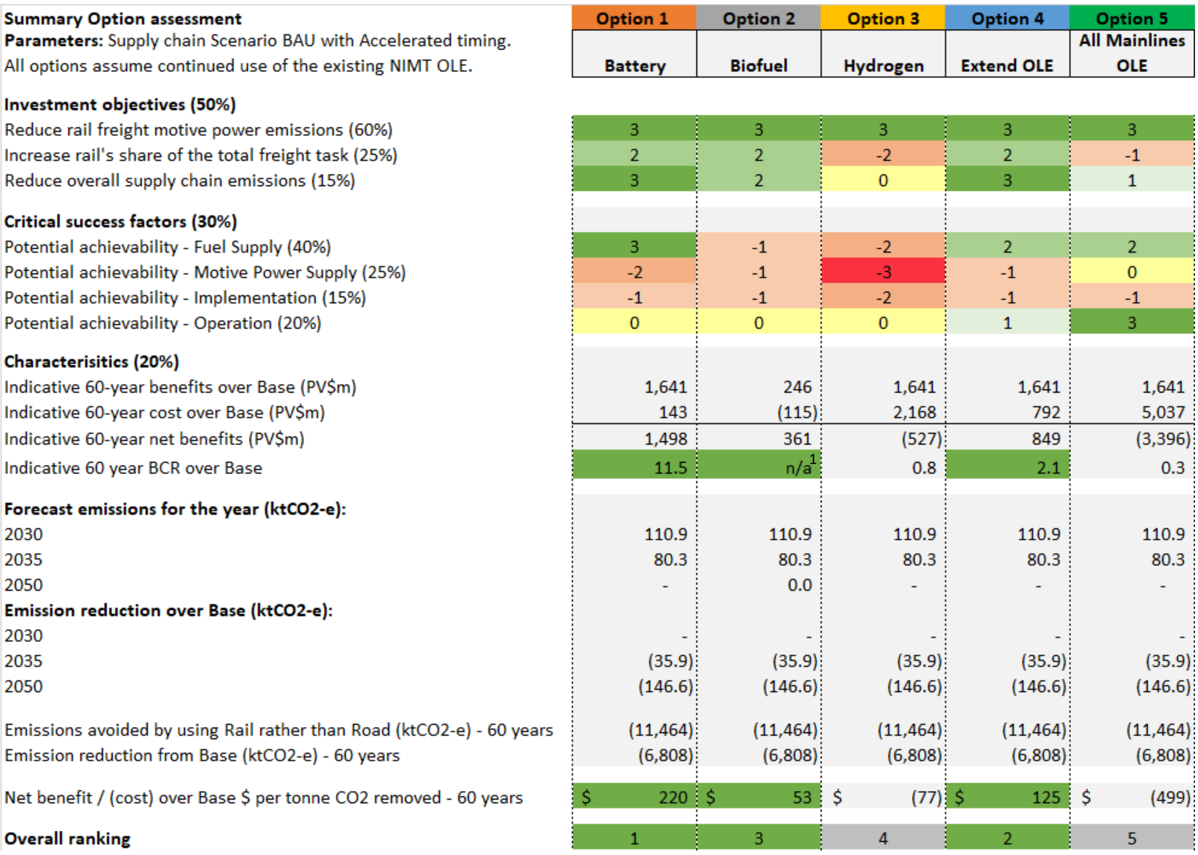
1.7. Diesel locomotives

KiwiRail is in the middle of a programme to replace its oldest diesel locomotives with new generation DM class diesel locomotives from Stadler Rail AG. While not offering ZGHG, these locomotives increase fuel efficiency and reduce emissions over legacy fleets without incurring the delay and risk incurred by the new technologies considered and recommended in this study. As such they contribute to the recommended programme for a staged reduction of locomotive GHG to zero by 2040.

The emission reductions from any shift of freight onto rail will be further improved by the use of higher efficiency conventional diesel locomotives. Therefore this study recommends that this diesel locomotive renewal programme be expanded, to displace further legacy locomotives, handle traffic increased by mode share shift and reduce emissions during the period of transition to ZGHG options.

1.8. Summary of Multi-Criteria Assessment and Economic Analysis

Table 1 summarises the results of the MCA and 60 year economic assessment using the Supply Chain Scenario BAU and Accelerated transition timing. Base is continued use of diesel and the existing Palmerston North to Hamilton Trunk OLE. Options 1 (Battery), Option 2 (Biofuel) and Option 4 (Extend OLE) have been short-listed to take forward to detailed business case. All three options scored highly in meeting investment objectives, with Options 1 and 4 also performing best from an achievability perspective. From an economic perspective all three options had an incremental BCR greater than 1.



Summary Option assessment **Parameters:** Supply chain Scenario BAU with Accelerated timing. All options assume continued use of the existing NIMT OLE.	**Option 1** **Battery**	**Option 2** **Biofuel**	**Option 3** **Hydrogen**	**Option 4** **Extend OLE**	**Option 5** **All Mainlines OLE**
Investment objectives (50%)					
Reduce rail freight motive power emissions (60%)	3	3	3	3	3
Increase rail's share of the total freight task (25%)	2	2	-2	2	-1
Reduce overall supply chain emissions (15%)	3	2	0	3	1
Critical success factors (30%)					
Potential achievability - Fuel Supply (40%)	3	-1	-2	2	2
Potential achievability - Motive Power Supply (25%)	-2	-1	-3	-1	0
Potential achievability - Implementation (15%)	-1	-1	-2	-1	-1
Potential achievability - Operation (20%)	0	0	0	1	3
Characterisitics (20%)					
Indicative 60-year benefits over Base (PV$m)	1,641	246	1,641	1,641	1,641
Indicative 60-year cost over Base (PV$m)	143	(115)	2,168	792	5,037
Indicative 60-year net benefits (PV$m)	1,498	361	(527)	849	(3,396)
Indicative 60 year BCR over Base	11.5	n/a[1]	0.8	2.1	0.3
Forecast emissions for the year (ktCO2-e):					
2030	110.9	110.9	110.9	110.9	110.9
2035	80.3	80.3	80.3	80.3	80.3
2050	-	0.0	-	-	-
Emission reduction over Base (ktCO2-e):					
2030	-	-	-	-	-
2035	(35.9)	(35.9)	(35.9)	(35.9)	(35.9)
2050	(146.6)	(146.6)	(146.6)	(146.6)	(146.6)
Emissions avoided by using Rail rather than Road (ktCO2-e) - 60 years	(11,464)	(11,464)	(11,464)	(11,464)	(11,464)
Emission reduction from Base (ktCO2-e) - 60 years	(6,808)	(6,808)	(6,808)	(6,808)	(6,808)
Net benefit / (cost) over Base $ per tonne CO2 removed - 60 years	$ 220	$ 53	$ (77)	$ 125	$ (499)
Overall ranking	1	3	4	2	5

Table 1: Summary Option Assessment

Over the 60-year forecast period rail saves NZ 11.5 million tonnes of CO_2-e, with 6.8 million of that enabled through adopting the recommended strategy outlined in section 1.9. Benefits from decarbonising passenger rail are likely but not assessed for the purposes of this IBC.

Figure 1 shows rail with its significant emission advantage over road is a low cost solution for NZ to decarbonise its heavy long haul freight. Rail's advantage is sustained through to 2060.

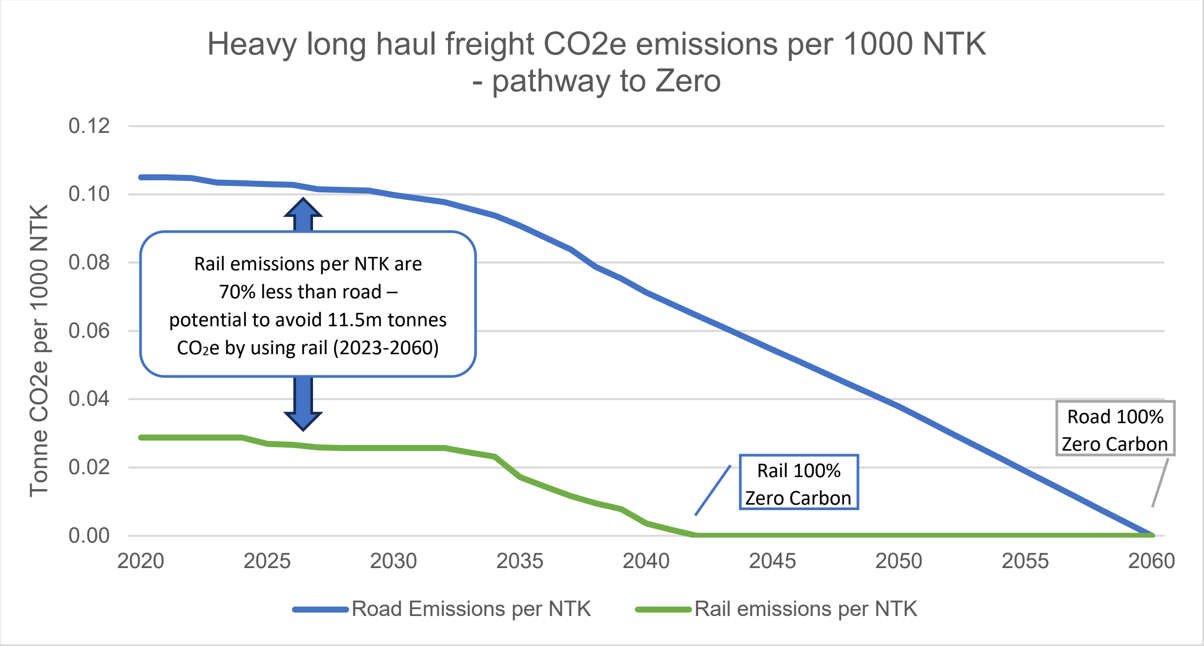


Figure 1: Projected heavy long haul freight CO_2 emissions per NTK road compared to rail over next 40 years

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[1] The biofuel option is lower cost than Base (diesel) leading to a negative BCR which is not meaningful. Greater weight is given to the net benefit / (cost) over base per Tonne CO_2e removed.

1.9. Recommended strategy

This study recommends a three front approach to mainline locomotive decarbonisation:

1. Navigate the transition by improved diesel operation

   Develop and run a mostly new build fleet of DM class diesel locomotives of the highest efficiency and performance on all non OLE routes until progressively displaced by battery electric locomotives during the 2030 – 2040 period. Retain a small fleet of upgraded lightweight legacy diesel locomotives to operate low axle load routes until this infrastructure is upgraded and free capital for DM loco purchase. Use biofuel or blends to further reduce GHG emissions, as/if these become available in the NZ supply chain.

2. Conventional electrification this decade for the busiest routes

   By 2030 extend the existing 25kV AC OLE networks to provide complete coverage of the Auckland – Hamilton – Tauranga and Palmerston North routes and enable operation by existing and new conventional electric locomotives. This initiative decarbonises nearly 50% of all KiwiRail freight traffic using proven off the shelf technology. Advance these projects methodically and cautiously, with a review before each increased level of commitment. Be prepared to adjust or abandon if battery locomotive technology has advanced such that the objective is better accomplished without or with less OLE.

3. Get ready for complete decarbonisation of the fleet 2030 - 2040

   Use the time made available by the above initiatives to allow battery, charging and battery locomotive technology to advance and to gain experience with battery locomotive operations. Use a small fleet pilot in 2027/28 to focus and drive this process. Begin progressive replacement of all remaining diesel locomotives with production battery locomotives from the early 2030's and complete by 2040.

This provides a flexible approach to mainline locomotive decarbonisation:

- Significant early guaranteed gains through improved conventional diesel locomotives
- Guaranteed route to ZGHG for nearly half of KiwiRail traffic by 2030
- Provides crucial time for battery locomotive option to reach maturity, for KiwiRail to gain experience and confidence before taking the final step to complete ZGHG operation 2030 – 2040, and provides the capacity for KiwiRail to accommodate mode shift growth as part of the national transport GHG reduction programme.

The report identifies that fully transitioning to electric locomotive propulsion will be a transformational change at least equalling the impact of the previous steam to diesel railway transition.

It should also be highlighted that the economic modelling shows there are positive overall benefits of rail regardless of the power mode. However, with New Zealand’s current cost and commercial settings, mineral diesel ranks relatively highly compared to other options. But remaining with the status quo of using mineral diesel does not deliver to the overarching objective of reducing greenhouse gas emissions. While this report models scenarios based on conservative/BAU volume scenarios, it also shows how policy and economic conditions would change the relative favourability of the decarbonised options.

The next phase of this decarbonisation work involves preparing a Detailed Business Case to further develop and consider a staged roll-out plan of the most effective and best electric solutions for our freight rail operations.

2. Decarbonisation of New Zealand's freight railway

2.1. Introduction

Rail carries an important share of the freight moved in New Zealand, especially over longer distances. It carries nearly 19 million net tonnes and produces over 4 billion net tonne kilometres[3] across its 3500km operationally active network. Use of the lines varies greatly**.** **Figure 2** shows the density of traffic on each line. Most traffic is concentrated in the Auckland-Waikato-Bay of Plenty "Golden Triangle', and to a lesser extent the line from Hamilton to Wellington.

Greenhouse Gas (GHG) emissions from transport are a significant part of New Zealand's overall GHG emissions[4]. To achieve the required drastic emissions reduction, New Zealand urgently needs a low emission supply chain. Diverting traffic from road to rail will give early gains towards that low emissions supply chain as diesel powered rail freight transport is already 70% more fuel efficient than road. On top of this, as set out in this study, rail can relatively readily decarbonise its freight locomotives, using existing technology, giving more gains, and do so more quickly than heavy road transport can decarbonise. Together, and with electric trucks for the "last mile", a worthwhile portion of the supply chain can be emissions free earlier than 2050.

The primary motive power source for rail freight in New Zealand is diesel, as it is for other freight modes. This IBC explains how rail can change its reliance on fossil fuels by investing in zero emissions mainline[5] freight locomotives to replace the existing diesel fleet. It uses different supply chain scenarios to test a range of motive power options. This investment proposal not only fits within KiwiRail's strategic intentions, but is vital in the wider context.

2.2. Business case format and approach

For rigor, this study follows the NZ Treasury Better Business Case Indicative Business Case (IBC) template and demonstrates how investment in the freight locomotive fleet can help New Zealand achieve its 2050 decarbonisation targets, beyond KiwiRail's existing commitment to a 30% reduction of its GHG emissions by 2030.

While not adopting the Treasury suggested Word document template, the Treasury defined purpose of each IBC section is set out in *italics* beneath main section headings to show that all the requirements of an IBC have been covered, somewhere. All material headings have been covered with only "potential business scope and key service requirements" omitted. These were not seen as completely relevant to this stage of the investigation.

There are three ways in which the analysis has been approached:

- MCA subjective evaluation
- Formal economic analysis
- Assessment of technical feasibility

These were then combined to inform a conclusion.

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[3] A net tonne kilometre is the movement over one km of one tonne of the freight being hauled

[4] Refer to section 3.1, https://environment.govt.nz/publications/new-zealands-greenhouse-gas-inventory-1990-2021/ and https://environment.govt.nz/assets/publications/Aotearoa-New-Zealands-first-emissions-reduction-plan.pdf

[5] 'Mainline' refers to locomotives hauling trains between loading and unloading points and excludes shunt locomotives or maintenance vehicles.

2.3. Some definitions

Within this document the term zero greenhouse gas (ZGHG) emission is used to describe propulsion technologies that are zero emissions at the point of use. For example, batteries, overhead electrification or green hydrogen that is produced without fossil fuels.

This definition does not include the emissions required to manufacture that propulsion technology, for example, batteries or overhead electrification. However supply chain emissions were considered as part of the MCA analysis. The economic analysis considered emissions from tank/meter to wheel and took account of the carbon intensity of grid supplied electricity.

Any emissions that cannot be eliminated are deemed residual emissions and would need to be offset for KiwiRail to be net zero carbon.

The terms “fossil diesel” and “mineral diesel” are used interchangeably in this report.

Finally, KiwiRail’s existing fleet of conventional diesel locomotives are, to be strictly correct, of the “diesel electric” type. In these the “electric” refers only to the drive system. The diesel engine drives a generator which in turn powers electric motors driving each axle. The electric component is only a way to practically transmit power in such a large vehicle, it has nothing to do with extra efficiency or using electricity to reduce emissions. All power is provided by a fossil fuel burning diesel engine. To avoid confusion with electric options that use electricity as the source of power we refer to the diesel electric locomotives as “diesel locomotives” from this point in the report.

The IBC conclusion is that KiwiRail should electrify its locomotive fleet using a combination of battery and conventional electric locomotives, along with a targeted extension to the existing overhead line electrification. Starting as early as 2028, this will put KiwiRail on a trajectory to reduce the emissions level to that of the national grid, potentially near zero, by as soon as 2040.

While this longer transition is under way, the new fuel-efficient diesel-electric locomotives currently on order will help increase fuel efficiency and reduce rail freight emissions, from their introduction in 2025. It is recommended that this order be increased, to further these early gains.

It is recommended the conclusions of the IBC be tested in more detail before final decisions are made to extend the overhead line, purchase and refurbish electric locomotives and confirm the battery

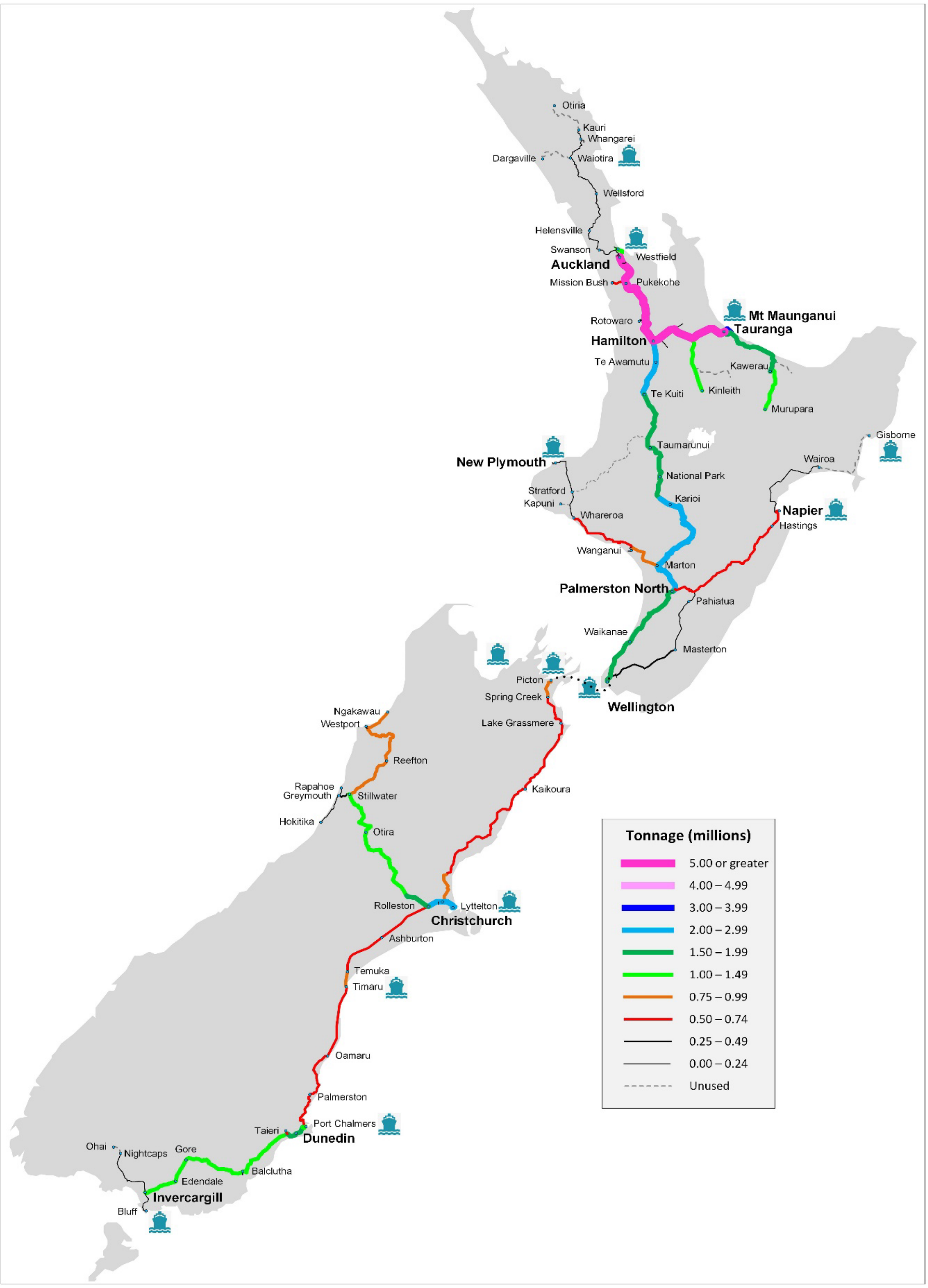

Figure 2: Density of freight movement on NZ's rail network (FY 2019)

3. Strategic Case

Why is this needed? What is the case for change and how does it provide strategic fit?

3.1. Emissions Reduction

Climate change is a threat, leading to higher temperatures, rising sea levels, changes in rainfall and wind patterns, and more frequent extreme weather events. The need for urgent action is accepted internationally. Reflecting this, the Zero Carbon Act commits NZ to net zero emissions (excluding biogenic methane) by 2050.

Transport is a major contributor to the production of carbon dioxide through the burning of fossil fuels such as diesel and petrol, contributing 18% of NZ's GHG Inventory (1990-2021). 91% of this was from road transport **(23% from trucks)**, and less than 1.6% from rail as captured in the 'Other' category. Diesel usage for transport continues to increase,[6] suggesting that truck emissions are also rising. During the period 1990-2021, road transport GHG emissions rose by 85.3%. By comparison, GHG emissions from rail and other modes were relatively constant. [7]

The small contribution rail makes to the problem is no reason to ignore opportunities to reduce its emissions. Removing nearly 10% of total freight emissions by decarbonising and using rail more is easier, cheaper and quicker to achieve, than just trying to decarbonise road freight.

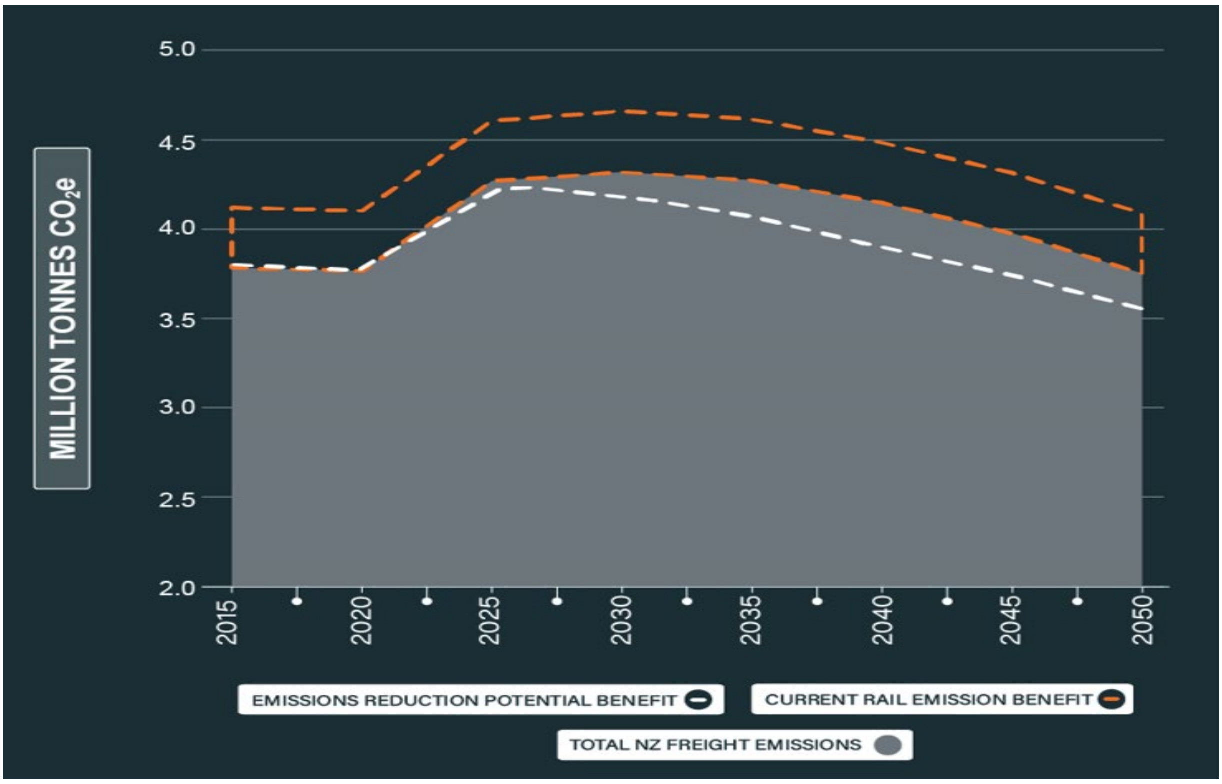

Figure 3: Emission reduction potential of rail freight

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[6] Ministry of Business, Innovation, and Employment, "Oil data tables - oil supply, transformation and consumption". (to December 2022).

[7] Ministry of Transport (2020), *Green Freight Strategic Working* Paper pp 16-17. Data based on Ministry for the Environment (2019), *New Zealand's Greenhouse Gas Inventory* 1990-2017.

3.2. Reducing emissions in the wider supply chain

Even though most domestic transport emissions come from cars, reducing emissions from trucks will still give significant gains. Nearly all trucks in New Zealand use diesel. Based on current projections for increased freight demand, with the light fleet electrifying, and without any new interventions, the share of emissions from trucks will grow, and they will be the main contributor to road transport emissions by 2055[8].

This is a worst-case scenario as there will be some reduction in GHG emissions as truck technology develops. However, progress is slow, and the road freight industry is unlikely to change until there is a cost effective alternative. In addition to increasing GHG emissions, the consequences of this increase include issues for road safety and high rates of wear across the road network.

In contrast to road freight, rail freight is inherently more carbon efficient. Even with its current locomotive fleet mix, rail generates 70% fewer carbon emissions per tonne-km than an equivalent journey by road[9].

Existing, proven technology allows rail to transition to zero carbon immediately through overhead line electrification on some lines. The IBC shows that investing in battery electric locomotives on other lines can reduce its GHG emissions to zero. These actions would require significant investment, but investment will be necessary if NZ is to meet its commitment to net zero. It will mean rail is essentially emissions free, compounding the gains that can be made from judicious freight transfer from road.

3.3. KiwiRail Locomotive Emissions

KiwiRail's 2022 financial year carbon footprint for Scope 1[10] and 2[11] emissions was 208,000 t CO_2-e. Over half were produced by locomotives, with the freight share 112,000 t CO_2-e. Freight locomotive emissions come from using 42 million litres of diesel each year.

KiwiRail's 2030 target is a 30% reduction in emissions (over 2012)[12]. Nationally, the target reduction for the freight sector is 35% by 2035, (over 2019) and 100% by 2050.[13] KiwiRail's 2050 target is also net zero emissions.

KiwiRail has recently committed to becoming a signatory member of the Climate Leaders Coalition (CLC). Meeting the minimum requirements of the CLC is likely to require toughening the 2030 30% target.

KiwiRail recognises that the ongoing use of locomotive diesel is unsustainable and has made a number of key strategic and operational decisions that move it towards achieving this emissions reduction goal. For example, KiwiRail has achieved a 23% improvement in fuel consumption (12-month rolling average) over the 8 years to June 2021 in its locomotive fleet, predominantly achieved through fuel saving initiatives such as optimising loads and timetables, and driver behaviour modifications.

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[8] MoT Green Freight Paper Fig 12

[9] The percentage is based on the emissions factors for road and rail.

[10] Scope 1 emissions are direct GHG emissions from operations that are owned or controlled by the reporting company

[11] Scope 2 emissions are indirect emissions from the generation of purchased energy consumed by a company (e.g. emissions from generating the electricity that KiwiRail buys externally

[12] Statement of Corporate Intent (2022-2024)

[13] See MfE Emissions Reduction Plan, p 172, also Climate Change Response (Zero Carbon) Amendment Act 2019 (now part of Climate Change Response Act 2002)

This improvement in efficiency over time is shown in **Figure 4**. These gains have been significant, but they start to level out by 2030. Importantly, efficiency improvements alone will not eliminate emissions.

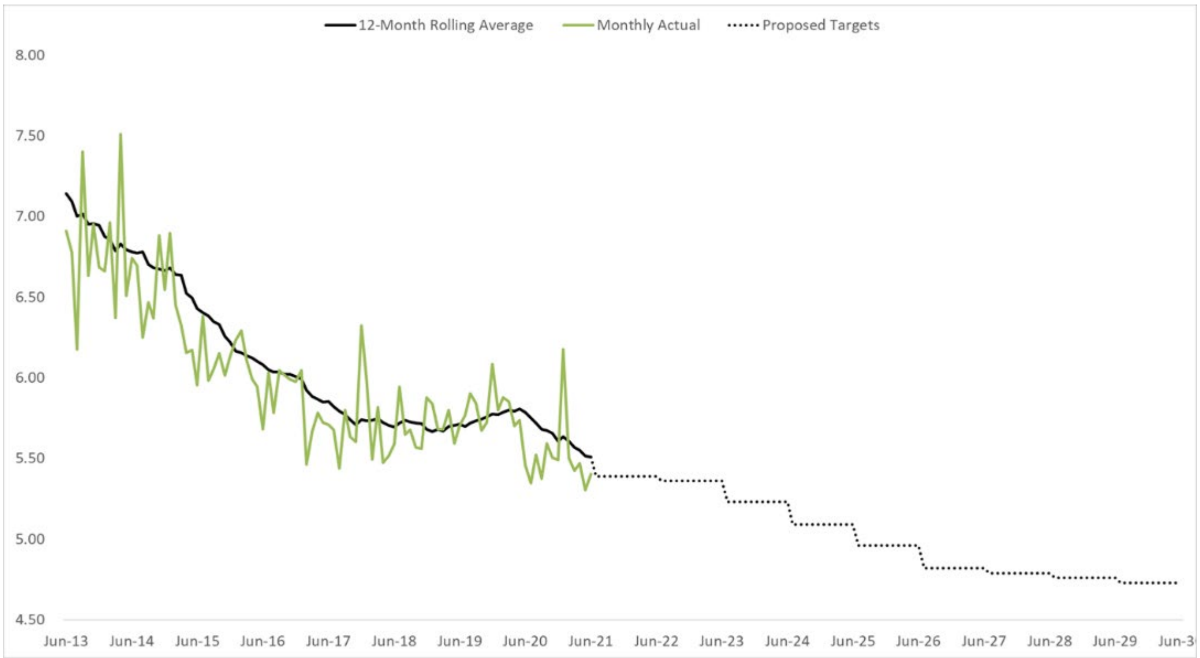

Figure 4: Change in fuel used per thousand gross tonne kilometres

KiwiRail's strategic investment decisions will make the greatest immediate difference to achieving the 2030 emissions reduction goal. Diesel-electric locomotive efficiency has improved over time, thus modern locomotives provide both improved fuel efficiency and decreased GHG emissions.

In line with this strategy, KiwiRail recently ordered 66 low-emission diesel-electric locomotives for the South Island and North Island from Stadler Rail AG, KiwiRail class DM. They are scheduled to be introduced from 2025 - 2027 and are projected to produce 20-25% fewer carbon emissions than the 1970s-era DX, DC and DF class locomotives they replace[14], as reflected in **Figure 4**.

However, KiwiRail is able to transition more quickly from reduced to zero emissions, if this becomes necessary. The relatively small number of locomotives with electric drive already standard, single ownership structure for rail and its freight locomotives and relatively consistent operating plans creates the unique opportunity for rail freight to transition quickly to new technologies. Investment decisions to achieve a low emissions supply chain can be made more quickly than is possible for the many owners and operators of the significantly larger road freight fleet which is also dependent on third party energy infrastructure.

Taking the initiative will help achieve government's GHG reduction goals, and will contribute to key national, regional, sector and organisational strategies and commitments such as the Ministry of Transport's *Transport Emissions - Pathways to Net Zero by 2050*.

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[14] This is a combination of improved drive train efficiency, engine automatic idle shut down, improved driver advisory aids and further operational efficiency gains.

3.4. Interaction with key stakeholders

The Communications and Engagement Plan, available from KiwiRail, includes a list of all stakeholders engaged as part of the development of this IBC, the engagement approach for each and details of engagement undertaken throughout the business case process. Of these, the project team[15] have actively involved key stakeholders MBIE, MoT, Waka Kotahi, Treasury, MFE, and the EPA in the development of this business case.

Key stakeholders and some targeted organisations participated in a number of workshops and meetings.

- Problem Definition workshop (August 2021). Stakeholders confirmed the problems, benefits, and strategic alternatives. There was a high level of agreement that the scope should include KiwiRail's contribution to a low emission supply chain, as well as a focus on reducing KiwiRail's emissions from the rail freight fleet.
- Long List workshops (November 2021). Stakeholders confirmed the case for change, provided feedback on the scope and content of draft Supply Chain Scenarios, identified a motive power long list of options and discussed project interdependencies, risks and uncertainties.
- Emerging Preferred Option workshop (September 2022). Stakeholders provided feedback and views on the preferred option and highlighted any risks and opportunities.
- Freight and ports – there were a number of targeted meetings with representatives from the distribution and transport sector, Ports of Auckland and Port of Tauranga through the second half of 2022. These were led by KiwiRail and explained the overall business case process and emerging options. Feedback was specifically sought on the assumptions that the team had developed relating to the likely rate of decarbonisation of the heavy vehicle fleet.
- Suppliers – Meetings during 2022 with international and national locomotive and prime mover suppliers[16] helped the team understand the feasibility of different motive power and locomotive options.

Overall, the stakeholders and the logistics sector indicated support for the preferred option. The freight forwarding sector were generally enthusiastic about KiwiRail's plan and thought it would add value and be an attractive proposition for long haul freight trips.

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[15] The project team comprised staff from KiwiRail, Stantec, and independent consultants Murray King, Richard Paling and KSP Consultants.

[16] Diesel engines.

3.5. Investment Objectives, Existing Arrangements and Business Needs

This section explains the existing arrangements and what KiwiRail is seeking to achieve (business needs). Investment Objectives represent the case for change – the gap between existing arrangements and future business needs.

A facilitated Investment Logic Mapping workshop was held in August 2021. Its purpose was to define the key problems, identify strategic alternatives and identify the benefits of investment.

Figure 5 shows the business purpose of this IBC, the problems constraining KiwiRail from achieving that purpose and the benefits that would be realised if the problems were addressed.

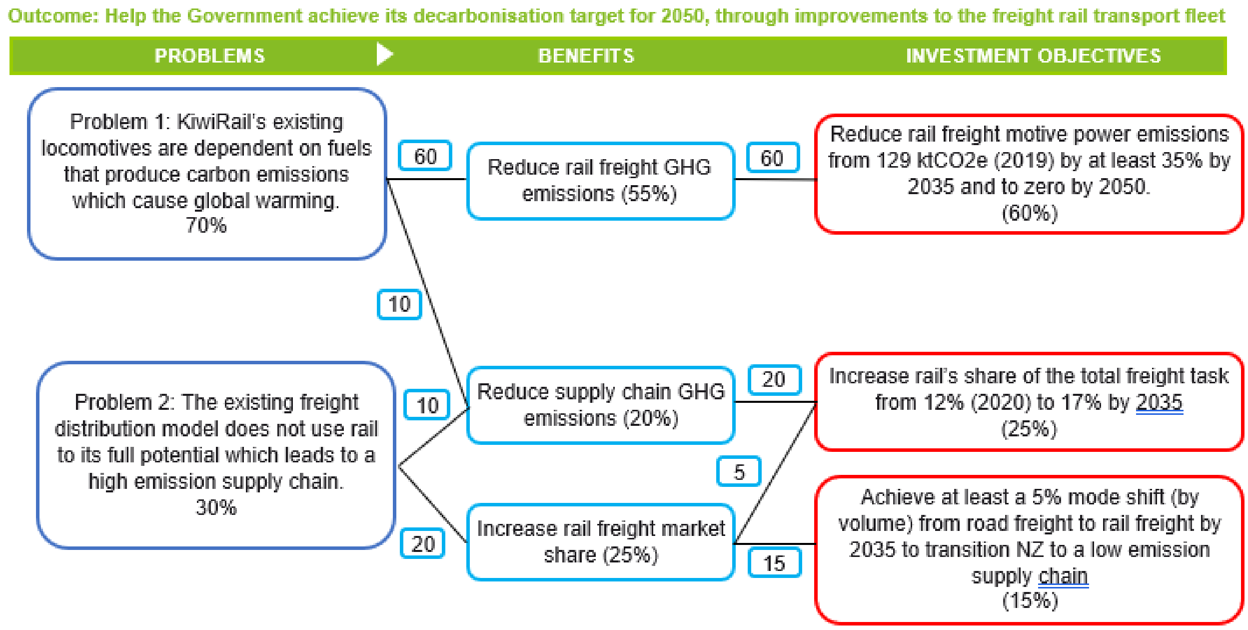

Figure 5: Investment Logic Map[17]

An analysis of the causes and effects for Problem 1 is shown in Table 2 and for Problem 2 in Table 3. Investment Objectives are set out in Table 4.

KiwiRail's existing locomotives are dependent on fuels that produce carbon emissions which cause global warming.	
Cause	**Effect**
• Historic reliance on low-cost fossil fuels • Historic investment in diesel locomotives that have a long service life • Level of investment required to change to low emissions power • Lack of proven alternative carbon free locomotive fuels	• Locomotives continue to run on diesel which releases carbon emissions (as well as creating other damaging pollutants e.g., particulates) • NZ continues on a trajectory towards runaway global warming • Uncertainty about future motive power options • Emissions reductions gained by increasing rail freight mode share will be undermined if rail freight continues to be reliant on fossil fuels

Table 2: Analysis of Problem 1

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[17] Note that some of the CO₂e numbers used in different stages of the study relate to different base years. Note also that % totals in centre column are wrong. 55 should be 60 and 25 should be 20. Unable to fix until original obtained.

The existing freight distribution model does not use rail to its full potential which leads to a high emission supply chain.	
Cause	Effect
• Long term investment in improving road transport relative competitiveness, including road improvements and vehicle mass increases • Many freight customers currently rely on just-in-time inventory management • Historically low price of fossil fuels • Externalities e.g., price of carbon, not previously considered in commercial decisions • New Zealand’s low population density, relatively short haul distances, distributed markets and large numbers of ports favour road freight	• Competitive advance of road transport relative to rail • High numbers of heavy trucks and reliance on road transport as part of the current supply chain systems • Demand for time critical freight delivery • Continued high emission supply chain, as road freight is not yet ready to transition to low emission power sources • Supply chain is not making best use of existing low emission modes (rail and shipping)

Table 3: Analysis of Problem 2

The problem statements and benefits were used to develop a set of three investment objectives, as shown in **Table 4**. Investment Objectives define the purpose of any investment to address the problems and realise the benefits. They define the investment required to transition from existing arrangements to future business needs (the case for change). Evidence is presented in support of each Investment Objective in Sections 3.5.1 to 3.5.3.

Investment Objective 1	**Reduce rail freight motive power emissions from 129 ktCO$_2$-e (2019) by at least 35% by 2035 and to zero by 2050**
Existing Arrangements	Mainline rail freight motive power is provided by 184 locomotives, approximately 95% diesel-electric locomotives The rest are electric freight locomotives operating between Hamilton and Palmerston North. In FY2022 emissions from the freight locomotive fleet were 112,000 t CO$_2$-e, making up 54% of KiwiRail's overall emissions. KiwiRail have started to reduce emissions through a) purchase of more efficient locomotives b) driver education and behaviour programs to improve fuel consumption efficiency, and c) refurbishment of electric locomotives
Business Needs	KiwiRail's Statement of Corporate Intent commits to 30% reduction in emissions by 2030. The Climate Change Response Act commits New Zealand to net zero by 2050. KiwiRail needs to rapidly reduce motive power diesel use, to help NZ transition to zero emissions. The Climate Change Commission has recommended a freight mode share shift from road to rail as a contribution to achieving NZ's emissions reduction goal.
Investment Objective 2	**Increase rail's share of total freight task from 12% (2020) to 17% by 2035 and maintain the share at 17% to 2050 (despite market fluctuations)**
Existing Arrangements	KiwiRail estimates it currently carries approximately 12% of the total freight task (net tonne km) with road freight 70% and the balance by coastal shipping. Road freight is a high energy intensity and high emissions mode, which means NZ has a high emission supply chain.
Business Needs	KiwiRail can increase total freight task share, moving NZ towards a lower energy intensity, lower emission supply chain (even with existing diesel operation for the first decades of transition). This will help achieve NZ's emissions target. A greater freight task may reduce the payback period of any investment in low emissions motive power.
Investment Objective 3	**Achieve at least a 5% mode shift (by volume) from road freight to rail freight by 2035 to transition NZ to a low emission supply chain**
Existing Arrangements	NZ currently has a high emission supply chain, relying heavily on diesel trucks. Trucks are not yet ready to transition to low/zero emission fuels. KiwiRail and others have started to invest more in inter-modal hubs for freight consolidation, thus creating the scale required to make rail a more cost effective solution, lowering the overall cost of the supply chain.
Business Needs	Using all modes to their strengths would mean a larger rail mode share. This will facilitate an early transition to a lower emission supply chain, which will help the country achieve its emissions targets. The resulting freight task on rail will enable investment under (1) above to become economic more quickly and reduce payback periods. More hub interchanges to facilitate transfer between road and rail. More competitive service – improving quality and lowering the overall supply chain price

Table 4: Investment Objectives

3.5.1. Investment Objective 1: Reduce rail freight motive power emissions

In the first half of the twentieth century, New Zealand Railways (NZR) carried more than six million tons of freight per year across a national rail network spanning over 5,500 km. Despite deregulation of distance limits in the 1980s, the overall trajectory of traffic levels has been growth, apart from the immediate period following deregulation. Recent traffic levels have been the highest ever.

Well-designed locomotives have long working lives and, with judicious upgrades, can remain in service for over 50 years. Some KiwiRail mainline locomotives entered the fleet as long ago as 1972[18]. 57% date from before the mid-1980s. The efficiency of fuel use is determined by a number of different factors, including the age of the basic technology. These early locomotives use older (legacy) technology.

The long life of locomotives means that motive power investment decisions made today may generate GHG emissions well into the future. Locomotive investment decisions therefore need to be flexible to enable cost effective upgrade/conversion or disposal.

Electricity[19] is already a known and proven low emission motive power. KiwiRail has 15 main line electric locomotives[20] and is refurbishing them. There is ongoing research and development into other potential low emission motive power sources and fuels, including for rail freight. These are discussed in more detail in section 6. Some of these lack technological maturity or an established supply industry and, as a consequence, suffer low or inconsistent market demand.

3.5.2. Investment Objective 2: Share of the Freight Task

New Zealand moves a variety of freight, including:

- Semi-finished components moving between manufacturers.
- Finished products moving from distribution centres to retail outlets and consumers.
- Movements to support household activities, including transport of waste, household deliveries and removal services.

The updated MOT National Freight Demand Study 2017/18 (NFDS) estimated that New Zealand moved approximately 280 million tonnes of freight in 2017/18. This was an increase of approximately 18% compared to 2012. The NFDS showed that manufactured and retail goods made up the greatest volume of freight moved within New Zealand - more than forestry and dairy combined, although much of the manufacturing and retail moved only short distances. Much of this volume was concentrated in the Upper North Island and around the key ports at Auckland (a key import port and distribution centre) and Tauranga (a key export port).

Most freight is transported by trucks, with relatively smaller quantities by rail and coastal shipping, although rail dominates in some key commodities. **Figure 6**[21] shows the percentage of freight tonnage by mode and net tonne-km by mode. It highlights the current dominance of road freight.

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[18] Some are remanufactured from a 1960's origin. DC locomotives – slated for withdrawal.

[19] As the primary onboard energy source, as opposed to simply being used as the transmission in diesel-electric locomotives.

[20] And electric haulage of freight trains is celebrating its 100th year in New Zealand this year (4th August 1923). Refer to Figure 12. 15 surviving of an original 22 EF locomotives from mid-1980's. Two further units survive in stripped condition.

[21] Ministry of Transport (2020) *Green Freight – Strategic Working Paper*, p11

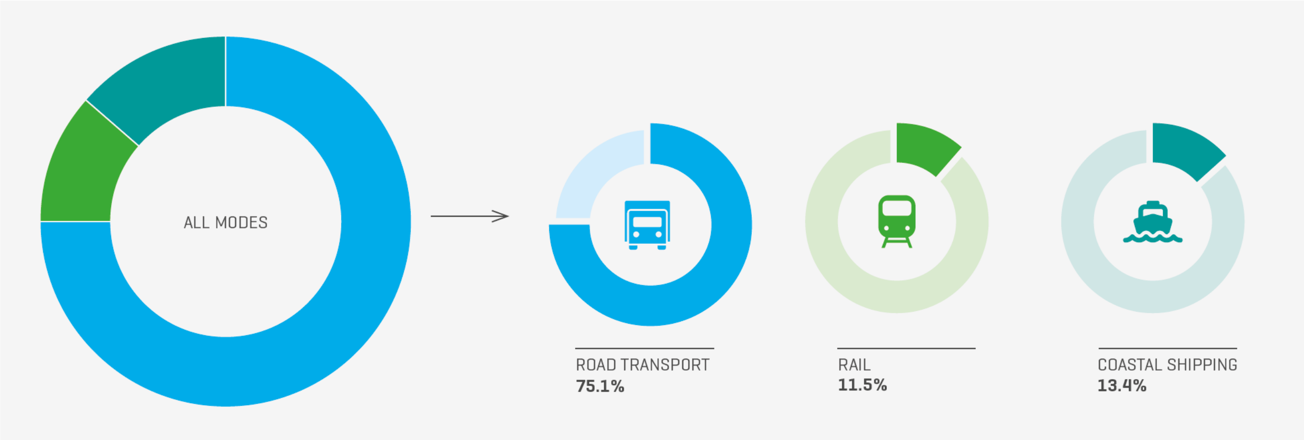

Figure 6: New Zealand's Domestic Freight Net Tonne-Km by Mode (2017/2018)

The NFDS 2017/18 projected New Zealand's freight task could increase substantially in the period to 2042/43, to 366 million tonnes. This increase is driven by population growth and demand for New Zealand goods (both domestically and internationally)[22]. More recent variants of the same model predict an increase from 280 m tonnes in 2017/18 to 411m tonnes in 2052/53, driven mainly by growth in demand for building materials and for manufactured and retail products linked to economic growth, but with relatively little growth in the flows of primary agricultural products.

KiwiRail can increase its share of the freight task now. **Figure 7** represents the total freight market as a task and breaks that down to understand KiwiRail's potential freight mode share. The extent of the rail network limits the market share that is available to KiwiRail, and some areas of the network that also carry urban passengers are operating at or near capacity. However, **Figure 7** also illustrates that the potential market share available to KiwiRail is much greater than its current freight activity, and that KiwiRail has capacity now to move more freight on its existing network today.

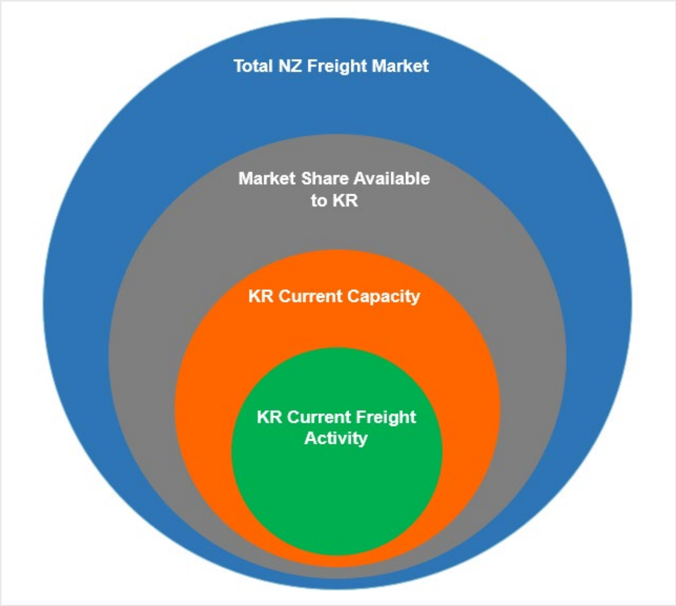

Figure 7: Total freight market relative to KiwiRail potential (not to scale)

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[22] This study does not address whether such increases in production and consumption are sustainable, or are compatible with achieving ZGHG.

3.5.3. Investment Objective 3: Supply Chain Emissions

The domestic freight system is varied and complex. Transport companies compete across road, rail, and coastal shipping, and may have a distribution/freight forwarding component to their business. Warehouses and distribution centres are dispersed across NZ, although strongly concentrated in Auckland. Many are only served by one mode of freight transport (road). Distribution centres that are concentrated and developed around a multi-modal freight system allow the best mode to be selected, not just road. To support freight mode shift and ensure transport integration with other modes, KiwiRail's container transfer sites, investment in regional hubs adjacent to the rail corridor (such as at Palmerston North) and use of existing KiwiRail owned land already connected to the network, will be invaluable.

Figure 6 above shows the percentage of freight tonne-km by mode. This highlights the dominance of road freight. As noted in section 3.1, road freight is the significant source of transport GHG emissions, with heavy vehicles producing 23% of NZ's domestic transport GHG emissions. **Table 5** shows just how much difference a shift from road to rail could make to emissions – rail produces the least emissions of any transport mode for moving freight.

Mode	Fuel Consumption (litres/ ntk)	GHG/ ntk (kg)	GHG Costs/ntk (c)
Road (HCV)	0.0375	0.118	1.1
Rail	0.0123	0.036	0.3
Coastal Shipping	0.0551	0.173	1.6

Table 5: Comparison of Fuel Consumption and GHG (CO_2-e) by Mode (Freight).[23].

The transport network has developed to accommodate trucks as the dominant freight mode. The extensive state highway network (approximately 11,000km in the North Island and 5,000km in the South Island) is consistently maintained and upgraded through significant and coordinated local and central government investment. Over half of the state highway network has now been deemed available for high productivity motor vehicles (HPMVs), and all of it for the 50-tonne "50 MAX" type.[24]

The movement of freight by road has been steadily increasing since 1993. Policy decisions have favoured road over rail, making road more competitive. For example, HPMVs, introduced in 2010, were promoted as enabling fewer trucks to carry the freight on offer. However, the number of trucks has steadily increased since, in part because the increased weight made trucks more competitive for some freight that would otherwise have moved by rail or sea. Ongoing investment in roads is an enabler of the road freight sector and contributing to reducing the market share of other modes.

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[23] Source: Draft DTCC Working Paper D4: Air quality and greenhouse gas emissions. Well to wheel basis, including maintenance and shunt operations. Input data for rail corrected. HCV= >10t gross.

[24] HPMV's are trucks permitted to exceed the standard 44t gross weight limitation, The principal type is the "50 Max" 50 tonne maximum gross combination weight trucks which have near universal running rights,

The relatively high number of seaports across New Zealand – 13 in total - also helps explain why road freight is so dominant. They are located relatively close together, with seven in the North Island and six in the South Island. The ready accessibility of ports makes road transport a highly convenient choice, as short haulage of freight is often more cost competitive on road. But this historic land use pattern is increasingly problematic in many urban areas, where traffic congestion, particulate matter from emissions, noise and road safety issues come from large numbers of heavy road freight movements through communities to these ports. This is especially acute in Auckland.

Freight journeys by road tend to be relatively short and localised, on average only 111km. 78% of all freight (tonnes) stays within the originating region, and an additional 14% is transported to an adjacent region. Road is generally more competitive than rail or coastal shipping for this type of short-distance freight. Only a small percentage of freight travels long distances or “long-haul”, and there is relatively little movement of freight by road between the North and South Islands, only 1% of total tonnes.

Road freight generally has the “last mile” advantage, driven by consumers demanding door-to-door service. KiwiRail’s current strength is moving large volumes and heavy volumes over long distances, but real opportunities exist if rail can become more agile and responsive, particularly at the inter-regional scale. **Figure 8** shows the growth in the commodities to 2052-3. Some of these commodities are more attractive to rail than others, and not all flow inter-regionally. Overall the inter-regional freight task presents rail’s greatest opportunity.

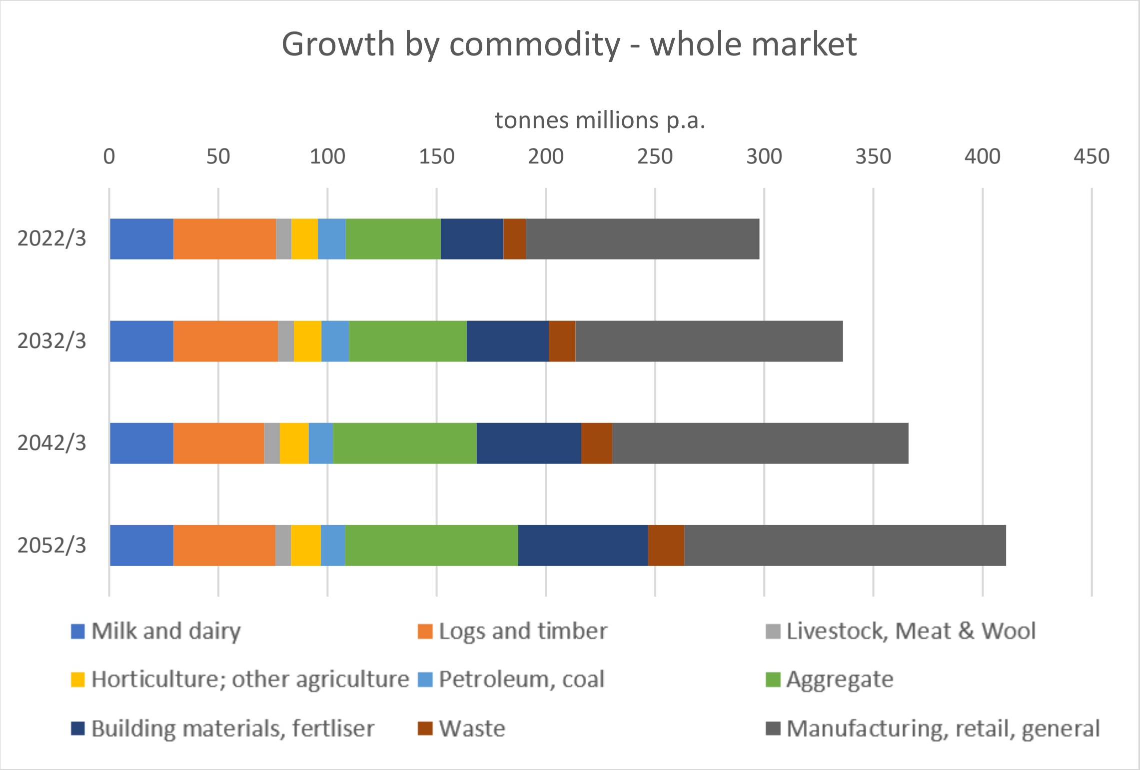

Figure 8: Growth in overall market, by commodity[25]

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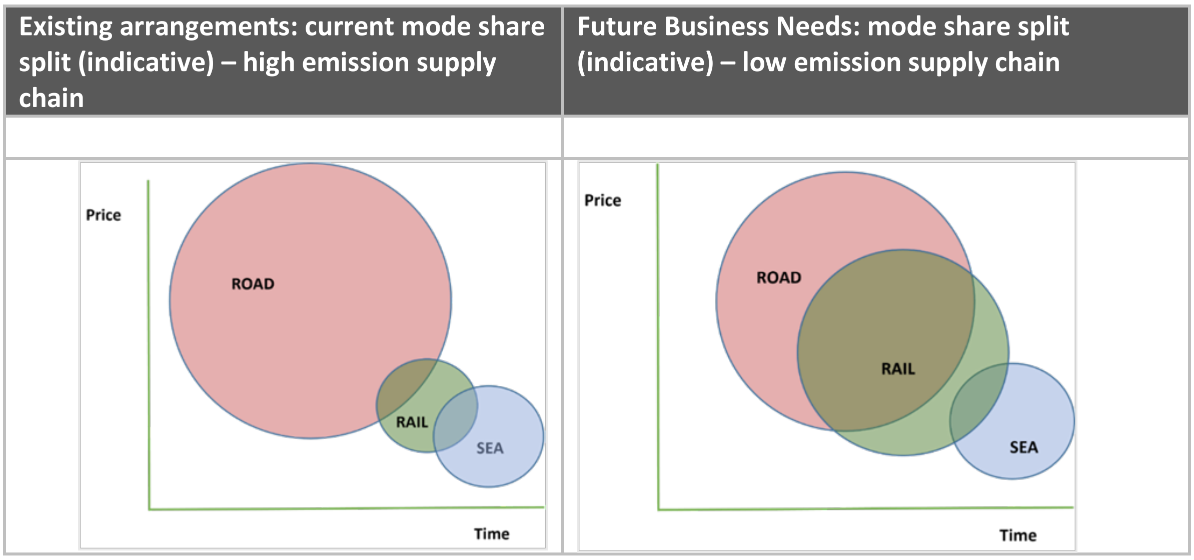
[25] Source: MOT Freight Futures Model, as updated for this study

Most respondents in MOT’s 2010 study *Understanding Transport Costs and Charges* said they favoured road transport due to its flexibility and timeliness. Time-sensitive, refrigerated, and dangerous goods can be moved door-to-door and on-demand to almost any community. Quantity of goods, cost efficiency and the distance of travel also drive freight transport decisions. So too does the absence of social and environmental costs in quoted rates.

In contrast, the *Valuing Freight Transport Time and Reliability (2020)* study undertaken for Waka Kotahi found that time sensitivity was largely a feature of manufacturing and retail only. This reflects the tendency of these sectors to operate Just-In-Time inventory management. An overall slowing of the supply chain is positive for rail, as rail has, in general, a slower overall transit speed than road.

However, the COVID-19 pandemic subsequently exposed major supply chain vulnerability within New Zealand and around the world. In April 2021, New Zealand Trade and Enterprise (NZTE) indicated that businesses could no longer assume products would flow to markets and customers with ease, at the lowest cost. Commentators are increasingly noting a shift from ‘Just in Time’ to ‘Just in Case’, as companies begin ordering early and holding more stock. The domestic freight system is vulnerable to external effects such as driver shortages or fuel price increases. Centralised distribution is also problematic, particularly when border closures or international shipping changes reduce product availability.

The MOT 2010 study also found respondents were keen to increase the use of rail and coastal shipping, wherever possible, if the reliability of these services improved and freight rates became more competitive. KiwiRail’s interpretation of this scenario or shift in freight mode preference is graphically shown in **Figure 9**. Changes to price and time (including recognition of social and environmental costs) could reduce road freight mode share in favour of rail and increase the area of competition between the two modes.



Existing arrangements: current mode share split (indicative) – high emission supply chain

Future Business Needs: mode share split (indicative) – low emission supply chain

Figure 9: Existing arrangements and future business needs

3.6. Main Benefits

The benefits and disbenefits of investment were discussed with stakeholders. These are presented in **Table 6** using the Treasury Living Standards framework, which requires the approach to benefit identification and measurement to be prudent, proportionate and appropriate.

The most important benefits are those (20%) that are likely to provide the greatest (80%) value. Benefits build on and further integrate with those identified at the ILM workshop. Requirements under the Climate Implications of Policy Assessment (CIPA) are also included. More detailed benefits analysis will be undertaken in later business cases.

The primary benefit of investing in a low emission motive power for rail freight is that it will reduce emissions for KiwiRail's existing task. Additional benefits are likely to reduce KiwiRail's exposure to price shocks for fossil fuels and make rail a more attractive mode for those wanting a 'green' option for freight transport (assuming road freight is not able to achieve this as quickly or as completely as rail).

The other benefits are those which arise from a road to rail mode shift. This business case will demonstrate how increased use of rail could help to achieve a lower emissions supply chain. Policy shifts and infrastructure improvements could enhance the reduction. These need to be further evaluated by a specific study led by MOT.

The motive power options have been tested using different percentages of mode shift (using a set of different possible supply chain scenarios), as the amount of freight carried will influence the timing for viability of different motive power options. The wider benefits flowing from different scenarios are therefore also important for the overall business case. To some extent, this study's understanding of the full benefits is limited by lack of information on these benefits. Third parties may have to supply the information needed to quantify these.

Domain	Benefit	Direct/ indirect	Qualitative/ Quantitative	Monetised / non-monetised
Environment	Reduce KiwiRail's freight GHG emissions, through transition to low emission power source for locomotives.	Direct and indirect	Quantitative	Monetised
	Reduce supply chain emissions: By increasing rail freight market share.	Direct and indirect	Quantitative	Monetised
	Reduce road congestion: shifting freight to rail and reducing truck numbers	Indirect	Quantitative	Monetised
Health	Improve road safety: By reducing the number of heavy road vehicles	Indirect	Quantitative	Monetised
	Improve local air quality: By reducing the number of diesel trucks in populated areas.	Indirect	Quantitative	Monetised
	Reduce noise: By changing motive power/fuel for locomotives	Indirect	Quantitative	Monetised
Other benefits (not part of Living Standards Framework)	By reducing the number of heavy vehicles, reduce investment in new roads and allow maintenance spend to arrest the deterioration.	Indirect	Quantitative	Monetised
	Reduce exposure to diesel price shocks and rising fossil fuel prices as result of carbon pricing: By reducing KiwiRail's reliance on fossil fuels.	Direct	Qualitative	Monetised

Table 6: Benefits of investment applying Treasury Living Standards framework

The Investment Objectives, Benefits and Key Performance Indicators (KPIs) are set out in **Table 7** below.

Investment Objective	Benefits	Key Performance Indicator
Reduce rail freight motive power emissions from 129 ktCO$_2$e (2019) by at least 35% (2035) and to zero by 2050	• Reduce rail freight emissions • Reduce exposure to rising diesel price	KPI 1: Decrease emissions by rail per NTK KPI 2: Decrease carbon emissions by land freight transport
Increase rail's share of total freight task from 12% (2020) to 17% by 2035	• Reduce supply chain emissions • Reduce road congestion • Improve local air quality • Improve road safety	KPI 1: Increase total freight volumes by rail KPI 2: Increase rail freight revenue KPI 3: Decrease total heavy road freight volume KPI 4: Increase overall rail market share
Achieve at least a 5% mode shift (by volume) from road freight to rail freight by 2035 to transition NZ to a low emission supply chain		KPI 5: Increase distribution of supply chain activity across the country KPI 6: Improve air quality in centres KPI 7: Reduce number of deaths and serious injuries from crashes involving trucks KPI 8: Decrease energy/cost per NTK

Table 7: Investment Objectives, Benefits and Key Performance Indicators

3.7. Main Risks

This section sets out the top risks, with a focus on achievement of outcomes and benefits. These are summarised in **Table 8** below. Risks were initially identified at the long list workshop. A more detailed risk management strategy for these, and other risks identified throughout the business case will be developed as part of any follow on business case phase.

Risk	Consequence (H/M/L)	Likelihood (H/M/L)	Mitigation
Market share and fuel supply risks			
Competition for rail capacity when demand for rail freight and passenger rail is increasing.	**H**	**H**	All fixable by careful investment. Collaborate with the Auckland Rail and Greater Wellington PBC teams to share knowledge, information, and infrastructure constraints. Consider joint infrastructure application to increase rail capacity.
Commercial drivers for KiwiRail may limit what is achievable in terms of investment in low emission alternative power sources for locomotives.	**H**	**H**	Discuss options with MOT and Treasury early, regarding traditional economic viability vs wider benefits of early emission reductions for NZ. Seek policy changes so social and environmental costs are recognised.
Changing political aspiration/appetite for investment in rail or other modes.	**H**	**M**	Work closely with MOT particularly in developing the National Supply Chain Strategy during 2023.
Uncertainty with future energy supply options for road and rail, including rate of decarbonisation in road freight.	**H**	**M**	Monitor changes overseas and in NZ and ensure information is up to date.
The public/stakeholder appetite for supply chain change may be limited.	**H**	**M**	Careful consideration will be given to a communications strategy so that consumers can understand the benefits of increased rail mode share.
Carbon pricing may result in wider economic impacts, such as more expensive products, which could lead to reduced consumption, or more local production, both of which will reduce freight carried.	**H**	**M**	KiwiRail will closely monitor this. Investments that benefit passenger rail as well as freight will build resilience for KiwiRail if consumption patterns decrease.
Changes to the product mix away from those supply driven commodities where rail is a competitive transport option.	**M**	**M**	Ensure analysis does not focus only on supply driven commodities and take proper account of rail's competitive position across demand driven commodities

Risk	Consequence (H/M/L)	Likelihood (H/M/L)	Mitigation
Technology risks			
The improvements forecast in (battery) economics are delayed. The electricity network struggles to support charging of locomotive scale batteries.	**H**	**M**	The proposed overhead line electrification of two infill routes decarbonises nearly 50% of NZ rail freight traffic using proven technology, allowing time for developing solutions to mature for use on remaining lines.

Table 8: Key Investment Objective Risks

3.8. Key Constraints, Dependencies and Uncertainties

The proposal is subject to the constraints, dependencies, assumptions and uncertainties in **Table 9**:

Constraints		**Notes**
C1	Extent of the rail network	Parts of NZ are not accessible by rail, i.e. Nelson and (currently) Gisborne, making those markets not easily available to rail.
C2	Extent of existing electrification	Limits use of fully electric locomotives for freight to the 409km between Hamilton and Palmerston North.
C3	Network capacity	Impacts the total freight market available to KiwiRail. Increased demand for passenger rail services will increase competition for access to constrained rail networks. Some urban lines are at or near capacity now.
C4	Reliability and congestion at Container Transfer sites	Delays deter customers from using rail.
Dependencies		**Notes and Management Strategies**
D1	Auckland Rail PBC	This covers long term metro rail plans for Auckland. KiwiRail and Auckland Transport (AT) are partners and there is two-way flow of knowledge and information between the two projects.
D2	Wellington Regional Rail Plan PBC	PBC covers long term metro rail plans for Wgtn. Needs systematic stakeholder engagement with its sponsors to ensure two-way flow of knowledge/information.
D3	National Supply Chain Strategy (2022)	This strategy is being developed by the MOT, since 2022. Needs stakeholder engagement as for D2
D4	Alignment with local emissions targets	AT and GW both have more ambitious emissions targets than KiwiRail's 30% by 2030. There will be ongoing dialogue with AT and GW to understand aspirations and identify opportunities/ potential alignments and constraints to achieving more ambitious freight targets.
D5	Decisions (and timing) of changes to Ports of Auckland	Needs stakeholder engagement as for D2.
D6	Timing of potential reduction in ports with direct international ship calls	Needs stakeholder engagement as for D2.
D7	Development and maturity of alternative fuel supply industries	Consult with MBIE and industry partners to understand maturity and progress of alternative fuels.
Uncertainties/ Assumptions		**Notes and Management Strategies**
A1	Rail can transition to zero emissions more quickly than road.	Current indications are that this is the case. Keep a watching brief on developments in low emission road freight. This assumption is tested in the Economic Case.
A2	The cost of carbon will progressively increase.	This is one of the key economic levers to reduce emissions and achieve the zero-carbon goal. It takes place through the Emissions Trading Scheme. It is assumed prices for fossil fuels will continue to rise as a result. This assumption is tested in the Economic Case.

Uncertainties/ Assumptions		Notes and Management Strategies
A3	Consumption patterns will not change radically and so freight demand changes will continue as per current predictions.	This is examined in the Economic Case.
A4	The extent to which NZ's overall freight task will grow.	This is examined in the Economic Case.
A5	Changes in freight volume will affect the timing at which different motive power options become economic.	This is tested in the Economic Case.
A6	Different motive power options may drive changes in freight volume.	Not tested.
A7	New commodity markets will arise through the period of this business case	Included in scenarios.

Table 9: Constraints, Dependencies and Uncertainties

3.9. Strategic Summary

Taking measures to arrest and reverse climate change is a key national policy for New Zealand. As transport is a major contributor to climate change, actions need to be taken in this sector.

Even though a substantial part of transport emissions result from light vehicles, the heavy vehicle emissions are important enough to do something about.

Rail is a minor contributor to the total, but decarbonisation is easier with rail than with road, and so rail's contribution will be important. Rail is already more fuel efficient (and so GHG minimising) than road, and it is expected that as it decarbonises, its share of the market will increase, compounding its contribution.

There is a problem in that the existing supply chain model does not use rail to its full potential, and so GHG emissions are higher than necessary. Policy changes encouraging mode shift may be required to make the most of this opportunity.

The study has identified investment objectives of:

- increasing rail's share of total freight task from 12% (2020) to 17% by 2035
- maintaining the share at 17% to 2050 (despite market fluctuations);

and

- achieving a 5% shift from road freight to rail freight by 2035 (to help transition NZ to a low emission supply chain).

At present most of KiwiRail's locomotives run on diesel, which produces GHG. A further investment objective is to reduce rail freight motive power emissions from 129 ktCO_2e (2019) by at least 35% (2035) and to zero by 2050.

The study has identified investment objectives of increasing rail's share of total freight task from 12% (2020) to 17% by 2035 and maintaining the share at 17% to 2050 (despite market fluctuations), to help transition NZ to a low emission supply chain.

4. Economic Case

What is the best choice for optimising value to New Zealand?

4.1. Overview

The purpose of the economic case is to identify the option that optimises value for government and New Zealand. Having determined the strategic context for the investment proposal and established a robust case for change, the Indicative Business Case considers the economic case in several parts:

- Section 5 deals with traffic and train projections
- Section 6 is a multi-criteria analysis of fuel and motive power choices
- Section 7 develops a practical locomotive for each of the short listed solutions
- Section 8 estimates capital and operating costs for these locomotives
- Section 9 covers the most relevant Pathway to Zero options, and the economic assessment, using a standard cost-benefit model.

Together these five sections:

- Consider rail's 'full potential'" by developing five **supply chain scenarios** which represent different ways to configure NZ's freight supply chain to achieve lower emissions and looks at possible **policy levers** to achieve a shift from road to rail.
- Identify a long list of **fuel type and motive power options** and explains the assessment process used to create a short list of credible combined fuel type and motive power options with a high degree of confidence in their technical maturity and feasible supply.
- Present the multi-criteria analysis for the **fuel type and motive power option** long list and uses these assessments to confirm a short list of **fuel type and motive power options**.
- Explain the **feasibility investigation** completed to understand and confirm the requirements for each short-listed option.
- Apply the short list of motive power options to representative routes on the network, informed by the feasibility investigation, to provide **pathway to zero options.**
- Present results of economic modelling for the **pathway to zero options,** allowing identification of the optimum mix of motive power/fuel options for the entire network.
- Use the economic model to **sensitivity test** different timeframes for change and delivery, and understand the impact of different mode shift levels via the supply chain scenarios
- Use the above to recommend a **preferred way forward** for rail freight decarbonisation.

Figure 10 illustrates the process that was followed to identify the preferred Pathway to Zero options:

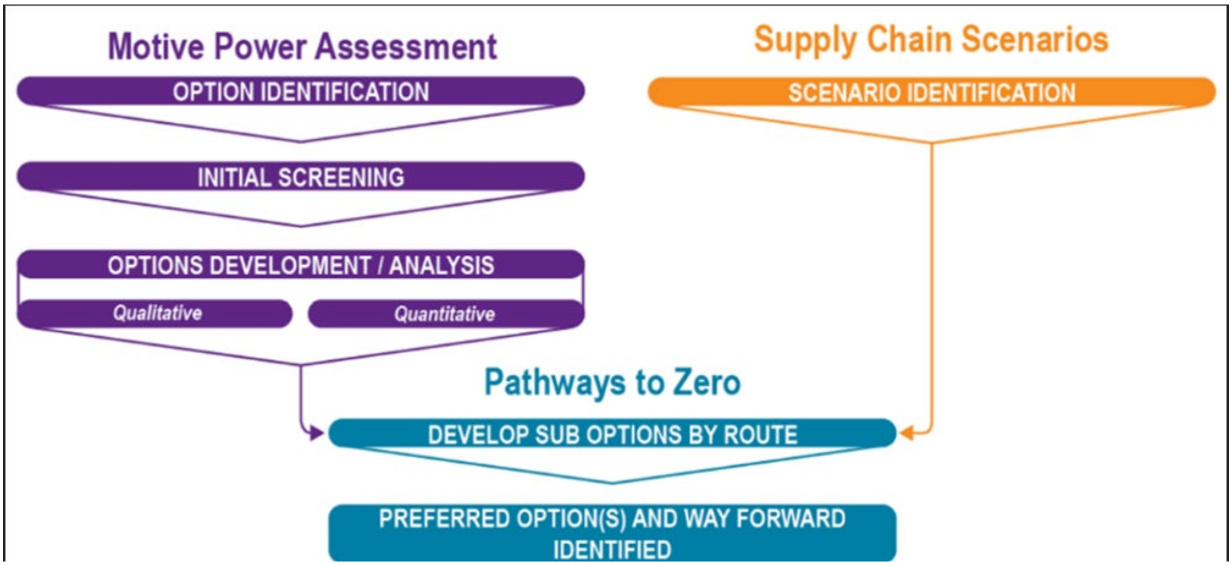


Figure 10: Option Development Process

5. Input to Economic case - Traffic and train projections

5.1. Low Emission Supply Chain Scenarios

To better understand rail's full potential in an uncertain future, scenarios were developed to allow experimenting with supply chain configurations and show the effect on rail mode share. This also allowed an understanding of the possibilities for increasing the volume of freight carried by rail.

Five scenarios plus a Do Minimum were developed, with input from stakeholders, to test the limits of what could be possible for rail. They relate to Investment Objectives 2 (increasing rail's market share) and 3 (achieving a mode shift from road to rail). The scenarios deliberately tested commonly held assumptions about the NZ supply chain and considered the influence of port location and activity on the attractiveness of the rail network.

The scenarios were developed using the National Freight Demand Study (2017/18) as a starting position. The work identified a range of mode shift goals and established a list of scope factors to build detail around each scenario. The process allowed the 'Big Moves' to be understood (see **Table 10**) – radical changes that would have a significant impact on the supply chain.

The following scope factors were considered:

1) Shipping – domestic and international.
2) Intermodal centres/hubs – number, size and location.
3) Government policies and cost by mode.
4) Rail network extent – high volume and other routes.
5) Interisland traffic volumes.
6) Warehousing storage – amount and location.
7) Commodities requiring transport.
8) Carbon price.
9) Changes to KiwiRail capability.

The following assumptions were made:

10) Road cannot decarbonise as fast as rail.
11) A low emission supply chain will be slower than current.
12) Reliability of rail services will be improved.
13) Supply of infrastructure/equipment can match demand.
14) No major route capacity implications (e.g. tunnels).

The MOT Freight Futures model,[26] which was developed using the National Freight Demand Study, was used to estimate freight volumes. It was updated to reflect different assumptions about patterns of manufacturing and retail traffic, and population growth. Initial modelling was at a total freight task level, although commodity level analyses are possible with the model.

The scenarios were used with stakeholders to discuss possible alternative supply chain configurations and their relative costs and benefits, which resulted in some changes. Scenarios B, C

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[26] www.transport.govt.nz/area-of-interest/infrastructure-and-investment/transport-outlook/

and E were not progressed after stakeholder feedback that these scenarios were less certain, but they give a scale of possible change.

Scenario		Big Moves			
Category	**Name**	**Enhanced KiwiRail Investment**	**Ports of Auckland closed**	**Limit import/export container ports**	**Strong Pro Rail Policy**
Resilient and Reliable	BAU (Do Minimum)	**N**	**N**	**N**	**N**
Resilient, Reliable and Growing	A. Enhanced KiwiRail Investment	**Y**	**N**	**N**	**N**
Resilient, Reliable and Substantial	*B. Northern Ports Focus v1 (not progressed)*	***Y***	***Y***	***N***	***N***
	B1. Northern Ports Focus v2	**Y**	**Assumed no growth**	**N**	**N**
	C: Port Consolidation (not progressed)	***Y***	***Y***	***Y***	***N***
Resilient, Reliable, Substantial and Incentivised	D. Strong Policy Push	**Y**	**N**	**N**	**Y**
	E. Rail Max (not progressed)	***Y***	***Y***	***Y***	***Y***

Table 10: Scenario Summary

The remaining scenarios were modelled using the updated MOT Freight Futures Model, which gave indicative mode share and volume for rail, and an estimate of emissions if the extra freight was carried by road instead (based on existing road freight emissions assuming next to no change in road freight decarbonisation). This information is provided in **Table 11**.

Scenario	Base 2020/21	BAU (Base/Do Minimum)	A: Enhanced KiwiRail investment	B1: Port Change	D: Strong Policy Push
	updated NFDS baseline	Resilient and Reliable programme	BAU + additional rolling stock capacity to meet likely demand.	Scenario A + Port of Auckland volumes held at 2020/21 levels and growth diverted to Tauranga	Scenario A + carbon price of \$250/t by 2035, \$600/t by 2050
Indicative mode share 2035 (% ntkm)	12.5%	15.2%	17.4%	18.7%	20.8%
Implied volume at 2035 (bn ntkm)	3.6	4.8	5.5	6.0	6.5
Volume increase relative to base year	-	32%	51%	65%	81%
Emission reduction from using rail not road (tonnes CO_2e pa)	282,000	371,000	423,000	464,000	508,000
Additional emission reduction from using rail not road, compared to 2021 base	-	89,000	141,000	182,000	226,000
Additional emissions saved compared to 2035 BAU projection	-	-	52,000	93,000	137,000

Table 11: Freight Scenario Modelling Results: impacts on rail

The volume of freight carried by rail under each scenario is relevant as this can influence which motive power options may be cost effective. This is particularly the case for the high fixed infrastructure cost OLE options. Payback periods will be longer if lower volumes of freight are carried by rail, but shorter with high volumes, and benefits realised far more quickly.

- Scenario BAU - was used for the baseline assessment and recommendations. This Scenario involves least radical change and was generally agreed to be feasible and achievable.
- Scenario A – Enhanced KiwiRail Investment - provides for additional rolling stock to meet growth
- Scenarios B1 and D were used to sensitivity test the economic assessment - to see what would happen to the costs and benefits if freight volumes increased on parts of the network, and to understand the motive power tipping point - when more expensive motive power options might be economically viable.

Scenario D would involve changing some policy settings. At the problem definition stakeholder workshop, stakeholders identified possible policy levers which would encourage a lower emission supply chain.

Supply Chain Scenarios will be reviewed and updated as part of the Detailed Business Case for new information, in particular the revised Government Policy Statement, IREX termination and any decisions around Auckland Port's future.

5.2. Reference Locomotives

The new Stadler DM class ordered by KiwiRail was selected as the reference locomotive, as this represents the most capable and economical practical diesel-electric locomotive for the New Zealand network, thus providing a relevant baseline for the next generation to be tested against. All the proposed locomotive options for this report were required to meet the same duty cycle as a DM hauled train[27] and then be compared to the DM for economics and emissions.

The reference locomotives, and supporting investigations and modelling for each option allowed the team to contrast the following attributes:

- Design – weight, size.
- Range before refuelling required.
- Power output and efficiency.
- Recharge/refuel method and times.
- Energy density (which informs fuel storage volumes).
- Energy consumption and regeneration by route.
- Capital and operating costs.

Figure 11: Stadler Rail AG locomotive. KiwiRail class DM

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[27] Noting that some of the energy types required two smaller locomotives to match the pulling power of the single reference loco, while still achieving useful range.

5.3. Concept rail freight plan

Understanding the likely future freight task across the network was required to contrast relative advantages or disadvantages of fuel/motive power options The Low Emission Supply Chain Scenarios A, B1 and D were used (see section 5.1) to provide estimates of future annual rail freight volumes and different mode shift percentages, to understand their impact on each options' performance.

The most conservative economic scenario (Scenario BAU) was selected as the base case for the purposes of assessment, as this scenario did not assume any significant external interventions and had a modest increase in the market share of rail freight in line with current commitments.

Freight volumes from BAU were assigned to the network subdivided into twelve sections, to create the concept rail freight plan. Over these twelve sections, routes between fifteen key origin-destination pairs (30 one-way movements) were assessed for rolling-stock needs. This allowed the composition of the locomotive fleet required to meet the freight task to be determined and the relative performance of the options assessed.

5.4. Train Modelling

The annual freight flows for each route section were then translated into numbers of wagons and then into trains of realistic length for that section and within the pulling capacity of DM reference locomotive. The result was the number of identical trains of this given size required each day on each route in each direction to handle the annual traffic target for each scenario[28]. The size of each train reflects the constraints of each route segment, smaller trains on routes with challenging grades and larger ones on flatter routes. See section 7.2 for modelling detail.

The train modelling was then used, on a network basis, to develop the Financial Model and the Economic case (see section 9). It was also used on an individual train basis to develop the hypothetical feasible locomotives and fuel types.

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[28] Not a realistic real-world plan but appropriate for modelling purposes.

6. Input to Economic case – MCA Analysis

6.1. Fuel and Motive Power Assessment

It was important the IBC considered the full range of possible fuel and motive power choices before focussing on a few.

A long list of 18 possible fuel and motive power (different ways in which the fuel can provide power to the locomotive) choices was created after a stakeholder workshop in November 2021. The Do Minimum was defined as fossil diesel motive power.

These choices included short-term ‘transitional’ and long-term ‘transformational’ ones. Transitional choices may not eliminate emissions completely but will provide a short-term emissions reduction, enroute to elimination. Transformational choices will be zero emission, although may not be available or affordable in the short term.

To better understand the maturity of different technologies and inform the screening and multi-criteria assessments, the team held a series of facilitated discussions with suppliers. The key findings were:

- Diesel prime movers used to be able to provide for a wide range of power outputs and duty cycles (from a hand held tool to a container ship) but it is unlikely that any zero carbon solution will cover such a range.
- Many different approaches towards decarbonisation of rail freight are being taken across the world, depending on the interaction of local economic conditions and operating requirements, and further complicated by the technologies being in a phase of rapid development.
- The solution for NZ will be tailored to local conditions.
- The conditions over the New Zealand network vary so significantly (route segment length, energy used per journey, density of traffic and availability of energy) that no one solution will fit all parts of the network.
- Virtually all suppliers of internal combustion engines are exploring opportunities to use alternative fuels, however these efforts are hampered by the absence of global standards for consistent non fossil liquid fuels.
- The “electric” part of a locomotive is mature and well established from a century of electric and diesel-electric locomotives, with innovation focussing on battery storage systems, recharge and energy recovery systems.
- Hydrogen is broadly considered as potentially feasible in the long term but is dependent on the maturity of hydrogen production. There are also significant technical challenges in its application.

6.2. Screening Process

The screening process was applied to the fuel choices and to the different motive power choices. Each fuel and motive power choice was compared to the Do Minimum.

The assessment criteria developed to assess fuel and motive power choices are in **Table 12.**

Assessment Criteria	Explanation
GHG Emissions	Investment Objective 1: Option must produce lower GHG emissions than Do Minimum
Maturity	Option must have established fuel production processes and be developed beyond concept stage.
Operational performance	Option must provide close-to equivalent or better operational performance to Do Minimum.
Safety	Option must not increase the risk profile of KiwiRail
Transitional viability	Can the option be used in the short term, to help in the transition to lower carbon rail freight?
Transformational viability	Will the option transform rail freight, representing a viable long-term pathway to zero emissions?

Table 12: Assessment criteria

The possible choices were assessed by technical specialists in the team and reviewed by the rest of the project team. Each fuel and motive power choice was assessed against the criteria to see how it performed compared to the Do Minimum. This allowed it to be assessed as being either acceptable, marginal, or flawed. This allowed a comprehensive list of in-scope choices to be confirmed.

- Acceptable fuels and motive power choices were carried forward to the short list for detail consideration.
- Marginal fuels and motive power choices required further assessment/clarification, which allowed some to be excluded.
- Flawed fuels and motive power choices were excluded from further consideration.

6.3. Fuels Long List and Screening

The detailed results of the screening assessment for the fuel choices are available from KiwiRail. This includes a description of how each fuel type performed against each of the assessment criteria, and whether it was acceptable, marginal, or flawed. The fuel or energy types identified are summarised in **Table 13**.

(Key: Green text indicates the choice was short listed, Red text with grey shading indicates the choice was excluded).

Category	Fuel type	Primary rationale for decision
Fossil Fuels	**Mineral Diesel**	Taken forward for comparison purposes as the Do Minimum
	Coal – Solid fuel/dust; petrol; natural gas, clean diesel; blue and grey hydrogen	Not considered practical, or still highly carbon intensive
	Blended diesel	A blend of biofuel and diesel, which can be used in a normal unmodified diesel engine. The proportions can vary, but the assumption is up to 20% biofuel 80% diesel. The key point with blended fuels is they are essentially a transition pathway toward a drop-in biofuel. Blended fuels by themselves will not achieve zero carbon emissions.
Biofuels	**Agricultural bioethanol**	**Biofuels** include a range of organically derived liquid fuels that may be used in place of fossil liquid fuels. They are considered carbon neutral as they capture carbon during growth, which is then released on combustion. Considered separately, these fuels all scored 'acceptable' against all criteria. Following the initial assessment these fuels were grouped together as '**Drop-in Biofuel**' as the production pathways and applications of these fuels are broadly similar, and this market is evolving rapidly.
	By-product bioethanol	
	Agricultural biodiesel	
	By-product biodiesel / renewable diesel	
	Biomethane	
Carbon Free Fuels	**Ammonia**	Although ammonia is a carbon free fuel, production is well established and it may evolve as a carbon free solution for blue water shipping, the development of ammonia locomotives has not progressed beyond concept and the fuel is therefore not considered technically mature for rail traction use.
	Green Hydrogen	Although operational performance is marginal, and availability quickly enough to be a 'transition' fuel unlikely, green hydrogen was carried forward because it is a carbon free fuel and there is a lot of research and trialling of green hydrogen for both road and rail internationally.
Electricity	**Electricity**	Electricity was carried forward as a technically mature fuel source, well established and in use domestically, with highly efficient generation and transmission, and safety risks well understood and managed. If electricity is generated from renewable energy this fuel is carbon free and represents a viable long-term solution for motive power.

Table 13: Long List of Fuels and Decision for each

6.4. Motive Power Long List and Screening

The overall results of the screening assessment for the different motive power choices are summarised in **Table 14**.

(Key: Green text indicates the choice was short listed).

Motive Power choice	Description
Internal Combustion (Do Minimum)	Internal combustion engines (ICE) generate power by burning fuel which expands gases to push a piston and rotate a crankshaft. This was taken forward for the Do Minimum only.
Electric Locomotive (Do Minimum)	Electric motors draw grid electricity from an external source (via overhead wires) and convert this electrical energy to motive power.
Internal Combustion Hybrid[29]	An ICE running on liquid fuel, with a battery. The battery is charged when the train is operating, e.g. during braking. The battery can then be used to provide power. This increases energy efficiency and decreases fuel consumption. At the time of the assessment – subsequently abandoned - it was assumed likely that all future internal combustion locomotives would be hybrid, given the fuel consumption and emissions advantages.
Hydrogen Fuel-Cell Electric	Fuel cells convert the chemical energy of a fuel (typically hydrogen) into electricity through a reaction using hydrogen and oxygen, which produces electricity, water and waste heat. There is no combustion. Fuel cells were carried forward for hydrogen because fuel cells are the most efficient and practical means for generating power from hydrogen. Internal combustion was not carried forward for hydrogen, due to its extremely low overall efficiency. ICE is 30% less efficient than a fuel cell when producing power from hydrogen.
Battery Electric	Almost identical to an electric locomotive, with a battery added to store energy. The battery then provides the power when travelling on parts of the network which are not electrified. The battery is plugged in externally to charge. It also recovers energy during braking.

Table 14: Results of Motive Power Assessment

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[29] Subsequently rejected.

6.5. Confirmed Short List - Fuel/Motive Power choices

The screening process resulted in six combinations of fuel and motive power remaining for further assessment, as set out in **Table 15**.

No.	Fuel	Motive power	Description
1	**Drop-in Biofuel (2nd Generation)**	**Internal combustion hybrid**	Mineral diesel fuel is replaced with a drop-in biofuel, most likely some form of synthetic diesel.
2	**Blended Diesel**[30]	**Internal combustion hybrid**	Diesel fuel is mixed with liquid biofuel, with biofuel being between 5% and 20% of the mix. However, blended diesel still relies on fossil fuels and thus produces carbon emissions. Blended fuels are regarded as a transitional option only.
3	**Green Hydrogen**	**Fuel Cell Electric**	Hydrogen fuel cells using "green" hydrogen[31] replace the ICE as a motive power source. This would require substantial change and/or development of new locomotives, as well as fuel transport, storage and handling infrastructure.
4	**Electricity**	**Battery locomotive**	This replaces the combustion engine motive power source with electrical energy stored onboard in a battery. Batteries are charged at the origin/destination, at a stop enroute and during regenerative braking.
5	**Electricity**	**Continuous/full electrification** Electric locomotive with overhead transmission	Grid generated electricity is supplied directly from the grid to the locomotive (a pure electric loco) via an overhead wire (Overhead Line Electrification - OLE).
6	**Electricity**	**Discontinuous/ partial electrification** Electric locomotive with battery and overhead transmission	This option uses a mix of OLE and onboard battery stored energy. This option assumes locomotives will draw energy directly from the external supply while under OLE, Where there is no wire the battery supplies are used. This method allows the loco to run to destinations beyond the wire or the OLE to skip short line sections where it would be particularly expensive. On route segments operated entirely under the wire a pure electric locomotive can be used.

Table 15: Shortlisted fuel/motive power choices

Note that these Options and Option numbers were further refined as the study progressed and options were refined.

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[30] Subsequently discarded.

[31] Hydrogen can be produced in different ways, with "colours" assigned to each method to reflect the GHG emissions profile. Methods involving gas and coal to produce hydrogen have a higher emissions profile, even if the emissions are captured and stored ('grey' or 'blue' hydrogen). Green hydrogen produced from renewable electricity creates no (or very low) greenhouse gas emissions. Only green hydrogen is considered in this study.

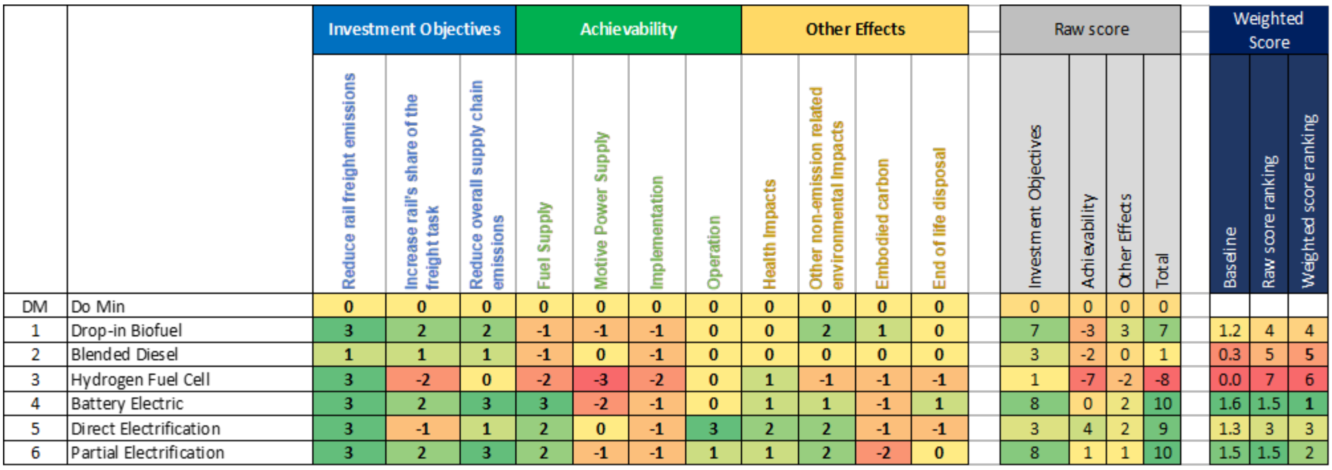
6.6. Multi-Criteria Analysis of Short List

A Multi-Criteria Analysis (MCA) process was used to assess the short list. The team worked through a formal process to consider each other's viewpoints and agree a final score (with rationale) for each choice, against each assessment criterion. The assessment criteria, their weighting and scoring, and the detailed process are explained below **6.7**.

The assessment criteria were the Investment Objectives from the Investment Logic Map (Strategic Case), a set of four Critical Success Factors which were identified and confirmed through team discussions, and four Opportunities and Impacts which are important for the project, but not critical.

6.7. Multi-Criteria Analysis Results

The assessment teams were selected based on their having relevant skills and experience for the criteria to which they were assigned. In addition, to get a thorough understanding of appropriate scoring for 'potential achievability', the team drew on the series of supplier interviews with locomotive and prime mover suppliers. **Table 16** shows the scores that were awarded for each option against the 11 criteria. It includes the overall score using the baseline weightings (as well as each option's ranking based on the final weighted score).



		Investment Objectives			Achievability				Other Effects				Raw score				Weighted Score		
		Reduce rail freight emissions	Increase rail's share of the freight task	Reduce overall supply chain emissions	Fuel Supply	Motive Power Supply	Implementation	Operation	Health Impacts	Other non-emission related environmental Impacts	Embodied carbon	End of life disposal	Investment Objectives	Achievability	Other Effects	Total	Baseline	Raw score ranking	Weighted score ranking
DM	Do Min	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
1	Drop-in Biofuel	3	2	2	-1	-1	-1	0	0	2	1	0	7	-3	3	7	1.2	4	4
2	Blended Diesel	1	1	1	-1	0	-1	0	0	0	0	0	3	-2	0	1	0.3	5	5
3	Hydrogen Fuel Cell	3	-2	0	-2	-3	-2	0	1	-1	-1	-1	1	-7	-2	-8	0.0	7	6
4	Battery Electric	3	2	3	3	-2	-1	0	1	1	-1	1	8	0	2	10	1.6	1.5	1
5	Direct Electrification	3	-1	1	2	0	-1	3	2	2	-1	-1	3	4	2	9	1.3	3	3
6	Partial Electrification	3	2	3	2	-1	-1	1	1	2	-2	0	8	1	1	10	1.5	1.5	2

Table 16: MCA Results

MCA reports for each criterion are held by KiwiRail. These reports prepared by the respective assessment teams explain the assumptions, methodology, scores and rationale for scores.

Table 17 shows the choices in ranked order based on their weighted scores.

Rank	Choice	Name	Weighted score
1	4	Battery electric locomotive	1.6
2	6	Partial electrification (assumes 50% of rail network is OLE and 50% is battery; in practice much less of the network would have OLE[32])	1.5
3	5	Direct electrification	1.3
4	1	Drop-in biofuel	1.2
5	2	Blended diesel	0.3
6	3	Green hydrogen (fuel cell)	0

Table 17: Fuel/motive power choices ranked in order

The scores are very close between the top four choices – the three electric choices and drop-in biofuel. There is a sizeable drop in score between the top four choices and the remaining two - blended diesel and green hydrogen. [33]

Overall, the three choices with electricity as the motive power source (choices 4, 5 and 6) scored better than the liquid fuels (1, 2 and 3).

This is because electricity is efficient and readily available, with no direct GHG emissions, or more correctly similar emissions as the national electricity mix (planned to move to very close to 100% renewable), and a very high Energy Return on Investment. In addition, no local emissions (gas, particulates) and reduced noise are released during use, giving positive health and environmental benefits. Implementation is expected to be relatively straightforward - the technologies are tried, proven and in use, except for widespread battery electric locomotives for mainline freight, which are expected within the decade.

Of those three top scoring electrical choices, direct electrification is slightly less favourable than the other two. This is because of its high capital cost. This became more important during the economic analysis.

Drop-in biofuel also scored relatively well, and better than blended diesel. This is because it is considered carbon neutral and so performed far better against the investment objectives. In terms of embodied carbon, drop-in biofuel scored better than the electrical choices. The more detailed phase of investigation did however uncover challenges with biofuel.

Blended diesel scored closest to the Do Minimum and the raw scores were only marginally different. The positives offered by blended diesel, in terms of slightly lower greenhouse gas emissions, were almost outweighed by uncertainties around availability of supply of blended diesel in NZ. Blended diesel has the advantage that it can be used in existing diesel engines, so would represent an immediate improvement in environmental performance that could be rapidly implemented and could assist KiwiRail in the transition to lower GHG emissions. But the solution is partial and transitional only.

Although green hydrogen is a zero-emission fuel, it scored relatively poorly. Hydrogen fuel cell locomotives are in very early prototype form and green hydrogen production is at pilot scale nationally and internationally, and in limited use domestically. This choice is not expected to be

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[32] Although this smaller proportion of the network carries nearly half of the total traffic.

[33] The MCA work was done ahead of a significant amount of work on the technical detail of the locomotive options. Advantages and disadvantages came more into focus after the initial MCA process. This is as would be expected when following a sequenced process that commences with a grading process to narrow this focus. This is however unlikely to materially alter the MCA ranking.

feasible within the next decade. Storage and transmission infrastructure would require radical change and have very strict safety and technical considerations. It is also expected to have a very low Energy Return on Investment in the NZ context (as low as 0.25) and to present the most challenge in terms of implementation, as a major business change will be required to store, handle and transmit hydrogen, and significant safety procedures will be needed.

6.8. Sensitivity Testing – Fuel/Motive Power choices

Sensitivity tests were completed to test for double counting and the effect of using four point rather than seven point scoring scale for three of the criteria. The tests assumed that each choice would be available where needed on the network, and in the quantities required. Any issues relating to supply/demand will be explored in the DBC stage.

The effect of these sensitivity tests on the scores and ranking is shown in **Table 18**.

		RANK			
No.	**Fuel/ Motive power choice**	**ST 1**	**ST 2**[34]	**ST 3**	**ST 3v2**
1	Drop-in Biofuel	4	4	3	4
2	Blended Diesel	5	5	5	5
3	Hydrogen Fuel Cell	6	6	6	6
4	Battery Electric	1	1	1	2
5	Full OLE Electrification	3	3	4	3
6	Partial OLE Electrification	2	2	2	1

Table 18: Sensitivity Test Results

The findings from the sensitivity tests were:

- Sensitivity tests 1 and 2 made no difference to the overall ranking of the choices. These respectively excluded Investment Objective 3, and tested that that objective was scored independently of Investment Objective 2
- For all tests, Blended Diesel and Hydrogen Fuel Cell remained ranked 5 and 6 respectively.
- Sensitivity test 3, which removed three of the criteria from the MCA, was conducted to understand whether those criteria were influencing the result, and the test demonstrated that they were, as the rankings were different.
- Sensitivity test 3v2 was completed once sensitivity test 3 showed the limited four-point scoring scale was introducing bias. Once this bias was removed, 6 - Partial Electrification became the top-ranking choice, followed by 4 - Battery Electric.

However, all the choices were taken forward to form the Pathway to Zero Options for testing in the economic model.

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[34] Sensitivity tests 2 and 3v2 involved changes to the input scoring, rather than to the weightings.

7. Input to Economic case – Technical Feasibility

7.1. Overview

The solutions short listed were then subjected to detailed analysis to arrive at a conceptual but practical locomotive, from which the parameters required to assess them in the economic model could be derived.

This included cost estimates for locomotives as well as lineside infrastructure, fuel/energy requirements and supply, reliability, availability, maintenance costs and a general assessment of maturity or technical readiness.

This practical concept had to be able to meet the same duty cycle as the standard (Stadler DM) reference locomotive. As will be seen, this sometimes required that the configuration of the locomotive be changed significantly to offset weaknesses and take advantage of strengths of that that particular power train and deliver a concept that could be substituted for the reference locomotive.

While the concepts could be built, they are not intended as models for locomotive procurement. Any actual locomotive procured will be a variant of an OEM standard and modular design and all it need be is the same or better than the concept in the crucial areas of performance.

7.2. Developing a locomotive duty cycle

As introduced in **5.4**, train consists[35] were developed for each route and for each freight scenario so that the performance and behaviour of the various reference locomotives in response to the freight task could be understood. Each train was built around the capability of a Stadler DM locomotive and took account of the grade limits of the route. Large trains for flat and easy routes, smaller trains for steep and curved routes. The number of trains required per day, week or year was simply the annual forecast tonnage in each direction for each scenario (adjusted for seasonality) on that route, divided by the net capacity of that train.

This was specific to the type of traffic. For the study, assumed to be predominantly mixed domestic and international containers transported between ports and the main centres, or between the North Island and South Island.

The train's trailing mass was limited to the payload capacity of KiwiRail's modern flat deck container wagon design, taking into account realistic load factors from inability to fully occupy all container slots, and lower loading for axle load restrictions. The train composition was optimised around utilisation of the locomotive horsepower and range. Short trains maximised the trailing mass for the total hauling capacity from one or two locomotives, limited by the ruling gradients and required range. Long trains were required for high line flow tonnages including on the MetroPort route and North Island Main Trunk.

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[35] "Consist" is used as a noun in railway terminology (with emphasis on the first syllable) to mean the number and mix of vehicles on a train (or part of it, such as the locomotives).

Scenario:	BAU	A	B1	D
Annual freight tonnage (Million tonnes pa):	0.34	0.40	0.40	0.57
Weekly freight tonnage(tonnes):	6,858	8,039	8,039	11,499
Number of wagons per train:	25	25	25	50
Wagon tare (t):	400	400	400	800
Train length (m):	428	428	428	855
Train gross trailing mass (t):	1080	1080	1080	2160
Total container tare (t) (2.2t per used TEU slot):	103	103	103	207
Max net train payload capacity (t):	577	577	577	1153
Required trains per week:	12	14	14	10
Service level % relative to 2022 (10 trains) in TRAINS	120%	140%	140%	100%[36]
Required trains per day (6 day week Mon-Sat):	2	3	3	2
Required trains per day (6 day week Mon-Sat) - Peak Season:	3	4	4	3
Required number of locos per train:	2	2	2	4

Table 19: Simulated train loads and train numbers on Palmerston North-Napier route in 2050, using battery electric locomotives with 300kN tractive effort each.

The OpenTrack simulation programme was then employed to “operate” the train over each route segment each way, outputting a wide range of performance parameters, including the energy used each second of the journey. This was energy “at the wheel”. The various types of energy proposed use differing amounts of primary energy to deliver a given power at the wheel and this was factored in in the economic model.

An example of output from OpenTrack for the Palmerston North to Napier line is shown in **Figure 12**. This test was completed for all fifteen operationally sensible segments the NZ rail network was broken up into for this study. Battery locomotives have choices regarding battery capacity per train and enroute charging strategy so multiple scenarios were modelled for each route. These were used to optimise battery size, charging point location and charging duration enroute, or at least achieve an adequate combination of configuration and operating strategy.

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[36] But each train now double the length of baseline.

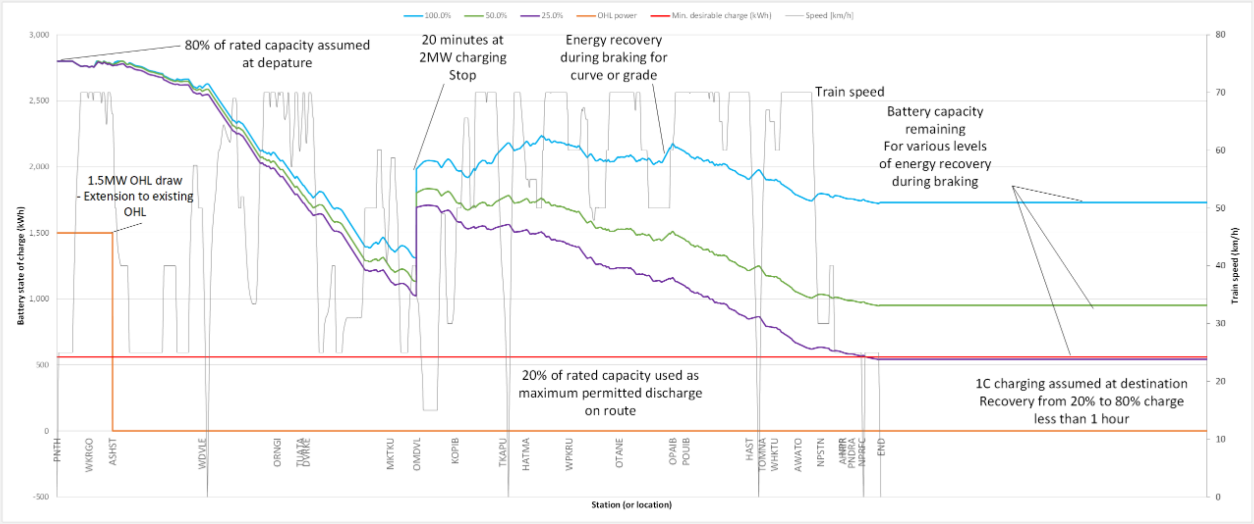

Figure 12: Example energy and time assessment for a 3mWh battery locomotive: Palmerston North-Napier

OpenTrack outputs energy used (more correctly – that needed to keep that particular train moving) per second, at the wheels. Not all the energy in the fuel is turned into useful work at the wheel, because of thermodynamic losses, transmission losses and parasitic losses (non-traction loads like driving fans and compressors) which occur between the meter point[37] and the wheel. So for each option, the economic model grossed up the energy at the wheel to take account of these loss, estimated by comparing the energy content of the input fuel with the output energy at the wheel. For example, the economic model showed only 29% of the energy in diesel fuel reached the wheels[38].

The total energy requirement was then converted into litres (diesel and biofuel) or kilograms (hydrogen[39]), and projected fuel prices (at the "meter") applied.

However, for convenience, the economic model actually used the energy consumption per 1000GTK based on the train consist for the BAU Freight Scenario in 2035. It was considered a reasonable and simpler estimate for different scenarios and time periods.

Because the battery locomotive, hydrogen fuel cell locomotive or even an electric locomotive is subject to different constraints and advantages it may require a different configuration from the fossil fuel diesel locomotive it is being configured to match.

Therefore, the OpenTrack results were also used to determine the parameters of the ZGHG locomotives being proposed to take over these duties; amount of on board energy storage required, per service energy supply demand and some infrastructure requirement e.g. fuel and energy storage and transmission infrastructure. This was an iterative process, particularly with the battery and hydrogen fuel cell locomotives, with early iterations falling short of the required performance in some criteria.

The number of trains and locomotive units to haul these trains required for each segment enabled the total fleet size to be determined – the number of locomotives needed per route and for all of NZ

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[37] Where the energy, whatever it is, is paid for.

[38] Other analysis showed higher efficiency than this for a locomotive working hard (37%) but the real world figure is likely to be lower than the 29%, allowing for locomotives being under utilised and for additional idling time. But assumptions are consistent for all modes in this report; high power/TE utilisation and no provision for wasted idling or work, allowing the required comparison.

[39] Using the Hiringa numbers, 42% of the input energy from the original electricity found its way to the wheels as useful work. From reported analysis this seems high, with factors of ~1/3 often reported. But the results would not be changed by introducing a lower figure, so the analysis was left as it.

The number of trains, locomotives and distance run over the network enabled total energy consumption, total emissions (including particulates and NOx), maintenance needs and cost to be calculated.

Each type of zero or reduced greenhouse gas emissions locomotive concept was then configured to be able to deliver the standard duty cycle with reasonable practicality. Where supporting infrastructure is required, this was conceptually sized to support locomotives delivering this duty cycle.

7.3. Conventional Overhead Line Electrification (OLE)

Electrification of the economy and decarbonisation of electrification underpins plans to achieve ZGHG in New Zealand and internationally.

Railways are one of the few transport modes for which electrification is long established[40] and conventional technology, the others being trams and trolleybuses.

This conventional approach is based on fixed overhead line electricity distribution or, in some cases, ground level live rail or conduit. The first overhead line electric trains in New Zealand began running through the Otira Tunnel in 1923, as shown in **Figure 13**.

The limiting factor for the adoption of OLE is the high capital cost of the fixed infrastructure required. This comprises the power supply, connections to the electricity grid and substations, and the lineside infrastructure of masts, overhead wires and associated equipment. With little or no cost placed on fossil liquid fuel emissions, traffic levels have to be relatively high or demanding[41] to warrant the fixed investment. In New Zealand, and on railways of similar density, this threshold is rarely passed and diesel-electric locomotives provide a far lower cost solution. OHL electrification does deliver value based on performance, service quality and local emissions for metro passenger operations, but this study is about rail freight operations running beyond and between the main centres.

The Beca-Systra 2021 electrification report[42] set out the cost of electrifying three selected North Island routes. Combined with experience in 21st century Wellington renewals and Auckland construction, these were used as a basis for calculating the cost of electrifying nearly all rail routes[43] in New Zealand. The excluded lines were assumed to either be closed by 2050 (coal route north of Stillwater) or be minor routes operated by battery electric locos (all others).

The costs used in the 2021 report varied between lines. Some effort was made to account for clearance improvements on specific routes and the costs of power supply, while at concept level, were also specific to each route.

The cost of power supply is currently high in New Zealand. A conventional single phase AC traction substation (TSS) requires a connection at the highest level of the Transpower National Grid, the 220 kV network. Three phase Static Frequency Converter (SFC) substations now offer the possibility of a connection to the 110kV network but they are expensive and have relatively higher maintenance costs. In both cases the cost of the grid connection and the TSS are substantial. Transpower’s 220kV

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[40] Dating back to 1879. First electric tramway application in New Zealand 1900.

[41] All three pre-WWII mainline electrifications in NZ were limited route sections and primarily about eliminating steam locomotive working, and resulting smoke nuisance, through long tunnels and/or providing high performance to deal with steep grades. Freight workings on all three were dieselised 1970 – 1990s when suitable diesel locomotives became available

[42] North Island Electrification Study. Beca-Systra for KiwiRail, May 2021

[43] All North Island routes except north of proposed Marsden Point branch, Mission Bush Branch, Napier - Wairoa and Upper Hutt to Woodville. All South Island routes except Stillwater to Ngakawau, Greymouth to Hokitika, Bluff Line and Ohai Line.

or 110 kV substations are not necessarily near to the railway and dedicated connections of several or tens of km are usually required.

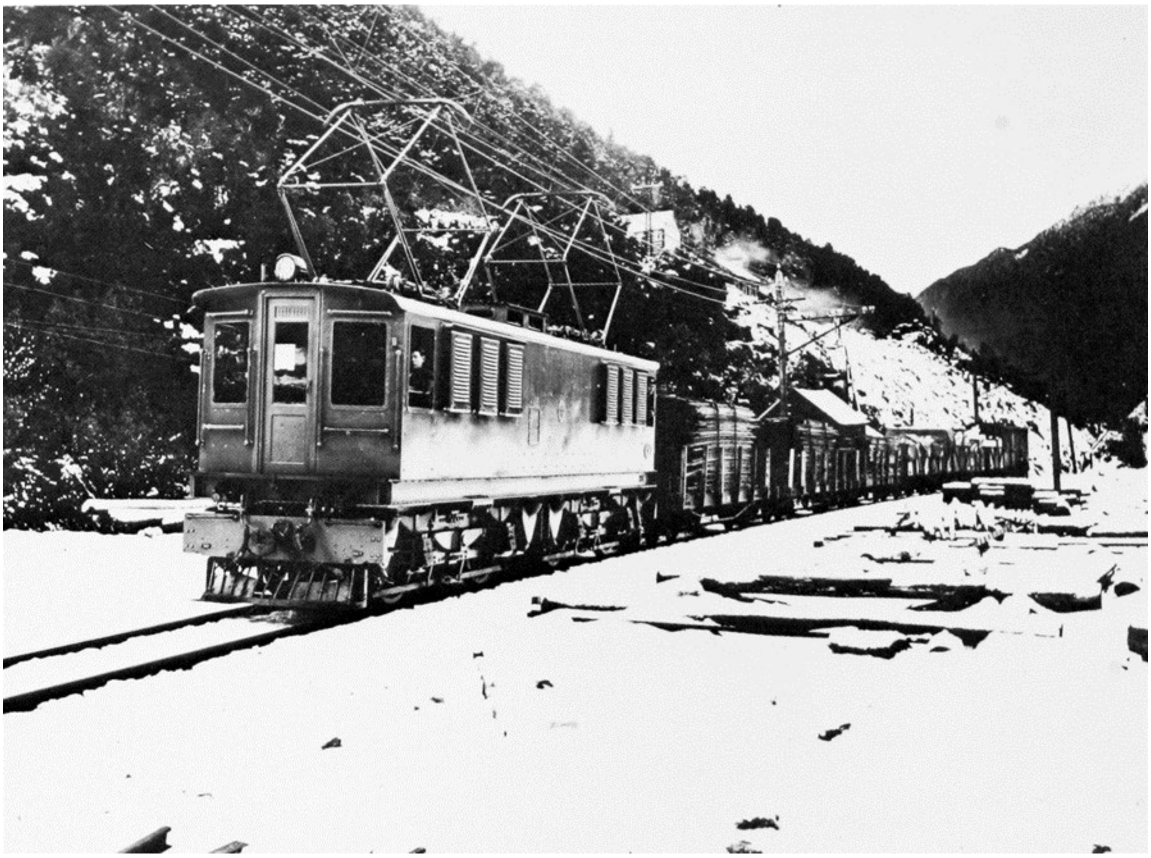

Figure 13: Railways in New Zealand have experience with operating overhead line electrification going back 100 years. First generation 1500 volt DC electric locomotive at opening of Otira-Arthurs Pass section in 1923.

Using the specific costs in the 2021 report the following average costs were derived:

Cost element	Cost ($m)
High voltage connection	9(2)(i) - Commercial Activities [redacted]
Traction substation	[redacted]
Cost per STK[44] of other works	[redacted]

Table 20: Average OLE Costs

The 50,000 volt auto-transformer system was assumed, allowing a typical traction substation to serve 100 km of track.

When applied to each of the routes throughout New Zealand the resulting average costs per STK were in the range of $3.0m - $3.7m per STK. The Murupara forestry line was able to be electrified (in concept) without a TSS assigned to this line and was the low outlier.

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[44] Single Track Kilometre. Electrification of one km of single line railway = 1 STK. With double track = 2 STK.

To illustrate the typical make up, the North island average was:

Element	Cost per STK ($m)	Percent
Wires, clearances and signals	9(2)(i) - Commercial Activities [redacted]	[redacted]
Traction substation	[redacted]	[redacted]
High voltage connections	[redacted]	[redacted]
Totals	**3.440**	**100%**

Table 21: North Island Average OLE Costs

While it should be possible to reduce the cost of wiring alone to well below $2m per STK on a well-planned and delivered electrification programme, the total cost per electrified track km will still be well above $2 million when all the elements are considered. Overhead line electrification remains not even close to viability as a universal solution to the freight railway decarbonisation challenge in New Zealand.

Full complement of other lines (NI and SI)	Cost ($m)
Full complement of other lines (NI and SI)	**7,093.5**
Beca-Systra 2021	
Line 1 Hamilton (Te Rapa) – Pukekohe	430.0
Line 2 Hamilton – Tauranga (Mount Maunganui)	426.0
Line 3 Waikanae – Palmerston North	339.0
Yards	8.0
Sub total	**1,203.0**
Grand total (NZ)	**8,297.5**

Table 22: Overhead electrification costs across whole network

As expected, the capital cost of this was considerable and the OLE option, when applied to all mainline freight routes, economically ranks as the worst performing of all the decarbonisation options.

7.4. Selective Overhead Line Electrification (OLE) "Option 4".

An industry rule of thumb suggests OLE can be viable at 5 million gross tonnes per annum on a route, if compared to obsolescent diesel locomotives of poor efficiency. If the comparison is high efficiency diesel locomotives, the balance point shifts towards 10 million gross tonnes per annum. The poor economic performance of electrifying the entire New Zealand network using conventional overhead line electrification is not surprising (Refer **Figure 2**, **Figure 25** and **Figure 26**).

Battery-electric locomotives should be seen as simply another way of electrifying a rail route and, due to the lower fixed costs, more suitable for lower density railways like in New Zealand. **In this respect the developing viability of the battery-electric locomotive is a game changer for electrifying the majority of the New Zealand rail network**.

However, OLE can be more cost effective when the investment is filling gaps in an electrified route, which includes extending electrification to allow electric operation over the full length of a partly electrified route, so long as traffic levels are sufficient (in excess of the 5 million tonnes guideline).

There are three routes which are possible candidates for expanding the reach of the current Palmerston North – Hamilton freight electrification and two of these exceed 5 million gross tonnes per annum albeit only just:

Route	Approx. length	Recommendation	Reason
Hamilton (Te Rapa) – Pukekohe	83km	Very likely	High volumes (just above 5 mtpa) and potential passenger demand. Gap to Auckland metro electrification only 83km.
Hamilton – Tauranga (Mount Maunganui)	97km (105km)	Likely	High volumes (just above 5 mtpa) and potential passenger demand. Relatively short distance of 110 km.
Palmerston North – Waikanae	80km	Possible but unlikely	Well below 5 mtpa. Strategic completeness, and potential passenger demand may offset this. But on face of it: not worthwhile on the basis of freight.

Table 23: Potential OLE extensions

Island	Diesel NTK bn	Electric NTK bn	Total NTK bn	Diesel %	Electric %
North	1.026	2.003	3.029	34	66
South	1.290	-	1.290	100	-
Total	2.316	2.003	4.318	54	46

Table 24: Net tonne Kilometres hauled by diesel and electricity if Pukekohe to Tauranga electrified

Pukekohe[45] to Auckland is already electrified as part of the Auckland Metro passenger system. If Pukekohe – Te Rapa and Frankton Junction – Tauranga (or Mount Maunganui) are provided with overhead line electrification, 46% of the total KiwiRail haulage task (66% of North Island task) would be converted to ZGHG (to the extent the national grid is decarbonised), using conventional railway technology.

Under the growth scenarios it is anticipated that the 46% proportion will increase to over 60% by 2050.

The cost of this targeted electrification was taken directly from the 2021 Beca-Systra report[46]:

	STK (km)	Low ($m)	Medium ($m)	High ($m)
Hamilton (Te Rapa) - Pukekohe	153	390	430	472
Hamilton – Tauranga (Mount Maunganui)	110	388	426	466
Total	263	778	856	938
Cost per STK		2.958	3.245	3.567

Table 25: Costs of OLE for Pukekohe to Mt Maunganui

The benefits of conventional electrification are leveraged by the investment being required only to fill gaps or finish a route. While the analysis shows that partial electrification is notionally of less economic value than electrification using battery locomotives (**Figure 25** and **Figure 26**, the economic model (currently) does not qualitatively account for the risk reduction value of this solution).

It uses conventional infrastructure and locomotive technology to decarbonise nearly half, rising to well over half over time, of KiwiRail's freight traffic, whereas the alternative solutions all depend on significant advances in technology and its adoption by the locomotive supply market or the growth of supply chains for biofuel in bulk, also using developing technology.

The only possible exception, under a battery locomotive option, is an isolated section (or two) of OLE on the Main North Line (Christchurch – Picton). This would be justified if it is the only practical means of bringing this route within the range of battery locomotives[47].

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[45] Pukekohe to Papakura electrification works currently (2023) under way.

[46] Note that in breaking down and building up the consultant costings in a different way, discrepancies in total cost of about 1% resulted, which was not seen as significant, in the context of this exercise. The 2021 report is based around the existing single track east of Hamilton and the Mercer swamp single track section. It is likely that this combined route would require extensive double tracking and realignment to meet mid-21st century demands, but the existing assumption is appropriate for the purposes of this exercise AND electrification of the existing ahead of later improvements is likely to be worthwhile, so long as passive provision is made for later double tracking.

[47] In this event it seems more plausible that assigning additional locomotives to each train would be a more cost effective solution.

7.5. OHL Maintenance Cost

The NIMT electrified area does not have reliable historical maintenance cost records[48], so maintenance cost was assessed on the basis of a literature search.

Half of the Japanese National Railways assumption[49] would seem to be suitable for the purposes of this exercise. That is 1% of capital cost per annum for maintenance and 5% every ten years for part life renewals. In the economic model this translated to approximately 50% of the original capital cost over the life of the equipment.

Figure 14: KiwiRail has current experience with Overhead Line Electrification and electric freight locomotives. This train shows the lead refurbished EF class electric locomotive on one of its early tests in December 2022. It is towing unrefurbished EF locomotives as part of the test load.

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[48] Due largely to it having had to be run on the basis of deferred maintenance for most of its history.

[49] 2% of capital cost per annum and 10% every ten years. Appropriate for a very densely operated Japanese railway.

7.6. Conventional electric locomotive

The conventional or "pure" overhead line electric locomotive conceived for comparison purposes is equivalent to the DM locomotive but equipped with 0.5 MWh of batteries to allow “last kilometre” operation. This is now relatively common practice in contemporary electric locomotives as it avoids the need to provide live overhead wires into a marshalling yard, freight terminal, container site, port, locomotive depot or along a short industrial line to a major customer.

The benefits of this are 1) safety, avoiding the need for high voltage wires above areas where people work, 2) cost, saving the considerable cost of often complex wiring arrangements over multiple tracks and junctions and 3) the ability to reliably recover and store some braking energy enroute[50]. An electric locomotive with a 0.5 MWh battery may even be able to handle a service on the unwired Mission Bush branch, for example[51].

Having said that, the North Island allocated X-64 battery locomotive concept has dual overhead/battery capacity and would likely be assigned to longer off wire hauls like Mission Bush. Certainly the North Island X-64 would operate as a medium power overhead line electric locomotive to travel to/from unwired full length lines branching off the electrified spines, for example Kinleith.

While the conventional electric locomotive (and all the other motive power options) concept was specified to match the 3MW DM diesel-electric reference, a new real world electric locomotive would be specified to be more capable than a DM. Tractive effort will be the same, set by a combination of same weight on driving wheels and equivalent state of the art traction control, but the power of the electric locomotive could easily be as high as 5 MW. The result of this will be that both can haul (start) trains of the same weight, but the electric locomotive will both accelerate a train to speed faster and run faster over the same section of uphill track.

Conversely, Stage 1 of Option 4 partial electrification would commence operation using the existing EF electric locomotive fleet. Under this scenario, all 15 surviving intact units[52] would complete the life extension programme and remain in service until approximately 2035. These have the same power as the DM reference but only ~ 70% of the tractive effort.

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[50] Regenerative braking can return current to the overhead line to be used by other trains, but is only effective if there is another train in the section and demanding energy. It is possible to arrange the power supply so this recovered energy is fed back into the public electricity network or charges batteries at the TSS, but there are complications in this. An onboard battery is required for last mile work regardless, so serves a useful dual function.

[51] Consideration should be given to a more capable battery during the detail phase of the project, checking if this is useful and adds value.

[52] Two further loco “hulks” exist, missing some parts.

7.7. Battery Electric Locomotive

7.7.1. Introduction

All battery locomotive equipment downstream of the batteries is the same as a modern diesel-electric or OLE electric locomotive, so exists as well developed commercial solutions.

The driving factor for battery locomotives relative to diesel-electric is the low energy density of batteries per unit weight compared to diesel fuel. Time to recharge compounds the impact of the resulting limited range. Within the constraints of the NZ network, the volume of batteries is not limiting, but the weight of a battery fit out is.

7.7.2. Size and layout

A range of different sizes of battery locomotive were considered, and two were explored in depth. They are referred to as "X-64[53]" and X- 66[54]". The X-66 represents a simple conceptual "conversion" of the new Stadler DM locomotive to battery power. That is a double cab, six driven axle locomotive of 3MW power with a gross weight of 108 tonnes. A six axle locomotive is conventional technology and the gross weight is derived from this and an allowable maximum axle load of 18 tonnes. The weight of the locomotive itself reduces possible battery capacity and the high power of the single unit exhausts this limited capacity quickly.

The X-64 starts with the DM configuration locomotive and optimises it to maximise battery capacity by minimising loco weight within the 108 tonne gross weight limit. The end result of this is a single cab locomotive of 1.8 MW power, with only four of the six axles driven, to reduce the weight over other components and leave more of the 108 tonnes available for battery.

The concept is that two 108 tonne X-64 locomotives are used on the reference train, this combination allowing a very high battery capacity to be taken on the journey. A towed battery tender[55] is often proposed and essentially two smaller locomotives is the tender concept stripped of its operational disadvantages by a series of logical steps. These are:

- the need to move the tender to behind the locomotive when reversing at the end of a journey, involving breaking and remaking heavy duty electrical connections in an operational environment.
- the provision of a cab on the tender to allow the coupled pair simply reverse at destination, with all this entails for the design of the unit, taking it a step towards being a locomotive.
- The need for battery cooling and management systems on board taking it another step towards being a locomotive.
- The need for more than six axles, to carry the weight of the batteries necessary for acceptable power with range.

The end result was that the tender concept of spreading batteries over two vehicles is essentially being adopted, but in the form of two medium power locomotives rather than a high power locomotive towing an unpowered battery tender.

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[53] Six axles and four of these driven hence the 6 and the 4. A1A-A1A wheelset configuration.
[54] Six axles and all six of these driven hence the 6 and 6. Co-Co wheelset configuration
[55] A wagon containing more batteries towed behind the battery locomotive and wired into the locomotive, significantly increasing on board battery storage capacity.

This should be seen less as two locomotives but conceptually as the functions of a locomotive and tender pair being spread between the two. For the conceptual purposes of the report we have a 216 tonne, 11.6 MWH, 500kN and 3.6 MWH “locomotive”. Standardisation, flexibility and convenience are optimised with this conceptual approach.

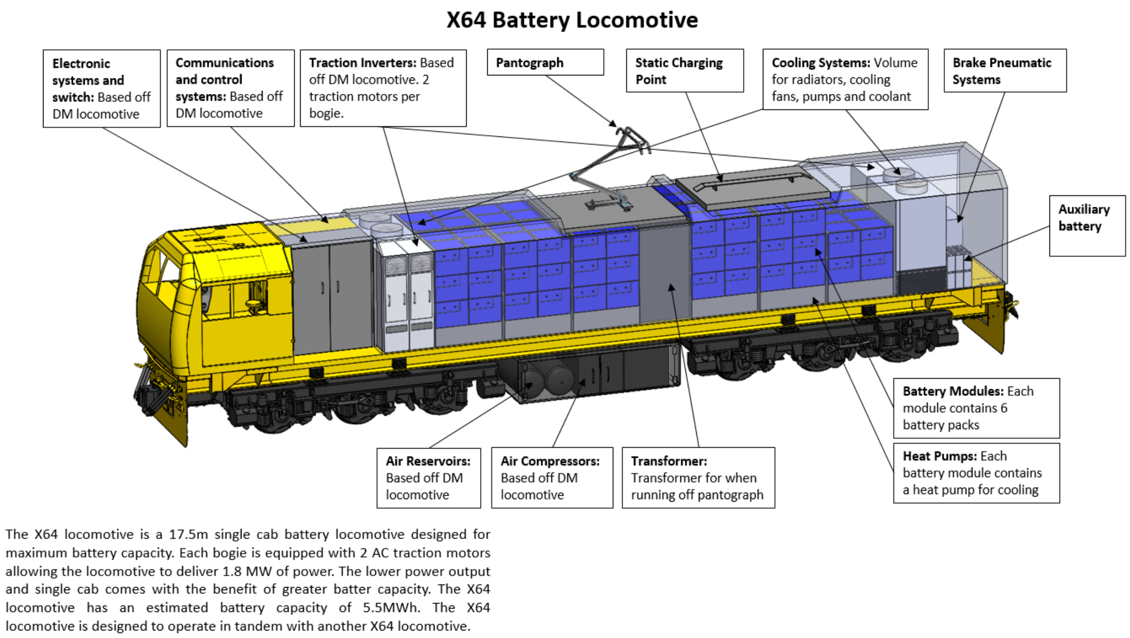
Concepts for an X-99 articulated locomotive with nine powered axles and a X-88 twin body locomotive with eight driven axles were also evaluated, but neither offered enough capacity or the flexibility of the medium sized X-64.

Loco	Power (kw at wheels)	Starting TE (kN)	Battery mass (kg)	Battery capacity by 2030 (MwH)	Gross Mass (tonnes)	Length (m)
X-66	2500	370	30,500	4.40	108	18.196
X-64	1800	250	37,900	5.80	108	16.200
X-88	3250	494	47,160	7.20	144	23.000
X-99	4000	556	59,000	9.00	162	23.000
X-64 pair	3600	500	75,800	11.60	216	32.400
DM	2500	415	-	-	108	20.000

Table 26: Comparison of battery locomotive configurations.

The X-64 is the preferred configuration at this stage, with the best ratio between tractive power and battery stored energy. All simulations, and technical analysis assume two X-64 locomotives being used on the reference trains and they are compared to single conventional electric, diesel or biofuel locomotives of DM size. However, the economic model has assumed that X-66 locomotives were used on some suitable routes. This is likely to be feasible in the mid to late 2030s but by assuming this earlier the benefits of the battery option are slightly overstated. However, it was judged this was not significant and more than offset by the conservative assumptions discussed in **13.11**. Certainly this does not change the overall ranking.

Figure 15 overleaf shows the basic concept of the X64 locomotive.



The X64 locomotive is a 17.5m single cab battery locomotive designed for maximum battery capacity. Each bogie is equipped with 2 AC traction motors allowing the locomotive to deliver 1.8 MW of power. The lower power output and single cab comes with the benefit of greater batter capacity. The X64 locomotive has an estimated battery capacity of 5.5MWh. The X64 locomotive is designed to operate in tandem with another X64 locomotive.

Figure 15: X64 battery electric locomotive concept layout

7.7.3. Batteries

Three commercial scale battery chemistry options[56] were considered, in terms of their energy density, specific energy, power density, charge and discharge rates, and lifespan vs depth of discharge vs charging rates. The OpenTrack modelling described earlier was used to understand realistic battery capacity options. Static charging was modelled by a ‘step input’ into the battery at a given location. The time required to deliver this amount of energy was added to the overall journey time.

For the purposes for assessing the battery capacity vs route demands, the batteries were required to complete the route operating between 20% and 80% of the nominal capacity. Lithium ferro-phosphate (LFP) is slightly less critical in this regard and can be charged to 100% without significant degradation so in practice could be operated to a greater fraction of its nominal capacity without significant loss in lifespan.

Because multiple locomotives are required, the more robust, but lower performing LFP chemistry is viable. This is attractive as it is not only safer and cheaper but is likely to last longer in service. Lower life cycle costs are expected although this is offset by the need for a slightly larger fleet of locomotives.

But overall, a generic battery chemistry is being assumed for the purposes of basing the simulations in reality. The supply industry will settle on the optimum battery for 2030 and onwards.

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[56] Lithium titanium oxide (LTO); Lithium ferro phosphate (LFP); nickel cobalt aluminium (NCA).

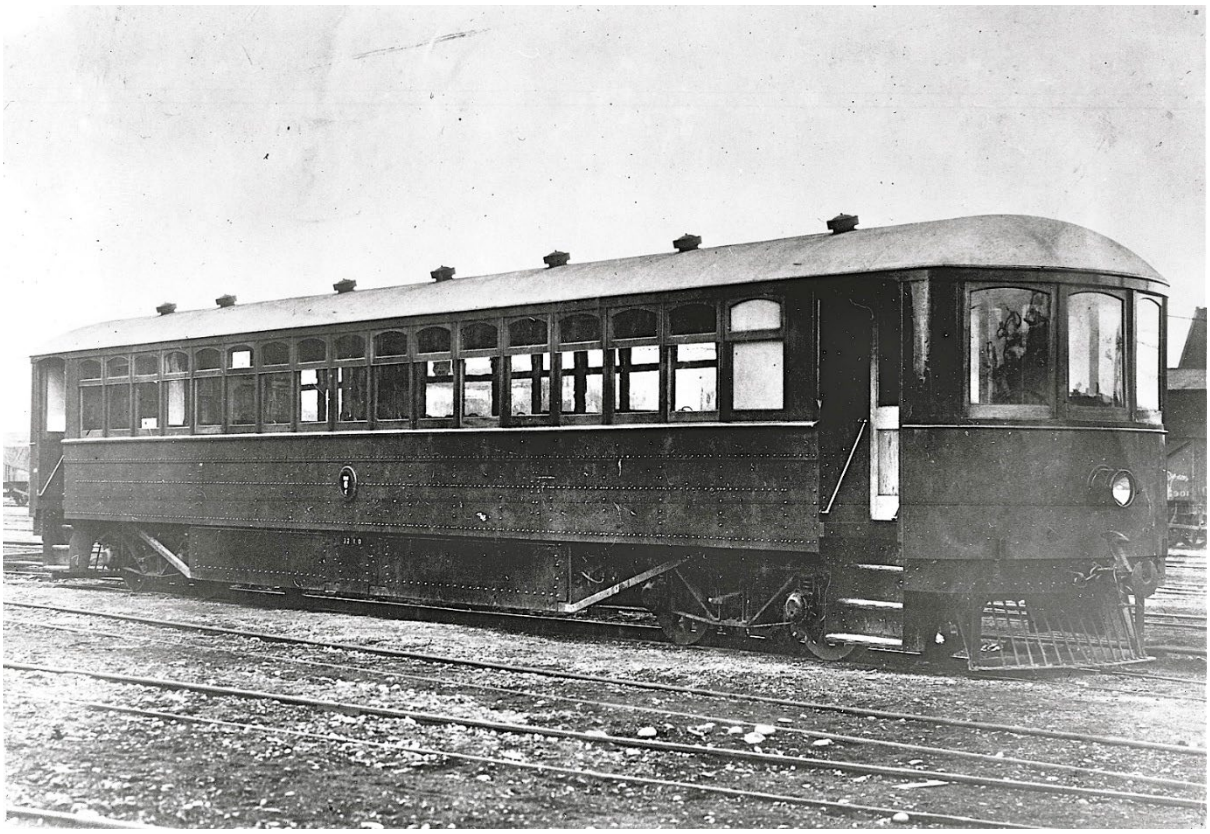

Figure 16 : Battery – electric mainline railway vehicles are nothing new, although the performance of the available lead acid batteries ensured they were of limited usefulness. NZR Edison Battery Electric Railcar ("Rail Motor") RM6. In service Christchurch 1926-1934. It was destroyed by fire during overnight charging in 1934, a keen reminder of the importance of sophisticated computerised battery management systems in the proposed battery locomotives (National Library Collection).

7.7.4. Battery Pack

The battery pack volume and mass requirements needed to consider cooling systems, battery management systems, safety systems, maintainability/accessibility, modular designs, packaging and supporting structures. Only modules designed for transport use and featuring provision for liquid cooling were considered suitable. Most of the modular packs currently marketed for rail purposes have around half the specific energy values being achieved for what are effectively monolithic packs in light road vehicles (passenger cars). An intermediate value was chosen as increasing pack density is a progressive area of research and is a key metric when comparing competing products.

Overall, the battery feasibility assumption depends heavily on forecast improvements in capacity, packing density and cost over the next decade.

7.7.5. Charging

KiwiRail's future lineside charging arrangements will primarily be driven by the solutions developed for industry worldwide. By 2030 static locomotive chargers, their voltage and other standards and the way they connect to locomotives will be product lines in the catalogues of major electro-technical companies and KiwiRail and its locomotive suppliers will select the variants that meet local needs. As bus sized chargers are today for buses. Charging and locomotive fleet need to be an integrated system.

Currently, the availability of economic charging for battery locomotives is the largest uncertainty surrounding the choice of battery-electric locomotives as KiwiRail's preferred option. This is a consequence of the sparse nature of the NZ electricity grid transmission and lines distribution network, the high-power demand of fast charging batteries of the large size required for a pair of locomotives and the distribution of the required charging facilities throughout NZ, including rural and regional areas. It is proposed this be a key area for further investigation in any Detailed Business Case.

7.7.6. Power supply

All charging options are dependent on the available high voltage (HV) supply. This means the main Transpower transmission grid or, for the majority of locations, the local lines company network. The power demands for rapid charging of two or four[57] X-64 sized locomotives at a rate of 1C[58] are equivalent to a decent sized town or a significant industrial facility. In many rural lines networks the basic network will not be able to supply the load at all. Significant upgrades will be required.

KiwiRail has already encountered considerable difficulty in connecting new traction sub stations (TSS) to the local lines or Transpower network in Wellington and Auckland. The 2021 electrification study also illustrated this, with some of the notional grid connections involving significant infrastructure upstream of the railway equipment (a 6.5km long HV feeder in Bay of Plenty for example) .

The electricity industry commissioned Boston Consulting Group report "The Future is Electric" [59] sets out the areas where the NZ electricity system needs investment if it is to support the national imperative to decarbonise by electrifying currently fossil fuelled activities. This covers generation, transmission and distribution. Finally, a recent news article[60] reported on the same type of challenges being encountered by a provider specialising in converting industrial fossil fuelled boiler users to electricity. The current situation is that the large new electricity user has a "first mover disadvantage" and had to bear much of the cost of upgrading regional electricity infrastructure, which usually renders conversion impractical.

This challenge could seriously undermine the viability of a battery based operation that depends on judicious enroute charging. With the costs of static chargers and connection, provision of alternate sites able to cover for an unavailable prime site will be a substantial investment, to be avoided if possible. This study is assuming that a national initiative will overcome these connection and supply difficulties but recommending that the practicalities of this be more closely examined in the next stages of work, including practical experience during the proposed pilots.

7.7.7. In-motion charging

It had initially been assumed that a battery locomotive would be able to charge from an overhead wire strung for a few tens of kilometres at the right places on a battery operated route: In-Motion Charging (IMC)[61]. This would enable locomotives to be able to complete the more demanding duty cycles without stopping to top off batteries. While superficially appealing, the need to install high

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[57] If two trains were to be charged simultaneously while paused at a single track crossing loop (passing place) four locomotives would be involved.

[58] "1C" means charging the battery at a **rate** that moves it from empty to full in 1 hour

[59] https://web-assets.bcg.com/b3/79/19665b7f40c8ba52d5b372cf7e6c/the-future-is-electric-full-report-october-2022.pdf

[60] https://businessdesk.co.nz/article/infrastructure/breaking-down-the-barriers-to-electrification-one-boiler-at-a-time (Pay walled)

[61] IMC is now accepted and developed technology for light rail and trolleybuses but the magnitude and rate of charging and the drivers for adoption differ from heavy rail.

capacity on-board chargers, technical capacity limits with standard pantographs when stationary and the particularly high cost of the power supplies for isolated sections of wire after analysis resulted in IMC being set aside in favour of static charging. The consequence of this was to remove the need for an on-board DC charger (refer 7.7.9), freeing weight for more battery capacity. The twin unit X-64 concept further reduced the need for and benefit of not including IMC.

Where range extension of battery locomotives by the use of OLE was beneficial, this was found to be best achieved, if needed, by the extension of an existing OLE a distance up the unwired route. This delays the need to begin drawing down batteries, without a very expensive isolated OLE section and standalone power supply.

This approach can only be applied to lines attached to the NIMT electrified area (and proposed extension). Adoption depends on the relative cost of static charging, use of additional locomotives and the cost of the extensions. With the time and capital cost of providing for static charging or OLE extensions, in some cases taking more batteries along, in the form of an additional locomotive, will be the best value solution.

Balancing these to determine the optimum for each North Island route are matters for the detail phase of work. As a battery loco being equipped to use OLE comes with a weight and capital cost, this feature would only be installed in NI locomotives. All X-64 style battery locomotives would likely make provision for this equipment but South Island assigned locomotives would use the unused space, weight and budget to install extra batteries.

7.7.8. Battery Backup

Sustained high power charging facilities place demands on the HV system that may introduce voltage instability and exceed the capacity of HV equipment and lines. One way of reducing this peak is to provide each charging station with a substantial battery storage capability (ESS or Energy Storage System). These batteries would be of capacity roughly equivalent to the battery capacity of the locomotives to be charged at any one time, so 10 MWH at a lineside charger. This would allow very high 1C charge rates to be largely covered by the battery stored energy, with a manageable line supplement during charging and steady recharging at rates much less than 1C for the hours between charging. This will also provide limited but potentially crucial resilience back up for sites with single source HV connections.

Limited study of the option for ESS at charge points suggests this offers a way to make high rate locomotive charging viable in areas served only by local lines networks.

7.7.9. Locomotive DC charger

Batteries operate on direct current (DC). Whatever system is used to supply the power to the charger or site, the last stage is to produce DC at several thousand volts and apply this directly to the battery. As a result of this study, KiwiRail's assumption is that its battery locomotives would use off-board DC charging[62]. A static charger would be fed grid or lines HV AC and convert this to DC at up to 3000 volts, which would be fed to the locomotive batteries through a static reverse pantograph[63]. This avoids the cost, weight and volume of a substantial charger on each unit, replacing this with a shared off - locomotive installation. This also allows a relatively straightforward approach to ensuring a balanced load on the 3 phase HV supply. The lineside DC charger is fed by a three phase

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[62] As employed in any battery light road vehicle capable of being charged at very high rates.
[63] A retractable connector that reaches from a gantry down to connect with a loco parked below and, unlike a conventional locomotive pantograph, is designed to handle the high currents involved while static. See Figure 12.

transformer and AC/DC rectifier in the same way as any traction substation in the Wellington electrified area.

Figure 17: An example of a Reverse Pantograph Charger intended for charging heavy road vehicles. Rail will be similar but sized and rated for power and current several times that required by road vehicles.

Source: ABB HVC ACM ACD CE 300 D-0-0 | ABB

7.7.10. “Spare” battery locomotives

For the outlier routes, those that have a combination or particularly high energy used and difficulty in accessing high capacity electricity supplies, an economic solution is simply to add an additional locomotive to the train to provide a 50% increase in battery capacity.

While on the face of it “wasteful”, the cost of the more difficult charger power supplies is such that the trade-off is easily made case by case: between more locomotives and fewer charging stations.

7.7.11. Charging time

The models all assume 1C rate charging and a pause long enough to enable the train to complete its duty cycle. There will be an impact on train running times but these will reduce as battery performance improves. But modelling suggests that the delays are relatively minor and by the 2030s some charging stations will no longer be required for regular use. The next phase of this project will need to model charging time and operational trade-offs in more detail.

7.7.12. Regenerative braking

Electric drive locomotives use their traction motors as generators where extended braking is required, such as when descending a long grade. The energy gathered is dissipated as heat by diesel locomotives and (sometimes) returned to the overhead line by electric locomotives.

The battery simulations assume 25% of available energy is recovered in the batteries when a battery locomotive is braking.

Note that there are limits at the rate that batteries can accept charge, so it may be necessary for suppliers to combine capacitors with batteries to ensure no braking energy is wasted. This is an important technical detail underpinning the development of practical battery locomotives but will be advanced by suppliers, not KiwiRail.

The resisting force applied to the leading wagons by two or more locomotives applying high levels of regenerative braking from the front of the train can be sufficient to buckle the train and derail it. The combined braking forces all pass through the couplers of the trailing loco and the lead wagon. In curves the lateral and vertical component of these forces may exceed that required to lift a lighter wagon near the front of the train up or derail it sideways.

Having to keep these forces at a safe level means not all the available energy can be recovered and used to charge batteries. Spreading any trailing locomotives through the train mean each can apply higher braking forces to its adjacent wagons safely. Such “distributed power” operations may be necessary to recover sufficient energy and offset some of disadvantages of employing two X-64 locomotives rather than a single high power unit.

7.7.13. Battery swaps

The potential for battery swapping as a rapid alternative to charging was not considered in any detail. This is being considered for road vehicles. In the rail context, swapping locomotives enroute could be seen as the equivalent of road vehicle battery swapping.

Nevertheless, the option for battery (or complete locomotive) swapping should be reviewed in more detail in the future phases of this project.

7.8. Hydrogen and hydrogen fuel cell electric locomotives

7.8.1. Hydrogen in internal combustion (IC) engines

The burning of hydrogen in an IC engine was eliminated from the study at the “long list” stage[64]. The reasons for this were:

- This combines the poor EROI of hydrogen with the low thermal efficiency of an IC engine.
- The technology and hydrogen supply at scale will not be available for at least a decade.
- There are significant technical challenges to be overcome: at the R&D level, storage of hydrogen on the locomotive, the establishment of a completely new supply chain and likely the re-engineering or replacement of existing locomotive prime movers despite;
- Local emissions are not eliminated.
- This being an interim solution only, wedding high maintenance and low efficiency existing technology with expensive new generation energy carriers, so transformation is not achieved.

Substantial effort and expenditure would be required to deliver a poor performing interim solution. This would likely distract from and delay transition to a genuinely transformational solution.

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[64] Toyota's Developing A Hydrogen Combustion Engine! - YouTube and The Unfortunate Truth About Toyota's Hydrogen V8 Engine - YouTube provide a laypersons (and entertaining) engineering guide to the use of hydrogen in IC engines.

The preferred extended transition solution, for reduced GHG emissions from conventional internal combustion diesel-electric locomotives, should this be required, is drop in biofuel, pending a direct transition to transformational technology.

In the event hydrogen is to be used in a locomotive, a fuel cell is the preferred energy conversion approach.

7.8.2. Hydrogen fuel cell locomotives.

7.8.2.1. Approach

While there are early production road vehicles and some prototype passenger trains in demonstration service, hydrogen fuel cell locomotives exist only as a handful of prototypes. Pilot city bus fleets represent the main application of hydrogen fuel cells in vehicles in a working environment. Green hydrogen supply chains are also far from being established.

Beca Group Consultants was engaged to develop concepts for the hydrogen supply chain and a hydrogen fuel cell locomotive. They achieved this by partnering with Hiringa Energy and Systra Consultants respectively.

7.8.2.2. Overall issues

Hydrogen has a low energy density. Even at very high pressures or cryogenically liquified a large storage volume is required on board a locomotive if it is to be able to complete its required duty cycle – run from one terminal to another hauling a useful load.

The highest pressures (700 bar or 10,000 psi) or liquid hydrogen (-252.8 degrees C) introduce their additional own cost, safety, and complexity challenges. Hydrogen embrittles steel, further complicating the challenges of storage and driving the use of composite tanks.

A lower, but still very high and demanding, storage pressure of 350 bar (5000 psi) was assumed for the KiwiRail exercise. This reduced pressure is accepted as being practical for larger rail vehicles with greater volumes of onboard space, whereas road vehicles require the very highest pressures to deliver useful quantities of volume without excessively compromising the useable space remaining.

Fuel cells are not suited to varying loads. A hydrogen fuel cell locomotive (or road vehicle) must incorporate a substantial battery to average out constant changes in power settings. In effect, an H_2 fuel cell locomotive (or road vehicle) is a hybrid.

Fuel cells are very simple in concept, but the practical execution of this concept results in a precision device requiring significant support equipment and clean operating conditions. These systems include the delivery of air at above atmospheric pressure to improve power density, a dual circuit cooling system (keeps cell internal coolant segregated from locomotive cooling system), a system to humidify incoming H_2 gas to maintain the membrane and purging cycles to prevent impurities from building up. In addition the cells and their support equipment require protection from the shock and vibration that can be experienced in the rail environment. The membranes are a lifed item and either new cells are required relatively frequently or, more likely, an exchange refurbishment industry will develop[65].

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[65] This was not covered in detail in this study, but reading suggests that all this work will likely be concentrated on suppliers working to OEM standards in a major economy. Currently KiwiRail refurbishes all major locomotive components locally, either itself or using sub-contractors, or at

Fuel cells are of moderate output and a significant number are required to be combined together in stacks with the above support systems to provide power output in the range of a mainline locomotive.

7.8.2.3. Hydrogen Fuel Cell Locomotive

The initial concept for a locomotive used the required starting point of the DM rolling chassis and performance.

Systra was unable to package the required H_2 storage, batteries and fuel cells on a locomotive of this size and performance and deliver a useful range. On essentially any route a DM sized locomotive would require mid route refueling, whether double or single cab. While not impossible, the cost, complexity and time delay of mid route H_2 replenishment makes this option effectively impractical.

The characteristics of hydrogen impose constraints of weight and volume that are more severe than occur in a diesel locomotive, with its energy dense fuel and relatively compact prime mover. The result is to drive a similar solution as the battery locomotive, the required performance being spread over two smaller locomotives, that provide more total spare weight carrying capacity and volume per unit of performance than the single locomotive. The major difference from the battery case is that the limiting factor for batteries is weight, while for hydrogen weight and volume are both limiting.

Therefore the recommended H_2 fuel cell locomotive is a lower power single cab unit, used in pairs in the same way as the optimum battery locomotive.

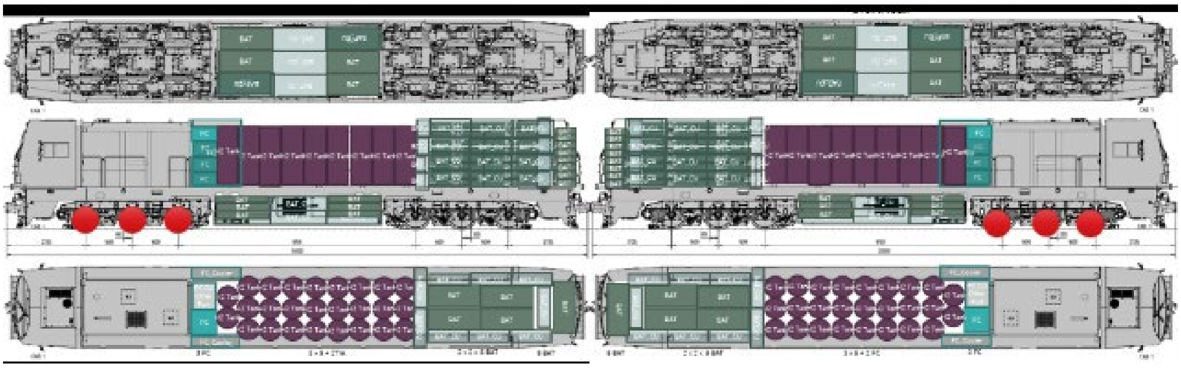

Figure 18: Hydrogen locomotive layout. From Systra study.

Unlike the battery locomotive, each H_2 unit has to be full length (nominal 20m) to provide the required storage volume. The body is preferably full width, to maximise the volume of H_2 storage. The result is presented in **Figure 18**, above.

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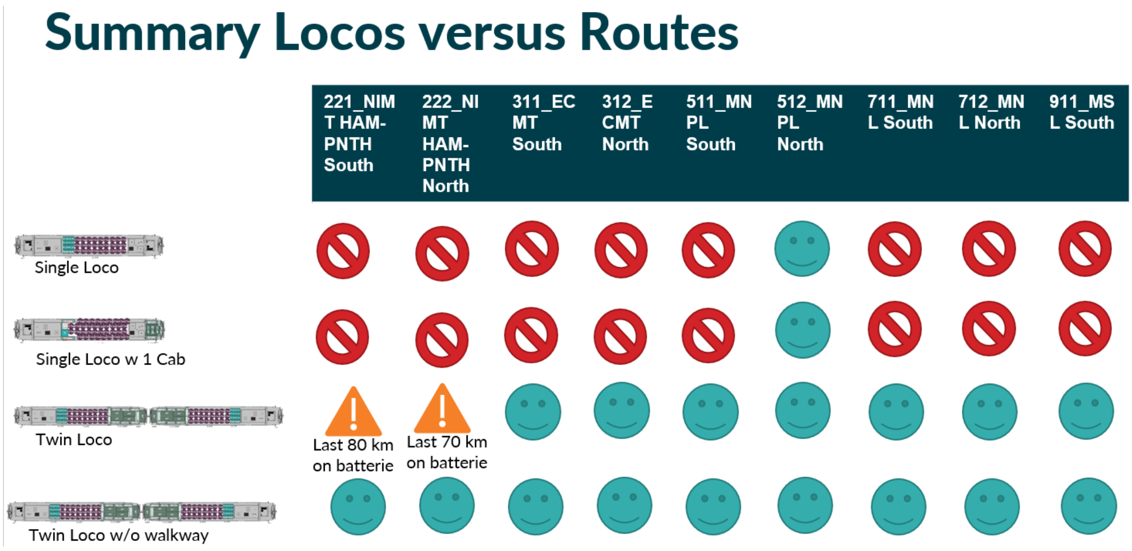
least has the capability to do so. A matter to be considered is the additional supply chain complexity and fragility that some of this new technology could introduce.



Summary Locos versus Routes

	221_NIMT HAM-PNTH South	222_NIMT HAM-PNTH North	311_ECMT South	312_ECMT North	511_MNPL South	512_MNPL North	711_MNL South	712_MNL North	911_MSL South
Single Loco	🚫	🚫	🚫	🚫	🚫	☺	🚫	🚫	🚫
Single Loco w 1 Cab	🚫	🚫	🚫	🚫	🚫	☺	🚫	🚫	🚫
Twin Loco	⚠ Last 80 km on batterie	⚠ Last 70 km on batterie	☺	☺	☺	☺	☺	☺	☺
Twin Loco w/o walkway	☺	☺	☺	☺	☺	☺	☺	☺	☺

Figure 19: Hydrogen locomotive types suitable for particular routes. From Systra study.

The full width body twin unit can meet the duty cycle on all routes. Systra however selected the slightly lower hydrogen capacity “hood with side walkway” body[66]. The only adverse consequence of this in the model is that the locomotive completed two of the routes on battery power (having used up all hydrogen), which has no material impact on the comparison.

The total hydrogen capacity of the recommended twin body locomotive is 743kg, stored in 52 x 594 litre tanks, 26 in each of the twin locomotives.

Conceptually, the use of two smaller locomotives is equivalent to the pairing of one full power locomotive with a hydrogen tender, but the logic applied was that this avoids the logistics challenges of having to shunt and reconnect the hydrogen tender at terminals. Similarly, a semi permanently coupled single cab full power locomotive and an unpowered (single cab) driving tender could be employed, but the net result is economically similar to two medium sized locomotives and is a technical refinement below the resolution of an economic comparison exercise.

Throughout the Systra report their nomenclature is to refer to these two smaller locomotives as “one locomotive”, their logic being that this is a twin body locomotive. Systra therefore costed the hydrogen specific equipment required to completely fit out two bodies. For economic comparison, the H_2 fuel cell DM loco equivalent is assumed to be two medium sized locomotives operated in multiple and KiwiRail added in the cost of two bare DM rolling chassis, with only three traction motors each, and their associated costs.

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[66] Due to a misunderstanding that a walkway along the units was essential.

7.8.3. Hydrogen Refueling constraints

Surprisingly, Hiringa advised significant constraints to the rate at which the sizeable volume of hydrogen tanks can be replenished. This is a consequence of the on board tank becoming heated by the effect of increasing pressure to move the product from refueling tank to loco tank, requiring cooling, and the cost and practicality of paralleling multiple such pumping and cooling systems to feed a locomotive simultaneously. **Figure 20** is from the Hiringa report:

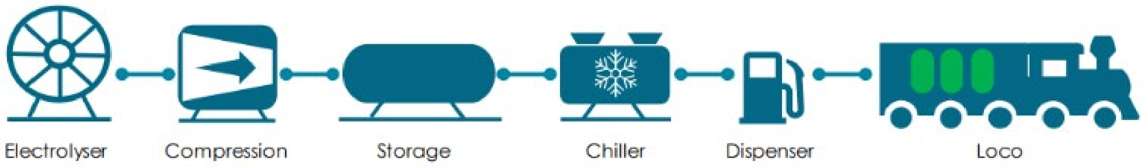

Figure 20: Components of a hydrogen gas supply system. From Hiringa study.

Hiringa recommend a dual dispenser for each locomotive to deliver a theoretical maximum rate of 864 kg/h. Hiringa estimate that a practical dual dispenser can fill an empty locomotive in 1-2 hours, Typically the refill is more in the range of 600kg, 45 minutes with a dual dispenser, 1 ½ hours with one.

7.8.4. Production of hydrogen

Hiringa produced a well thought through study showing how the green production of hydrogen for KiwiRail locomotive use was practical and credible. Because of the difficulty of storing and transporting hydrogen, their business model is based around hydrogen being produced on the dispensing site using nearby renewable electricity sources installed to meet this need. Storage is limited and only provided to the extent required to balance demand during a 24 hour period against the cost savings of avoiding peak electricity tariffs, while minimizing capital spend on electrolyser capacity.

The hydrogen production network required to service the 2030 KiwiRail need has a capacity (demand) of 199MW. This can be compared to the planned Hiringa heavy road transport production network of 140MW. A hydrogen production and dispensing network for rail is credible, within the same order of size as their planned initial road network. See **Figure 21**.

While complex optimisation of installed hourly capacity, on site storage volume and most economical location for energy supply would be carried out as part of implementation, for the purposes of this study the average cost of hydrogen is sufficient. Price curves for Hydrogen were provided by Hiringa and combined with MBIE data. Refer to **Figure 30**.

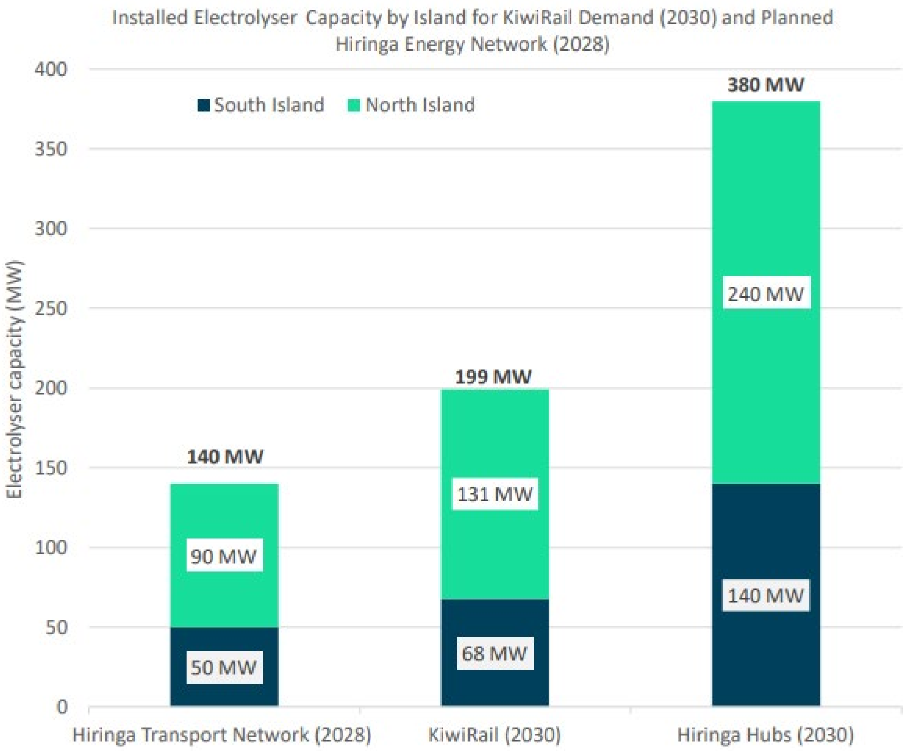

Figure 21: Comparison of total proposed size of KiwiRail network with planned Hiringa networks for other markets.

7.8.5. Discussion of H_2 fuel cell locomotive

The battery locomotive uses the generated electricity almost directly, without the complex technology, energy losses and risks resulting from interposing an additional intermediate energy carrier (H_2) between generation and locomotive wheels.

The combination of poor overall energy efficiency, complexity, maintenance requirements, the requirement for a battery in addition to the fuel cell equipment, development risk, and also requiring a pair of locomotives, mean that an H_2 fuel cell locomotive compares poorly to a battery locomotive (also a pair) wherever the duty cycle is within the capability of a pure battery locomotive.

Major Australian rail operator Aurizon supports this conclusion in a recent presentation on their investigations[67]. For trips of up to 800km battery locomotives are favoured. This covers 80% of their traffic.

For Aurizon hauls longer than this, hydrogen is indicated. It is of interest that this is not a hydrogen locomotive, rather a towed hydrogen generating unit, providing electricity to extend the range of standard battery-electric locomotives. See **Figure 22**.

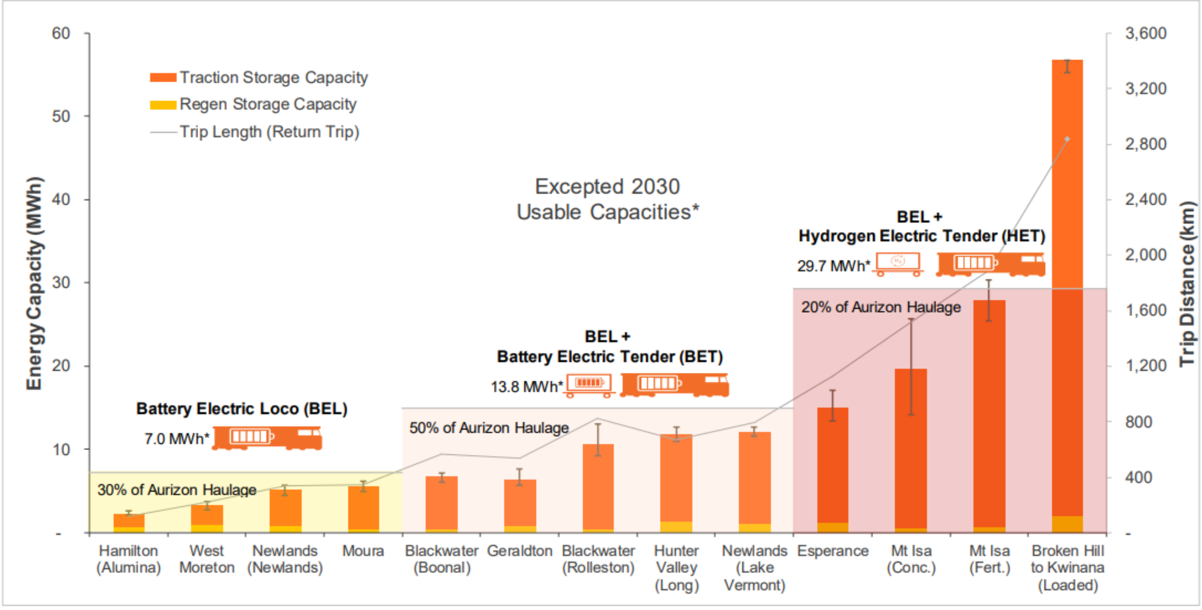

Figure 22: Aurizon: optimum locomotive types for different journey lengths.

The crucial issue is that, within the limits of the assumptions underpinning this study, most duty cycles on the KiwiRail network are within the capabilities of a plausible battery electric locomotive consist.

There may be a role for an Aurizon style hydrogen charging tender for some challenging routes with high power demand and poor electricity supplies, but even these are more likely to be best met by taking an additional standard battery locomotive along as a working battery tender. Indications are that hydrogen fuel cell locomotives are unlikely to be proven products before the late 2030s so as an option they intersect with the DM diesel locomotive life extension c.2040 rather than KiwiRail needs

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[67] Hydrogen Connect 2022 Summit: Putting Aurizon's Climate Strategy Into Action. Presentation by Aurizon. https://www.uq.edu.au/news/article/2023/04/charging-towards-more-sustainable-heavy-rail-network provides a summary of the work and a link to its publication.

over the coming decade. Finally, there remain significant concerns on the acceptability of hydrogen in tunnel operations. These have yet to be addressed in overseas pilot operations and were not considered in this study.

For these reasons hydrogen fuel cell locomotives (or range extender units) have been rated as a future fall back option to 1) battery-electric locomotives and 2) biofuel, if required in the late 2030's.

7.9. Bio-fuel

There are detailed definitions for biofuel (non-mineral fuel) but this summary report simplifies it into two streams. Sustainable fuels that are blended with fossil diesel to be used in a conventional locomotive prime mover and those used pure (100%) in a conventional locomotive prime mover. In both cases the engine fuel system may be modified to suit the exact fuel characteristics.

Benefits of biofuels include:

- They are a renewable, low-emissions high energy density fuel that can reduce GHG emissions from transport now[68].
- They are not as dependent on new fuel infrastructure or new vehicles as other ways of reducing GHG emissions (for example, electric vehicles or hydrogen fuel cell vehicles).

7.9.1. Blended biofuel

Invariably the blended component is conventional biofuel (also known as first generation). These have been used for many years and are made from edible biomass / agricultural crops such as starch (from potato, wheat, barley and corn), or sugars (from sugar cane and sugar beet), or oil (from rapeseed oil and soybean oil).

First generation biofuel can be problematical. Considering the full lifecycle of fuel production and use, there is considerable evidence that many 1st generation biofuels increase emissions relative to the use of fossil fuel[69]. It uses food crops and contributes to the conversion of natural areas to agriculture, not always visible to the end buyer[70]. Production from waste sources is not scalable.

Legacy locomotive prime movers can successfully use 1st generation biofuel blended into fossil diesel, to a limit of about 20%. The consequence of such blends or beyond, if any, is increased maintenance, wear and deterioration of fuel system components, ash deposits and algae infestation of fuel tanks. These are all elements that can be overcome or managed and KiwiRail is confident that the locomotive prime mover supply industry will provide its customers solutions to biofuel blends.

However, blended fuels are not considered in detail in this study. KiwiRail takes its diesel from the general supply and will be a consumer of a blended product rather than needing to take active steps to create the supply or adopt it, aside from the need to adapt locomotives to cope. In addition the solution is transitional, making relatively minor reductions to GHG emissions while retaining all the other disadvantages of internal combustion engines.

Combined with this, KiwiRail has particular concerns regarding the potential for adverse ILUC effects of generation 1 biofuel and does not see its use as a desirable path to rail decarbonisation, bearing

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[68] Setting aside the constraints holding back increasing volumes of supply

[69] https://www.eeca.govt.nz/insights/eeca-insights/liquid-biofuels-insights-summary/ Note that the EECA has failed to appreciate that rail can electrify using batteries and records rail as being one of the limited areas that advanced biofuels would be appropriate for. This actually aligns with the findings of this KiwiRail report, set aside batteries/electrification and KiwiRail agrees that biofuel is the next best option.

[70] ILUC – Indirect Land Use Change. Penalising and reducing this is becoming a more important part in northern hemisphere biofuel regulations.

in mind the other alternatives available to rail. As a customer of the general diesel supply KiwiRail may be required to employ a diesel biofuel blend but it is not proposing that such fuels form a planned part of its zero carbon transition.

7.9.2. Drop in biofuels

Advanced biofuels (also known as second generation) are produced from non-edible biomass including agricultural and forestry residues, such as grasses and algae, and industrial waste and residue streams. They have low net CO_2 emissions and cause zero or low indirect land use change (Biofuels | Ministry of Transport).

Some of the advanced biofuels do not need to be blended with fossil fuels to be used in conventional vehicles and fuel infrastructure as they are chemically almost identical to fossil fuels. These biofuels are called **"drop-in" biofuels.**

In addition, are the **third and fourth generation biofuels**. Third generation biofuels use microorganisms as feedstock, while fourth generation biofuel focuses on modifying these microorganisms genetically to achieve a preferable hydrogen to carbon (HC) yield along with creating an artificial carbon sink to eliminate or minimize carbon emissions. These last two generations of biofuel are still in early development stages but potentially could provide zero carbon diesel for KiwiRail in the later period of this study (2050).

Regardless of source, this report assumed that the resulting fuel could be used in a conventional diesel locomotive, either directly or with realistic modifications to the fuel system.

KiwiRail engaged with Air New Zealand, which has a project to advance the production of Sustainable Aviation Fuel, a drop in replacement for aviation kerosene. Drop in diesel fuel is a by-product of the production of SAF.

The Air New Zealand proposal is based around the collection of forestry and agricultural waste, its concentration at intermediate plants for refining into "bio-crude" then its transport to a new plant at Marsden Point for refining into SAF and diesel. Municipal solid waste also has a role in the supply chain Air NZ is studying. The Scion report[71] covers the prospects for 2nd generation biofuel in New Zealand. While there are some real issues with this option, it is a credible route to achieving ZGHG while retaining conventional diesel-electric locomotive technology.

Issues with second generation biofuel are:

- It is a developing technology. There are risks and reasonably long lead times.
- Poor EROI. Collecting waste from a wide area, bio-crude production at numerous sites, transporting bio-crude to a refinery and then distributing the finished product. Transport, two stages or refining and distribution all consume significant energy.
- The conversion of sunlight to a useful form in the shape of a 2nd generation liquid biofuel is inefficient compared to other options like solar panels converting sunlight into charged batteries.
- Hence significant land area needed to produce the biomass required to replace the fossil diesel used by KiwiRail (let alone other users)

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[71] New Zealand Biofuels Roadmap Technical Report by Scion Research. Summary at: www.scionresearch.com/nzbiofuelsroadmap.

- There is competition for second generation biomass from other users, such as wood pellets to replace coal for industrial process heat.
- Time to bring the land into production and to establish the processing chain. As a solution it will be well into the 2030s before any production is available at scale.
- Some often quoted sources are also not scalable. Waste vegetable oils and the now closed Z Energy tallow plant, for example.
- KiwiRail will not have a dedicated diesel supply chain so it will take whatever the diesel source or blend is in the national diesel supply. Any work to convert this to a second generation source will be national and led by others. It is not considered practicable for KiwiRail to have a dedicated biofuel supply chain parallel to the national fuel supply chain.
- KiwiRail anticipates that electric battery technology, and the necessary supporting infrastructure, will have matured by the 2030s and will be a superior option for rail, compared to biodiesel to decarbonise its fleets.
- Therefore retaining liquid fuel powered locomotives is not KiwiRail's favoured solution given technology exists now (battery) that offers a lower emissions alternative, a simpler locomotive configuration and the potential to be transformative.

Ultimately, biodiesel is not the only route available to decarbonise KiwiRail's locomotive fleet. KiwiRail has an option to directly electrify its operations, an option not practical for all transport modes. In particular international flying will depend on the high energy density of liquid fuels for many decades, hence the strong interest by Air New Zealand[72]. Flying and some other users will be depending on biofuel, so rail being able to use electricity frees up the limited biofuel supply for them.

In addition to the challenges above, at the lower blends, biofuel does not offer KiwiRail transformational step change in carbon reduction it needs. It could thus create a distraction from the primary task of achieving a material reduction by 2030 and net zero by 2050.

However, 2nd generation drop in biofuel was identified as the next best alternative to the battery and electric option. It also had the possibility of offering early decarbonisation of the conventional but new generation diesel-electric fleet being retained to 2040 or beyond, ahead of their scheduled retirement and replacement by battery-electric locomotives.

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[72] Electricity is projected to become viable for the shorter routes of regional aviation and Air NZ are advancing battery aircraft for this duty cycle, showing how different modes or duties suit different solutions.

7.9.3. Biofuel summing up

Biofuels will only be a part of New Zealand's future low-carbon economy, and will need to complement other options as the country transitions to a more sustainable economy[73].

Decarbonisation of the transport sector will require a range of options, including biofuels in applications where they are most suited, for example the use of SAF by the aviation sector. However, in the case of rail, technology exists now which enables it to produce fewer emissions than transitioning to biodiesel would.

KiwiRail prefers options that move completely away from internal combustion engines over the study period, as these options offer improvements in more than just GHG emissions. These include local emissions, noise, particulates and other gases, reduced use of lubricating oils and reduced maintenance and servicing requirements. Biofuel maintains dependence on legacy internal combustion engines and drive technology rather than offering a transformational step change to something better.

Prior to this study KiwiRail had assumed that biofuel was a promising option, offering the opportunity to transition to ZGHG without upending the existing locomotive fleet, support organisation and operational model. However, a step change to electric appears to be viable for railway technology in a usefully short timeframe, more so than for some other freight transport modes.

This decision can be revisited if future work indicates that a battery solution is further away than assumed and an extended transitional approach to reducing emission is needed. Otherwise, a direct transition from fossil diesel/mandated blended diesel to electric is preferred.

It is recommended that 2nd generation biofuel be taken forward as the backup option to battery electric, as protection against delays to the progress of battery electric technology and as a way of potentially reducing the emissions of the diesel locomotives that are slated to remain in service until 2040. This should include continuing to work with Air NZ on their development of a 2nd generation biofuel supply chain for New Zealand.

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[73] https://www.eeca.govt.nz/insights/eeca-insights/liquid-biofuels-insights-summary/ But of interest to note that EECA has missed the transformative impact of battery electrification for rail in NZ.

7.10. Hybrid locomotives

Hybrid locomotives, a battery locomotive range extended by means of an onboard diesel generator or a diesel-electric locomotive with its efficiency increased by the addition of a battery[74], were initially considered to have promise, but quickly rejected when examined more closely.

At the required size of diesel generator for a range extender the fossil fuel equipment quickly displaces significant battery capacity, leading quickly to a situation where as little as 1/3 of the energy used is battery sourced. In effect, adding a diesel power source to a battery locomotive on KiwiRail duty cycles you quickly "chase your tail" and undermine the ability to complete most of a route on battery.

This comes at the cost of a highly specialised dual power locomotive, a product not available from established suppliers - something that would have to be developed and procured, that serves only as a transitional solution and that is not under development by the leading OEMs.

What was found to have merit is hybrid consists. This is where a standard battery-electric locomotive is paired with a conventional diesel locomotive and the two (or more) work in multiple to maximise the use of battery energy and the amount of battery energy recovered. The major OEMs advocate this as a transitional solution and are developing on board software that would manage the consist in this way. Conventional diesel and electric locomotives already operate in multiple consists and the only change is a management system to optimise the use of battery power and energy recovery. This would form part of the battery locomotive control system. This opportunity, with no comparable equivalent for road vehicles, essentially renders hybrid mainline locomotive development a dead end.

Figure 23 is from the Wabtec FLXDRIVE battery electric locomotive presentation/brochure. Note that the Wabtec example is aimed at North American haulage lengths beyond the sector length identified by KiwiRail and Aurizon as being suitable for battery locomotives, hence the eventual transition to hydrogen. In the NZ case the final transition is to an all battery consist.

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[74] The locomotive equivalent of a Toyota Prius or subsequent hybrid cars. A mostly conventional IC drive line made unusually efficient by combining it with an electric driveline which can recover otherwise wasted energy and work to supplement the IC engine at times of peak load, allowing the IC engine to be smaller and more efficient.

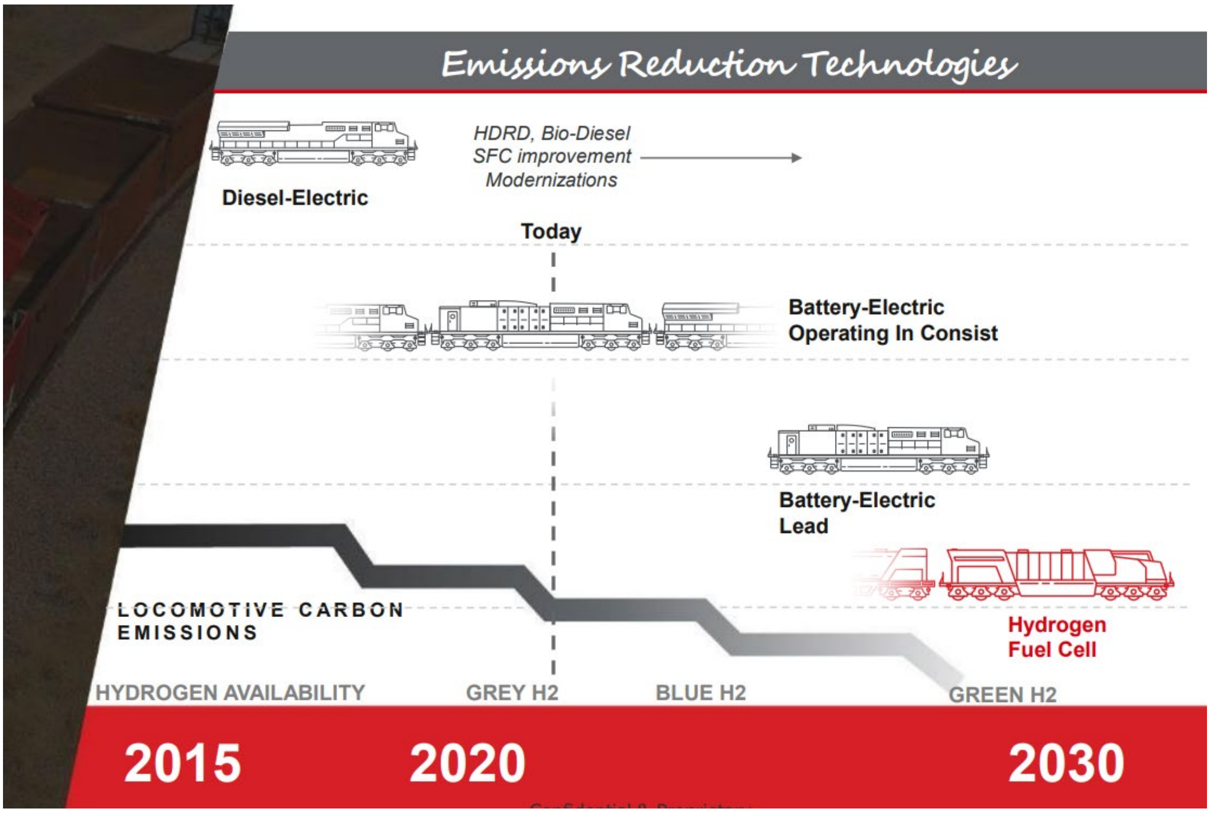

Figure 23: The role of hybrid consists in decarbonisation (long haul example – transition to H_2)

Mixed consist operation is recommended as a way to commence pilot operation of battery locomotives before the enroute charging infrastructure is in place, to gain experience in their operation and achieve early reductions in emissions on these routes.

8. Input to Economic Case – Locomotive Cost Estimates

8.1. Starting point

The Stadler DM locomotive served as the reference locomotive for performance and its basic rolling chassis is also used to represent the conceptual underpinnings of a pure electric, hydrogen fuel cell or battery locomotive. All these locomotives will use an electric drive line, including diesel locomotives, which is conventional for locomotives in this power range. A biofuel locomotive is essentially the same as a diesel locomotive in terms of capital costing.

The DM was also used as the reference for deriving capital costs for all the options because detailed costs were available. This is both practical and ensures relativity. All costs in a study of this nature can only be approximate, thus having a common basis for their derivation ensures that at least the relative rankings of conclusions are valid.

The same approach was used for maintenance costs and availability. The known costs and availability of diesel locomotives were used as the relative basis from which all other options were derived.

In summary, most locomotive economic inputs used in the economic model were derived from the known basis of existing or under order (Stadler DM) diesel-electric locomotives.

8.2. Capital cost calculations

While commercially sensitive, KiwiRail has precise information on the cost of the DM programme and thus the unit cost of each individual locomotive. The cost of major spares such as prime movers, traction system components and so on is also visible.

KiwiRail also has access to commercially sensitive information such as the cost of a locomotive cab, gained through other projects.

The Stadler DM locomotive was figuratively stripped of all diesel power train elements: fuel tank, diesel prime mover, main alternator and cooling system and the cost of these items removed from the unit cost. KiwiRail was thus able to estimate the cost of the bare rolling chassis ready to be (also figuratively) equipped with the competing zero or reduced carbon power trains. This “bare” chassis includes all structural elements, bogies, traction motors, cabs, braking systems and traction drive and control systems.

This approach was also used to estimate the cost of the bare rolling chassis six axle locomotives with only four of the axles powered. With the approximate cost of traction convertors and traction motors known, the cost of two each of these was removed. Finally, with the approximate cost of a cab known, the cost of a single cab bare rolling chassis could be estimated. In this way the cost of the medium sized A1A-A1A single cab units intended to be used in pairs could be estimated (hydrogen and battery options).

While an estimate only, it is referenced to the DM base locomotive, allowing a consistent comparison to be made.

A variety of approaches were used to then build up the alternative energy unit on this bare rolling chassis of known cost.

For the hydrogen fuel cell locomotive the costs provided in the 2022 Systra study were used. These costs were for a pair of locomotives, Systra taking the approach that this was a “twin body” locomotive, so their total was combined with the cost for two A1A-A1A single cab rolling chassis.

For the battery option, a variety of sources were used to estimate the cost of the above floor batteries and battery support equipment. Papers, commercial information and market studies searched on the internet were used to form a view of the costs per unit of capacity in the near term and for 2030 and later. This was combined with or checked against some information gleaned verbally from some of the major OEMs.

For this study the forecast performance and cost of battery systems in about 2030 was assumed and improvements to 2040 were also estimated.

Chemistry	LTO	LFP	NCA
Robustness / Thermal and discharge depth	High	Average	Lowest
Charge	Fastest	Lowest	Good
Discharge	Fastest	Lowest	Good
Capacity	Lowest	Good	Best
Lifespan (full cycles, 80% capacity)	>6,000 >10 years	>4,000 10 years	<3,000 <10 years
Recommended duty cycle	10-90%	20-100%	20-80%
Typical Cell Type	Cylindrical	Blade/Prismatic	Cylindrical
Specific energy kg/kWh	12.7	6.7 (2030) 11.8 (2040)	4.8
Energy density l/kWh	12.6	5.6 (2030) 11.8 (2040)	2.7
Cell surface temperature at failure	150	130	90
Minimum temperature (inc charging) (Deg C)	-30	0	0
Maximum temperature (inc charging) (Deg C)	55	55	45

Table 27: Summary of battery performance assumptions by chemistry

For the two energy types where two locomotives are needed to match the single DM duty cycle, the capital cost for two such, slightly cheaper per unit, locomotives were assumed in the model.

For the electric locomotive, two sources were used. A report by IPEX Consulting set out the cost of a modern electric locomotive with “last mile” battery capability, based on recent UK orders. While the configuration of this locomotive was not suitable for New Zealand, four heavy axles and high top speed, it was judged as still adequately representing the cost of one that was, in the context of this study.

8.3. Maintenance costs and availability

The same approach was taken when estimating the maintenance cost of each locomotive. Each new type was referenced to the cost of maintaining a conventional diesel locomotive. Availability, influencing required fleet size for the assumed freight task, was quantified on the same basis, as a percentage of that for a modern diesel locomotive.

8.4. Diesel loco assumptions

While KiwiRail has good “big data” records for the cost of maintaining its diesel locomotive fleet, these costs relate to a mix of legacy and high maintenance fleets. A more valid comparison is the cost of maintaining new generation new energy locos versus the cost same for new and modern diesel locomotives. For this reason the Total Ownership Cost (TOC) estimates provided by Stadler for the new DM locomotives were used to establish the diesel locomotive maintenance cost used as the base for all the options.

8.5. Electric locomotive assumptions

With the EF electric locomotive fleet having been allowed to run down pending a decision on reinvestment in the NIMT electrification, historic KiwiRail financial data could not be relied on for the maintenance cost of a 25kV electric locomotive, so two sources were used to compile the required estimate;

IPEX Consulting was asked to compare costs to a basic diesel-electric with rough equivalence to NZ practice. It was assumed that the relativity in costs between a new generation electric and a conventional diesel freight locomotive[75] in the UK environment would be approximately maintained in the NZ environment. Thus knowing the cost of operating a basic diesel freight locomotive in NZ, the costs for the new electric would be in the same proportion.

In addition internet searches were used to turn up information that was judged to be credible, papers and official websites. Of particular credibility was the searching Queensland Competition Authority, their equivalent to the NZ Commerce Commission, inquiry into access pricing for the electrified Queensland Rail coal network[76]. This catalogued a wide range of submissions and studies into the subject of the cost and pricing of an electrified railway.

These two sources were combined to estimate the cost of maintaining a new generation electric locomotive relative to an equivalent diesel locomotive.

It should be noted that the notional electric locomotive is in fact more capable than the DM reference locomotive. Tractive effort is the same, set by the limits of performance of a modern traction motor and wheelspin control system and the weight carried by each driven axle, identical for the DM and the electric. But the concept electric locomotive is more powerful and in reality would likely be even more powerful. With equivalent tractive effort, the maximum train size would be the same, but the electric locomotive will accelerate that train faster and haul it faster up grades. This difference, that the electric locomotive could do more work than the DM, is beyond the resolution of the model at the heart of the study. This is a detail[77] that need only be considered if the study proceeds to the next stage.

8.6. Hydrogen

The Systra report[78] hydrogen fuel cell locomotive maintenance costs were used as a starting point, with some judgement. With no real rail experience these Systra costs were in turn based on a comparison between diesel and fuel cell city buses.

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[75] Progress Rail Class 66, as close as things come to an equivalent with NZ freight locomotives and act as the reference against UK electric locomotives.

[76] http://www.qca.org.au/project/aurizon-network/previous-access-undertakings/2010-access-undertaking-ut3/blackwater-electric-traction-pricing-daaus/

[77] That the operating plan could be refined to take advantage of the greater performance of a practical electric locomotive – play to the strengths of an electric loco. The same applies to the battery option. The two medium X-64 locomotives are likely more capable than one DM, thus a refined operating plan taking advantage of this to move the assumed tonnage with fewer trains per year could begin to offset the 2:1 disadvantage assumed at this first level (option sorting) study.

[78] Page 38 of Systra report onwards.

For the two energy types where two locomotives are needed to match the single DM duty cycle, the maintenance cost for two such, slightly cheaper per unit, locomotives were assumed in the model.

8.7. Efficiency

While using a highly developed prime mover and refined modern electronics and electric motors, a conventional diesel-electric locomotive turns at most 1/3 of the energy in diesel into useful work. This is a primarily consequence of the laws of thermodynamics, with as much heat leaving in the exhaust or out of the cooling system as is used to turn the wheels. Most road vehicles are even less efficient in their normal duty cycle. But some of the energy has to be used to run supporting equipment on board the locomotive[79] and more is lost in the electrical transmission.

The same applies to electric locomotives, both conventional and battery. There are losses in the original generation process, at every voltage transformation and in the lines carrying the power to the battery charger or to the locomotive pantograph. Every step results in some waste heat being created. Once on board the locomotive, there are further small losses in the electrical transmission system, identical to those in the same equipment in the diesel-electric locomotive. There are further heating losses when charging a battery, particularly at high charge rates.

The process to release hydrogen from water uses considerably more electricity than this hydrogen releases as useful (net) electricity when fed into a fuel cell. In addition to this, the same losses as experienced by the electric locomotives occur in the original electricity generation and transmission process and on board the locomotive downstream of the fuel cell.

Overall as little as 1/3 of the primary electricity fed into a hydrogen energy chain delivers useful work at the locomotive wheels[80]. Used efficiently to feed an electric locomotive, as much as 2/3 of the original electricity can be turned into useful work.

To enable comparison of the energy costs and emissions on a constant basis, all calculations in this study start with the useful work done at the wheels. These inefficiencies and losses are then applied to determine the amount of energy used at the start of the chain for each locomotive type. For electricity, the financial costs are "at the meter", the tariff building in the inefficiencies that occur between power station and where KiwiRail is billed. For electricity the environmental cost is calculated back at the original source generation. Using electricity KiwiRail is as decarbonised as much as the overall grid.

For diesel the situation is simpler. Kiwirail could convert the work done at wheel to litres using the average efficiency of a diesel-electric locomotive. But it has good historic records of fuel consumed per unit work, and this was employed, modified as explained in the next section.

The primary energy information is immaterial. Fossil fuel is the result of hundreds of millions of years of sunlight accumulation being used up at an unsustainable rate, and this is not accounted for in selling price. A more sophisticated analysis might add the losses and emissions during production and transport (a full EROI analysis) but this was determined to be immaterial for the purposes of this report, which has ZGHG by 2050 as its basic hypothesis. The corollary to this is that fossil fuel use must be eliminated by 2050.

The volume of fuel needed, the cost to purchase the fuel and the cost of the CO_2 it releases was calculated by and used in the economic model as below.

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[79] Everything from the cab heating/cooling, through the main radiator cooling fans right to the braking system air compressor.

[80] The economic model assumed a generous 42% of input energy doing work at the wheels

8.8. Energy used

For the baseline diesel an approach blending KiwiRail records, Stadler TOC calculations and OpenTrack modelling was used.

The basis of the calculation was actual DL locomotive fuel consumption per unit of GTK work done. This was corrected to the expected performance of the DM by assuming the 10% fuel saving estimated by KiwiRail's Rolling Stock Asset Services team.

This base figure was then adjusted based on the OpenTrack calculated consumption for each route. For example, if OpenTrack results showed the route required 20% more energy than the average then the energy consumption for the DM was increased by 20%.

All other energy types had the supply chain inefficiencies back to the point of sale/metering calculated to derive the volume of energy purchased.

8.9. Cost estimates of fuel

The cost per unit (litre/kWh/kgs) of fuel were derived from fuel price curves provided by MBIE and MOT, Hale & Twomey[81] and Beca Systra Hiringa, modified for typical supplier margins/discounts, transport costs and cost of carbon.

For economic modelling, the cost of carbon passed on by energy suppliers was based the projected carbon intensity of each fuel source and the central Shadow Carbon price curve sourced from Treasury's CBAx[82] Guide October 2022. The actual carbon price incurred by KiwiRail and passed on to customers is based on the ETS price. If current ETS policy settings remain unchanged the ETS price would be significantly lower than the Shadow Carbon price curve.

8.10. GHG Emissions

For GHG emissions, the emission factors applied were sourced from the Ministry for the Environment's Guide for measuring emissions.[83] For electricity, the emission factors took into consideration the generation source, transmission and distribution line losses. For hydrogen, emissions per kg were derived based the quantity of electricity consumed to electrolyse this 1 kg and assumptions on the level of electricity used from grid vs dedicated green renewable generation over time. For diesel and biofuel the emission factors were based on the emissions from fuel combustion only.

Grid supplied electricity was assumed to be near 100% renewable by 2035 in line with Climate Change Commission projections[84].

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[81] Thinking energy (envisory.co.nz). Hale and Twomey have rebranded as Envisory.
[82] The Treasury's CBAx Tool
[83] Measuring emissions: A guide for organisations: 2022 detailed guide, published 16 August 2022 by the Ministry for the Environment
[84] Climate Change Commission projections of electricity generation – Electricity market modelling datasets 2021

8.11. Summary relative parameters

Cost and performance relative to DM diesel-electric					
	Capital cost (2030)	**Efficiency (meter/tank to wheel)**	**Maintenance Cost**	**Availability**	**Pulling power****
Diesel-electric	100%	29%	100%	100%	100%
Electric	109%	67%	70%	105%	100%
Battery/X66	91%	75%	83%*	105%	100%
Battery/OLE pair	214%	75%	138%*	105%	100%
Hydrogen pair	229%	42%	229%*	95%	100%

Table 28: Cost and performance of electric and hydrogen locomotives relative to the DM diesel-electric

*including Battery replacement

**in reality Battery and Hydrogen pairs are expected to have greater pulling power, reflecting their expected 3.6MW output vs DM’s 2.5MW and 1/3 greater tractive effort for a pair. This can be balanced against battery capacity to handle greater trailing loads on some routes.

9. Economic case – Identification of the best option

What is the best choice for optimising value to New Zealand?

9.1. The five options for achieving ZGHG

Based on the work in the prior sections, five options, plus base were identified as shown in **Table 29**. Fuel and locomotive types were selected based on the feasibility investigation outlined above and initial conversations with suppliers.

Economic Option:	Name	Main motive power	OLE
Base	No change	Diesel locomotives	Plus existing electrification
1	Battery	Battery electric	Plus existing electrification
2	Biofuel	Biofuel IC locomotives	Plus existing electrification
3	Hydrogen	Hydrogen fuel cell locomotives	Plus existing electrification
4	Extend OLE	Battery electric plus conventional OLE electric	Existing electrification extended (Te Rapa-Pukekohe and Hamilton – Tauranga)
5	All Mainlines OLE	Conventional electric	All main freight routes wired

Table 29: Selected Options for Achieving ZGHG

Options from Base through to Option 3 (no change, battery, biofuel, and hydrogen) assume the 409 km section of freight network that currently has OLE remains[85], and the remainder of the network is either powered by diesel, battery-electric, biofuel or hydrogen fuel cell locomotives respectively.

Option 4 (Extend OLE) assumes the current overhead electrified network is extended to incorporate Tauranga and Hamilton – Auckland, with the rest of the network battery electric operated.

Option 5 (All Mainlines OLE) assumes conventional OLE is installed on all major lines. Option 5 was included in the assessment for completeness only. Low traffic density on many routes means it is an unrealistic option for the NZ network by simple “inspection”.

9.2. Economic Assessment

The economic assessment compares the costs and benefits of continuing with diesel locomotives and 15 electric locomotives (Base) against the cost and benefits of transitioning to and operating the five alternative locomotive options that emit zero or near zero carbon emissions, as outlined above.

The assessment has been prepared in accordance with Waka Kotahi’s MBCM[86] guidance, and the following assumptions:

- A 60 year evaluation period from the start of the 2022 financial year to capture the majority of the benefit of long-life OLE infrastructure and planned replacement profile of existing and recently ordered locomotives, with DM end of life renewals occurring in late 2050s/early 2060s
- The fleet, infrastructure and motive power change implementation points noted in **Section 9.5**.

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[85] With new straight electric locomotives to replace the existing EF fleet, when the EFs reach the end of life

[86] Monetised benefits and costs manual updated 1 August 2021 by Waka Kotahi NZ Transport Agency

- A discount rate of 5% in line with Treasury's guidance[87], with sensitivity testing at 2% and 6% in line with Waka Kotahi's MBCM
- The cost elements noted in **Section 9.8**, and the benefits types noted in **Section 9.9**.

Both costs and benefits are sensitive to freight task net tonne kilometre (NTK) assumptions. On the cost side, fuel and maintenance costs are directly related to Freight NTK. Capital cost of locomotives and supporting infrastructure have an indirect link to freight task. As freight volumes increase, additional locomotives and supporting infrastructure are required to accommodate the growth. Growth in the fleet size was modelled to occur in 2035 and 2050.

The level of benefits is directly related to changes in NTK.

The four distinct but realistic freight task scenarios, highlighted in green below, have been tested.

9.3. Freight task scenarios

Table 30 shows the initial Low Emission Supply Chain Scenarios that were identified and initially developed by the project team and refined through the stakeholder workshops. The four scenarios highlighted in green were selected and applied in the economic model.

Scenario		Description
Scenario BAU:	**Base /Do Minimum**	Implement the Resilient and Reliable programme.
Scenario A:	**Enhanced KiwiRail Investment**	Resilient and Reliable programme plus additional rolling stock capacity to meet likely demand for rail freight.
Scenario B:	**Northern Ports Focus**	Building on A, Port of Auckland closed, traffic shifted to Northport (c.45%) and Tauranga (c.55%).
Scenario B1:	**POAL held at 2020/21 levels growth diverted**	Building on A, Port of Auckland maintains existing volume, growth shifted to Tauranga.
Scenario C:	**All Ports Consolidation**	Building on B, Port of Auckland closed, one international container port on North Island (Tauranga) and South Island (Lyttelton)
Scenario D:	**Strong Policy Push**	Building on A, carbon price of $250 by 2035, $600 by 2050
Scenario E:	**Ports Consolidation and Strong Policy Push**	Building on C, carbon price of $250 by 2035, $600 by 2050
Model Base (NFDS baseline date updated)		2020/21

Table 30: Low Emission Supply Chain Scenarios

Scenario B1 reflects conversations with key stakeholders about the future of the Port of Auckland. This additional scenario has the port remaining open and operational alongside others, but with static volumes, rather than assuming it is closed (as in Scenario B, C and E). Any growth in freight volumes is accommodated by Tauranga. Note that these closure/shift scenarios are just that. Scenarios for use in this comparative study.

Scenarios D and E assume a much higher carbon price than other scenarios - a carbon price of $600 per tonne by 2050. This estimate is higher than the interagency group recommended shadow price of carbon; $186 - $369 in 2050. The higher carbon prices represent a strong policy push by government.

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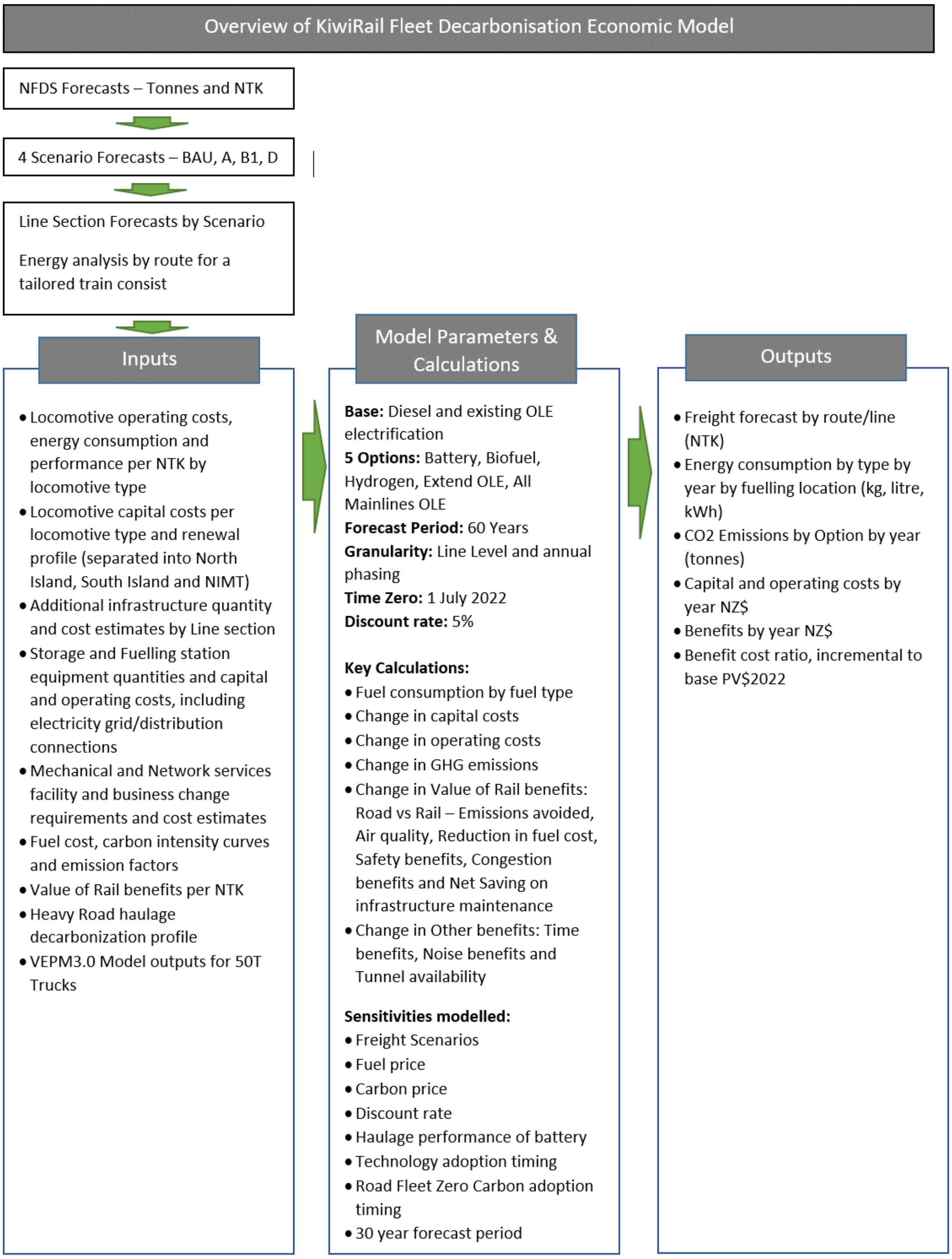
[87] https://www.treasury.govt.nz/information-and-services/state-sector-leadership/guidance/financial-reporting-policies-and-guidance/discount-rates

9.4. Economic model

KiwiRail developed the fleet decarbonisation economic model and it was peer reviewed by external consultant Richard Paling Consulting Ltd[88]. The model leveraged the Value of Rail Report of February 2021 by Ernst & Young, as well as previous Cost Benefit Analysis and Climate Impact Policy Assessments spreadsheet-based models developed by KiwiRail to support Crown Budget Bids and fulfil New Zealand Upgrade Programme requirements. An overview of the key inputs, model calculations and outputs are included below.



Overview of KiwiRail Fleet Decarbonisation Economic Model

NFDS Forecasts – Tonnes and NTK

4 Scenario Forecasts – BAU, A, B1, D

Line Section Forecasts by Scenario

Energy analysis by route for a tailored train consist

Inputs

- Locomotive operating costs, energy consumption and performance per NTK by locomotive type
- Locomotive capital costs per locomotive type and renewal profile (separated into North Island, South Island and NIMT)
- Additional infrastructure quantity and cost estimates by Line section
- Storage and Fuelling station equipment quantities and capital and operating costs, including electricity grid/distribution connections
- Mechanical and Network services facility and business change requirements and cost estimates
- Fuel cost, carbon intensity curves and emission factors
- Value of Rail benefits per NTK
- Heavy Road haulage decarbonization profile
- VEPM3.0 Model outputs for 50T Trucks

Model Parameters & Calculations

Base: Diesel and existing OLE electrification
5 Options: Battery, Biofuel, Hydrogen, Extend OLE, All Mainlines OLE
Forecast Period: 60 Years
Granularity: Line Level and annual phasing
Time Zero: 1 July 2022
Discount rate: 5%

Key Calculations:

- Fuel consumption by fuel type
- Change in capital costs
- Change in operating costs
- Change in GHG emissions
- Change in Value of Rail benefits: Road vs Rail – Emissions avoided, Air quality, Reduction in fuel cost, Safety benefits, Congestion benefits and Net Saving on infrastructure maintenance
- Change in Other benefits: Time benefits, Noise benefits and Tunnel availability

Sensitivities modelled:

- Freight Scenarios
- Fuel price
- Carbon price
- Discount rate
- Haulage performance of battery
- Technology adoption timing
- Road Fleet Zero Carbon adoption timing
- 30 year forecast period

Outputs

- Freight forecast by route/line (NTK)
- Energy consumption by type by year by fuelling location (kg, litre, kWh)
- CO2 Emissions by Option by year (tonnes)
- Capital and operating costs by year NZ$
- Benefits by year NZ$
- Benefit cost ratio, incremental to base PV$2022

Figure 24: Overview of KiwiRail's Fleet Decarbonisation Economic Model

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[88] Now also reviewed by MOT.

9.5. Phasing of introduction

The Pathway to Zero occurs over multiple decades with most of the transition occurring in early/mid 2030s.

With the last diesel locomotives scheduled to retire early 2060s, those locomotives are assumed to undergo motive power swaps/adopt biofuel at their mid-life overhaul to allow KiwiRail to achieve its goal of being net carbon zero by 2050. **Table 31** outlines the timing based on KiwiRail's Rolling Stock Asset Management Plan. The timing of Infrastructure, depot based storage and fuelling stations ensures the infrastructure is ready to allow commissioning of the new locomotives as soon as they are available. Solar and battery storage is scheduled for installation late 2030s, allowing KiwiRail to benefit from likely improvements in cost, performance and life expectancy.

		Timing			Relevant to Options					
Date of introduction		**Mid-life motive power swap**	**Construct /Replace**	**Renewal**	**Diesel**	**Battery**	**Biofuel**	**Hydrogen**	**Extend OLE**	**All Mainlines OLE**
Rolling Stock classes	**Units**									
DL gen 1, 2	40[89]		2035	2071	This timing applies equally to all Options. For Base (Diesel) the mid-life overhaul is considered to occur as per normal, in line with KiwiRail's AMP.					
DL gen 2.2, 2.3 and 2.3ii	33	2033-38	2051-54	n/a						
DM	66	2036-42	2025-27	2061-63						
EF (& future replacements)	15		2042	2078						
DX (replaced by DM)	47		2026-27	n/a						
DC (replaced by DM)	17		2024-26	n/a						
DFB/T (Life extended)	27[90]		2025-28	2040						
Growth (BAU)	26		2050	n/a						
Network Infrastructure (track and lineside)										
P2H2T	263 STKs		2026-30	n/a					Y	
All mainline OLE	2950 STKs		2026-40	n/a						Y
Lineside chargers	2-10		2029-35	2058-66*		Y			Y	Y
Storage and Fuelling (depot based)	**No of Sites**									
180MW Hydrogen production, storage and dispensers including Grid/network connections	11		2031-34	2051-54				Y		
Depot based chargers including Grid/network connections	14		2031-34	2061-64		Y			Y	
Solar 15MW and 14x 10MWh battery installations	14		2035	2055-65		Y			Y	Y
Fuel tank replacements	19		2031-34	2061-64	Y		Y			
Mechanical and Network Service Facilities										
Facility upgrades and equipment	14		Ongoing			Y	Y	Y	Y	Y

Table 31: Phasing of locomotive renewals and infrastructure construction/installation as per economic model

*with battery improvements some lineside chargers will not require renewal, see **Table 35**.

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[89] 20 of the 40 are not forecast to be replaced due to increased capability and efficiency of DM locomotives and anticipated future decline in coal.

[90] 27 reduces to 12 from 2031

9.6. Fuelling and Storage (Depot based infrastructure)

Table 32 shows the energy consumption by fuel type across the Freight Rail Network at 2050 compared to current fuel use. The projected growth, between 49-132%, requires capacity upgrades to servicing facilities.

Freight Scenario / Fuel type	Base Diesel M Litre	Option 1 Battery GWh	Option 2 Biofuel M Litre	Option 3 Hydrogen M Kg	Option 4 Extend OLE GWh	Option 5 All Main-line OLE GWh
2022 existing	42	-	-	-	-	-
2050 – Scenario BAU	55	233	63	12	245	256
2050 – Scenario A	61	263	71	13	276	288
2050 – Scenario B1	72	309	84	16	324	339
2050 – Scenario D	86	369	100	19	387	405
% increase Existing vs Scenario BAU	49%					
% increase Existing vs Scenario A	66%					
% increase Existing vs Scenario B1	95%					
% increase Existing vs Scenario D	133%					

Table 32: Total fuel consumption by energy type by Option and Freight Scenario at 2050

Base, Option 2 and Option 3 use a further 26-41 GWh of electricity across the NIMT Te Rapa to Palmerston North.

The specific details of key fuelling and energy storage equipment by site used to inform cost estimates is set out in **Table 33** below. The useful life of new Grid & Network Connections is 40-50 years and capacity is expected to meet KiwiRail's peak electricity demand, under the various options through to 2050. The adequacy of proposed Grid & Network connections will be tested further as part of the detailed business case.

	Diesel		Battery			Hydrogen						
	Biofuel		Extend OLE									
Production, Storage and fuelling throughput capacity by servicing site							2030 Base estimate			2050 Base estimate		
	Tank capacity	Dispensers	New Grid/ Network Connection	Battery Storage	Chargers	New Grid / Network connection	Electrolysers	Storage capacity	Refuelling capacity	Electrolyers	Storage capacity	Refuelling capacity
North Island	Ltr. 000	No.	Y/N	MW h	No. S = Small L = Large	Y/N	MW	Kg 000	Kg - 000 per 24hr	MW	Kg 000	Kg 000 per 24hr
Whangarei / Northport	5	1	Y	10	1S	Y	2	0.5	1	4	1	2
Westfield (excludes Southdown CT)	100	2	Y	10	1L	Y	45	10	19	91	20	38
Te Rapa	65	2	Y	10	1L	Y	15	3	6	31	7	12
Mt Maunganui (includes Tauranga)	106	1	Y	10	2L	Y	22	5	9	44	10	17
Kinleith	5	1	Y	10	0.5S	-	-	-	-	-	-	-
New Plymouth	40	1	Y	10	1S	Y	2	0.5	1	4	1	2
Palmerston North	80	2	Y	10	1L	Y	19	4	8	39	9	15
Napier	5	1	Y	10	1S	Y	1	0.3	0.3	3	0.6	0.6
Wellington (includes Passenger)	130	2	Y	10	1L	Y	26	6	11	52	12	22
South Island												
Picton	10	1	Y	10	1S	-	-	-	-	-	-	-
Middleton + Waltham	222	2	Y	10	1L	Y	52	12	20	104	24	41
Westport (Otira)	40	1	Y	10	1S	Y	4	1	1	8	2	2
Dunedin	20	1	Y	10	1L	Y	3	1	1	7	2	2
Invercargill	65	1	Y	10	1S	Y	9	2	3	18	4	6

Table 33 Summary overview of fuelling and storage by site by option

9.7. Locomotive type by route and Lineside chargers

Locomotives have been matched to specific routes based on the energy required to complete a return trip. The specific locomotive allocations by option and route are shown in **Table 34.** The specific Lineside chargers required by line and electric option is set out in **Table 35**. These chargers complement the Depot/Service Centre based chargers and OLE infrastructure.

Route details				**Option 1 - Battery**				**Option 4 – Extend OLE**
North Island		**Distance Return**	**Energy required for return trip**	**Conventional Electric locomotive**	**X-64 Pair 11MWh* with Pantograph**	**X-66 (2030) 4.4MWh* No pantograph**	**X-66 (2040) 7MWh* No pantograph**	**Same as Option 1 except for below change to Conventional Electric locomotive**
Line	**Route (both directions)**	**Km**	**MWh**					
NIMT	Te Rapa–Palmerston North	810	24.5	Y				
NIMT &ECMT	Southdown–Tauranga	445	15.7		Y - lineside	Y - lineside		Y
NIMT& MNLP	Palmerston North-New Plymouth	494	11.2		Y 20% OLE			
NIMT	Westfield-Te Rapa	241	10.7		Y			Y
NAL& MPL	Northport-Westfield	437	9.4		Y			
NIMT	Palmerston North-Wellington	273	8.9		Y			
NAL	Whangarei-Westfield	427	8.0			Y - lineside		
PNGL	Palmerston North-Napier	371	7.4		Y			
ECMT& MTMNG& KINLEITH	Mt Maunganui-Kinleith	243	5.4			Y – Kinleith		
MTMNG& ECMT& MUPRA	Mt Maunganui-Murupara	282	5.2			Y - Depot		
WRAPA	Wellington-Waingawa	168	3.1			Y		
NAL	Whangarei-Otiria	Various	Less than <4.0			Y		
NIMT	Auckland Port-Wiri					Y		
HTAPU	Cambridge Branch					Y		
CASLF	Castlecliff Branch					Y		
GRCFD	Gracefield Branch					Y		
MISBS	Mission Bush Branch					Y		
WITOA	Waitoa Siding					Y		
RTWRO	Rotowaro Branch					Y		
WGIFT	Wanganui Branch					Y		
South Island								
Line	**Route (both directions)**	**Km**	**MWh**					
MNL	Picton-Christchurch	697	16.7				Y - lineside	
MDLND	Christchurch-Hokitika	535	7.4				Y – lineside	
MSL	Christchurch-Dunedin	727	16.4				Y – lineside	
MSL	Dunedin-Invercargill	445	11.6				Y – lineside	

*usable capacity

Key:	Y	Completes journey without on route charging	Y	Completes journey with on route charging top-up	Y	Completes journey with access to OLE

Table 34: Locomotive type by line for Electric Options

Under Option 1 and 4, the 33 DL 2.2, 2.3 and 2.3ii locomotives[91] are assumed to transition 2033-38, initially through a diesel to battery swap, equivalent to an X-66 4.4MWh (2030). All South Island routes transition between 2036-40, initially through a DM Motive Power diesel to battery swap, equivalent to an X-66 7MWh (2040)[92].

Under Option 5, all mainlines are serviced by Conventional Electric Locomotive with last mile battery. Branch routes are serviced by X-66 4.4MWh (2030) battery locomotives in North Island, and X-66 7MWh (2040) in South.

	Option 1 - Battery		Option 4 – Extend OLE		Option 5 – All Mainline	
Line	**2030s requirement**	**2040s requirement**	**2030s requirement**	**2040s requirement**	**2030s requirement**	**2040s requirement**
North Island						
NAL	1	-	1	-	-	-
NIMT – Westfield to Te Rapa	1	-	-	-	-	-
NIMT - Palmerston North to Wellington	1	-	1	-	-	-
ECMT	1	1	-	-	-	-
PNGL	1	-	1	-	-	-
MNPL	1	1	1	1	-	
South Island						
MNL	1	1	1	1	-	-
MID	1	-	1	-	-	-
SIMT North	1	1	1	1	-	-
SIMT South	1	1	1	1	-	-

Table 35: Summary of Lineside chargers by line

9.8. Cost Estimates

Cost estimates were developed for operational and capital items for the five Pathway to Zero Options, plus a 'base' diesel fuel option. KiwiRail completed significant work to develop the cost estimates as reported in **Section 8**. A summary of the information sources and key assumptions is provided in **Table 36** with results shown in **Table 37.**

Operating Costs	Source and key assumptions
Fuel costs	Development of quantities and unit prices are explained in 8.8 and 8.9. Energy equivalents: Diesel 1 litre = 10.7 kWh Hydrogen 1 kg = 33.6 kWh Biodiesel 1 litre = 9.2 kWh

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[91] Refer to Table 31.

[92] NB, this is a modelling assumption. From a technical and practical perspective it is unlikely that, beyond underframe and bogie frames, much or any of the early series DL would be worthwhile reusing in a new generation battery locomotive. The value of this would be assessed in the (long in the future) project tasked with delivering this replacement.

Operating Costs	Source and key assumptions
Motive power & Other (maintaining the non-motive power components of locomotives)	Approach and key assumptions to develop maintenance cost estimates are outlined in 8.3. The maintenance cost includes both operating and capital (overhaul) maintenance. DM locomotives were assumed to travel 4.5m kilometres with an average payload equivalent to 1.1bn NTKs over its 36 year useful life, as per the maintenance plan supplied by Stadler.
Infrastructure maintenance	Maintenance cost of electrical equipment OLE and Lineside chargers was estimated to be approximately 50% of the original capital cost over the life of the equipment. Refer to 7.5. For OLE, that has a 50 year life, maintenance equates to 70% of original capital cost – based on annual maintenance of 1% and part life renewals every 10 years of 5% per cycle. All options and Base assume existing NIMT OLE continues to operate. No allowance has been made in cost estimates for future NIMT OLE infrastructure renewals. An allowance for maintenance at a rate of $0.003 per NTK has been included as part of Infrastructure Maintenance. Ongoing maintenance of the existing NIMT OLE is part of the established Rail Network Investment Programme. For Lineside chargers, that have a 30 year life, maintenance equates to 1.7% of the original capital cost per year.
Fuelling and Storage	Annual costs of operating and servicing KiwiRail's diesel fuel supply and storage were sourced from KiwiRail's general ledger for the 2021 financial year. Further consultation was undertaken KiwiRail's Facilities Managers around size and age of existing fuel tanks at each site, and with KiwiRail's Traction and Electrical Engineer teams to understand the condition and capability of existing assets and relevant sites. For hydrogen, production the maintenance cost was provided by Hiringa. For depot chargers, the maintenance cost equates to 1.7% of the original capital cost per year in line with the Lineside chargers. Cost of maintaining grid and network connections is part of the line charge tariff included in fuel costs.

Operating Costs	Source and key assumptions
Business change costs	KiwiRail used recent experience associated with its DM locomotive procurement and mechanical and network service facilities upgrades at Palmerston North, Waltham and Hillside to inform business change costs. A nominal allowance by fuel type ranging from $12m for biofuel adoption, to $128m for All mainline OLE. The nominal amount considered locomotive, refuelling and network services, and is expected to cover supply chain setup, process change, recruitment and training, HSE assessments, new equipment for servicing locomotives and maintaining a larger OLE network. These estimates will be refined through the detailed business case.

Other key model assumptions	
FX rate	NZD/USD 0.65 – RBNZ 5-year average NZD/EUR 0.55 – RBNZ 5-year average

Capital Costs	Source and key assumptions
Locomotives purchase cost and motive power swaps	The cost of diesel locomotives was based on the most recent DM locomotive order and includes the project management, design, manufacturing, shipping, insurance, commissioning, quality control, travel costs. Development of quantities and unit prices for alternative motive powered locomotives are explained in 8.2. In the Base (Diesel) cost estimates, the cost of the scheduled 10-year diesel motive power overhaul for DL and DM, is $2m and $1.35m respectively (motive power components only). This cost is excluded from Options 1 to 5 when a motive power swap occurs and replaced with the cost of the Motive power swap. The cost of Motive power swaps represents: - the cost of the motive power components (e.g. battery, cooling systems, fuel cells, tanks etc, for each Locomotive type), plus - labour estimated at $0.25m per unit. The residual value of the partially used diesel prime mover of up to $1m, provides contingency[93]. For simplicity, the cost of each locomotive is forecast to occur in the year that locomotives go into service. In practice, each locomotive batch has milestone payments which occur over several years leading up to and post commissioning. The cash flow phasing will be refined through the detailed business case.

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[93] Accepting that demand for large diesel engines may be reducing in the 2030's.

Capital Costs	Source and key assumptions
Network infrastructure	The development of OLE and Lineside charger quantities and unit costs are explained in 7.2 to 7.4. OLE estimates were developed for each line based on the specific route requirements, the main cost drivers being route length (in STK) and distance from likely grid connection points. The location of the lineside chargers was informed by the energy analysis assessment and ensured battery locomotives could complete the journey with battery staying above the minimum 20% battery state of charge thresholds. The energy analysis assumed locomotive left its origin fuelling depot with 80% charge. A number of lines have no lineside chargers as the journey was able to be completed with battery without requiring on-route charging, see **Table 34** . OLE renewals occur every 50 years and lineside chargers every 30 years.
Fuelling and Storage infrastructure	The development of depot based charger quantities and unit costs are explained 9.6 to 9.7. An overview of key equipment by site by option is included in **Table 33**. Solar generation capital cost is $1.2m per MW of installed capacity as per KiwiRail's 0.4MW Waltham Solar Installation. This compares to NZ research of 1MWp installations in 2020 which ranged between $1.36m and $2.04m per MWp, with average cost efficiencies from increasing scale from 0.5MW to 1MW of 6%.[94] Further improvements in panel efficiency, larger installation and has potential to further reduce costs per MW installed have not been factored into estimates. Depot based Battery Storage is based on $0.35m per MWh (USD0.2m per MWh @NZD/USD rate of 0.65, plus a 15% shipping and insurance allowance). Battery Storage is expected to have 20+ year useful life and round trip efficiency 93% by 2035.[95] One round of battery renewal is factored into cost estimates.
Mechanical and Network Service facilities	See Business Change cost section above.

Table 36: Summary of key assumptions relating to cost estimates.

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[94] Commercial-scale solar in New Zealand – An analysis of the financial performance of on-site generation for business published by Dr Allan Miller, Dr Gareth Gretton and EECA August 2021

[95] Cole, Wesley, A. Will Frazier, and Chad Augustine. 2021. Cost Projections for Utility-Scale Battery Storage: 2021 Update. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-79236. https://www.nrel.gov/docs/fy21osti/79236.pdf.

PV(2022)$m	Base	Option 1	Option 2	Option 3	Option 4	Option 5
Name	Diesel	Battery	Biofuel	Hydrogen	Extend OLE	All mainlines OLE
Extent of electrification	Existing OLE only				Existing + OLE P2H and H2T[96]	OLE All main freight lines
Motive power for remainder of network	Diesel	Electric Battery	Biofuel	Hydrogen	Electric Battery	Electric Battery
For Scenario BAU:						
Operating costs (for 60 years of operation)						
Fuel	[redacted] 9(2)(i) - Commercial Activities	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Motive power	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Non motive power	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Infrastructure maintenance	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Fuelling and storage	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Business change	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Total	**3,140**	**2,568**	**3,025**	**3,931**	**2,623**	**3,582**
Capital Costs						
Locomotive purchase – motive power	[redacted] 9(2)(i) - Commercial Activities	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Locomotive purchase – non motive power components	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Network infrastructure construction	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Storage and fuelling infrastructure	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Mechanical and Network Service facilities	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Total	**996**	**1,711**	**996**	**2,374**	**2,305**	**5,591**
TOTAL COST	**4,136**	**4,279**	**4,021**	**6,305**	**4,928**	**9,173**
TOTAL COST – other Freight Demand scenarios						
Scenario A	4,548	4,627	4,443	7,017	5,258	9,523
Scenario B1	5,015	5,020	4,898	7,842	5,605	9,886
Scenario D	5,751	5,564	5,621	9,009	6,147	10,439

Table 37: Cost Estimates for Pathway to Zero Options (60 year discounted cost at 5%)

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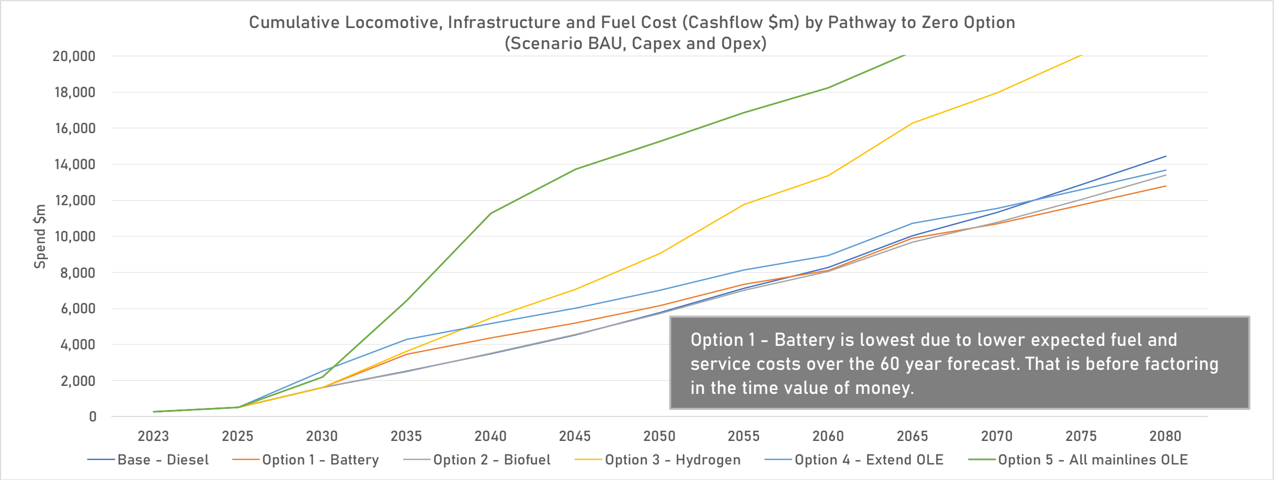
[96] P2H Pukekohe to Hamilton and H2T Hamilton to Tauranga

Figure 25 and **Figure 26** plot the cumulative cost estimates by option to present a comparative cost between the six "fuel types" assessed, on an undiscounted and discounted basis respectively. Cumulative costs take into account capital and maintenance costs over the lifetime of each type of locomotive, overhead line infrastructure, chargers and fuel. Upgrades to electrification infrastructure and connections at locomotive service centres are allowed for in Options 1 (battery), 3 (Hydrogen), 4 (extend OLE) and 5 (All mainlines OLE).

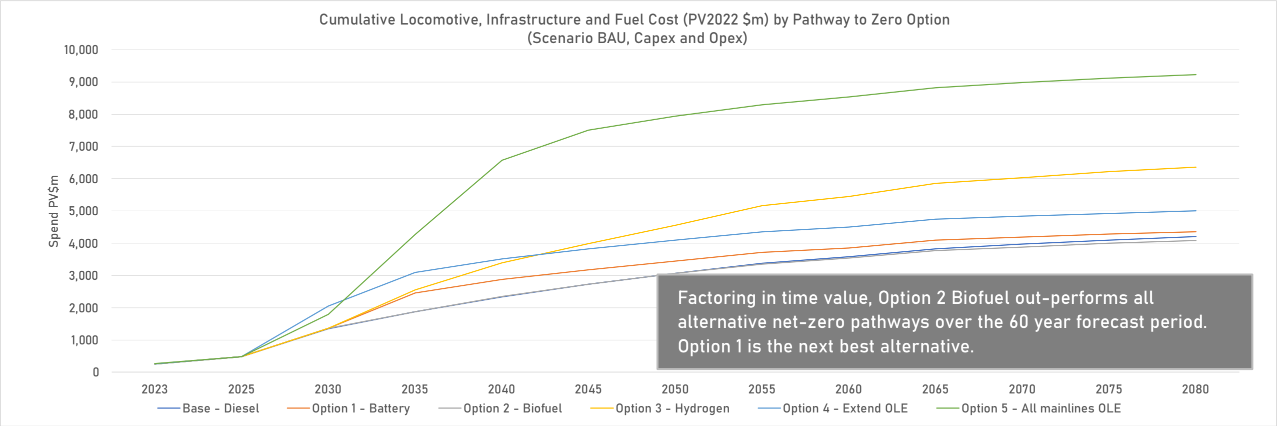
Option 1 (Battery) has the lowest undiscounted cost over the 60 year period with Option 2 (Biofuel) the lowest discounted cost option, due to minimal upfront transition cost. Option 5 (all mainlines OLE with battery electric on the small number of other lines) goes off the scale of the graph due to its very high capital cost. Less effort was put into estimating full costs for Option 5. Option 5 was not expected to be economically viable and was included for completeness only. A more detailed and accurate approach would only be warranted if high level costs indicated this option was close to being the preferred option.

Factoring in time value, Option 2 Biofuel out-performs all alternative net-zero pathways over the 60 year forecast period. Option 1 Battery is the next best alternative. The differential between Option 1 and Option 2 peaks at $572m in 2035 reducing to $265m by 2082 (differential of $7m per annum), and reflects the initial investment required to transition (e.g. power supply, charging infrastructure and mid-life motive power swaps) partially offset by lower ongoing fuel and operating costs.



Option 1 - Battery is lowest due to lower expected fuel and service costs over the 60 year forecast. That is before factoring in the time value of money.

Figure 25: Cumulative cashflow costs – undiscounted



Factoring in time value, Option 2 Biofuel out-performs all alternative net-zero pathways over the 60 year forecast period. Option 1 is the next best alternative.

Figure 26: Cumulative cashflow costs - discounted at 5%

Figure 27 shows **Table 37** in graphical form. Diesel and biofuel have the highest fuel cost but minimal transition costs. Hydrogen has a lower fuel cost but highest locomotive capital and operating costs with transition costs similar to battery locomotives. Battery locomotives and Extend OLE have the lowest fuel cost, similar locomotive costs to diesel but higher transition costs (infrastructure, fuelling and storage).

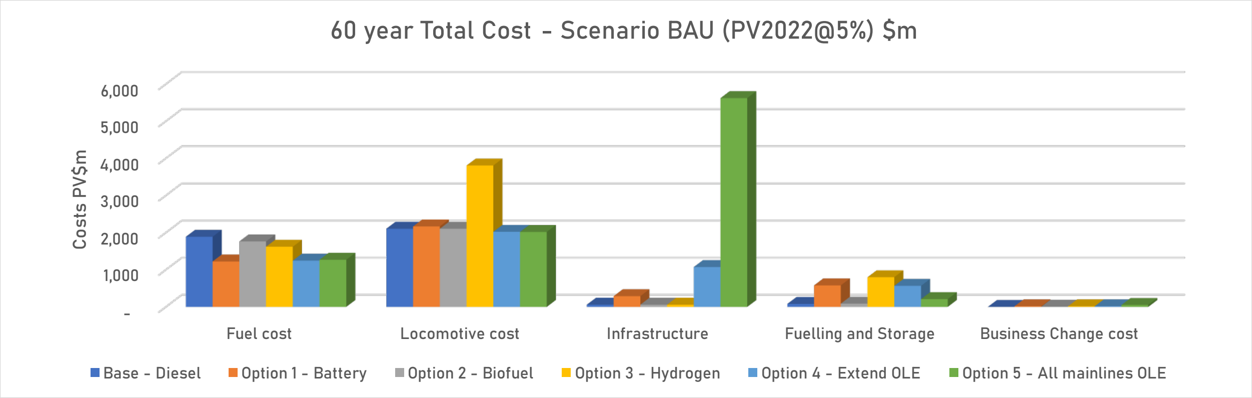


Figure 27: 60 year present value of Locomotive, Infrastructure and Fuel Costs by Option (BAU Scenario) (capex & opex)

The operating and capital costs per NTK by locomotive type, which drives the fuel cost and locomotive cost, are shown in **Figure 28**. It highlights the high capital and operating cost of the Hydrogen Twin unit and the lower capital and operating cost of electric units, except for the X-64 pair. The fuel cost is determined based on the average projected price between 2030 and 2050 and average expected consumption for each type of locomotive.

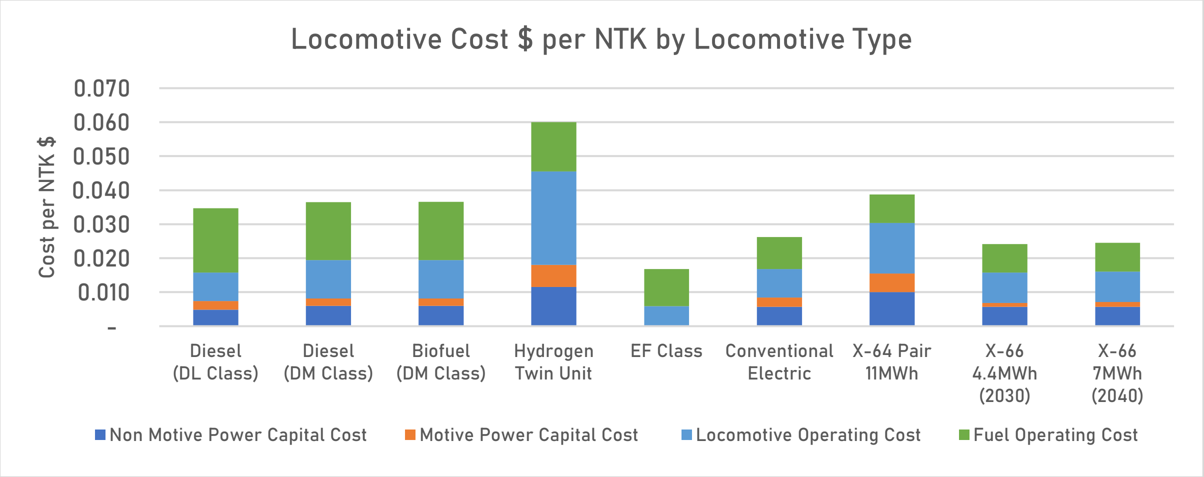


Figure 28: Capital, Operating and Fuel cost per NTK by locomotive type.

The cost of carbon will have a significant impact on diesel fuel price and is passed on to customers via KiwiRail's Fuel Adjustment Factor. With fuel cost forming a significant portion of total cost, it is a key driver of the relative difference between the options. Shadow Carbon price curves sourced from The Treasury, are shown in **Figure 29**, noting the degree of confidence decreases the further forward prices are predicted.

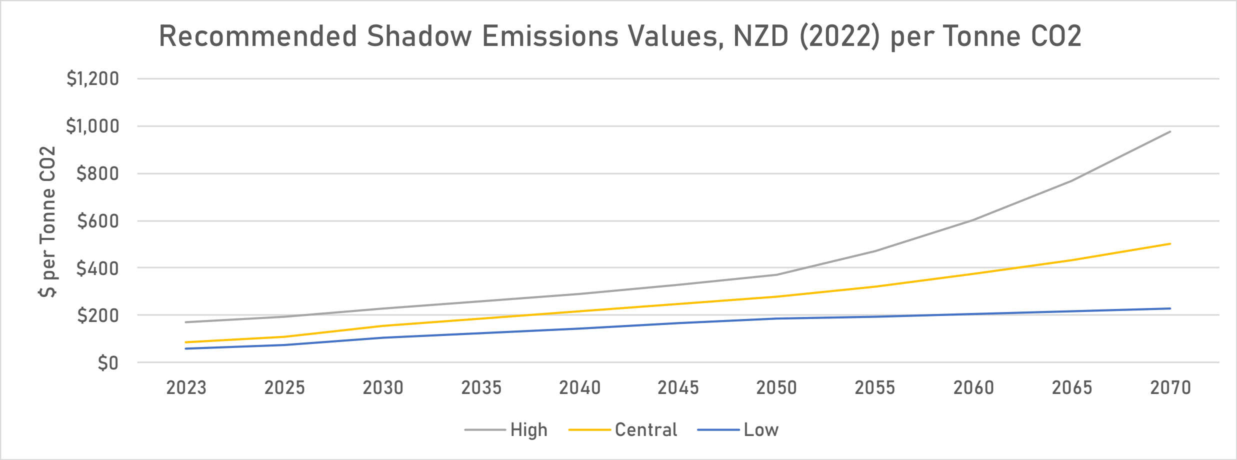


Figure 29: Shadow Cost of Carbon (Source: Treasury CBAx Tool User Guidance October 2022)

Projected fuel price curves were provided by MBIE, MOT, Hale & Twomey[97] and Beca Systra Hiringa, modified for typical price discounts. The hydrogen and electricity prices below are based on the electricity consumption component only and includes an allowance for transmission and line charges but exclude initial capital costs associated with establishing hydrogen production and refuelling facilities, grid connections, battery storage, solar installation and electric chargers. **Figure 30** shows the comparative costs between the four fuel types assessed, for 1 kWh at the wheel[98]. The diesel curve rises steadily after 2025, and biodiesel is also expected to stay flat. Electricity remains relatively steady and is the cheapest for 1 kWh at the wheel, at around 40 cents. Hydrogen starts from second highest price per kWh at the wheel, but the price is expected to reduce steadily after 2030. By 2030, hydrogen and diesel are expected to cost approximately the same (50 cents per kWh at the wheel), assumes production of hydrogen ramps up leading to efficiencies. Diesel becomes more expensive because of the rising price of carbon.

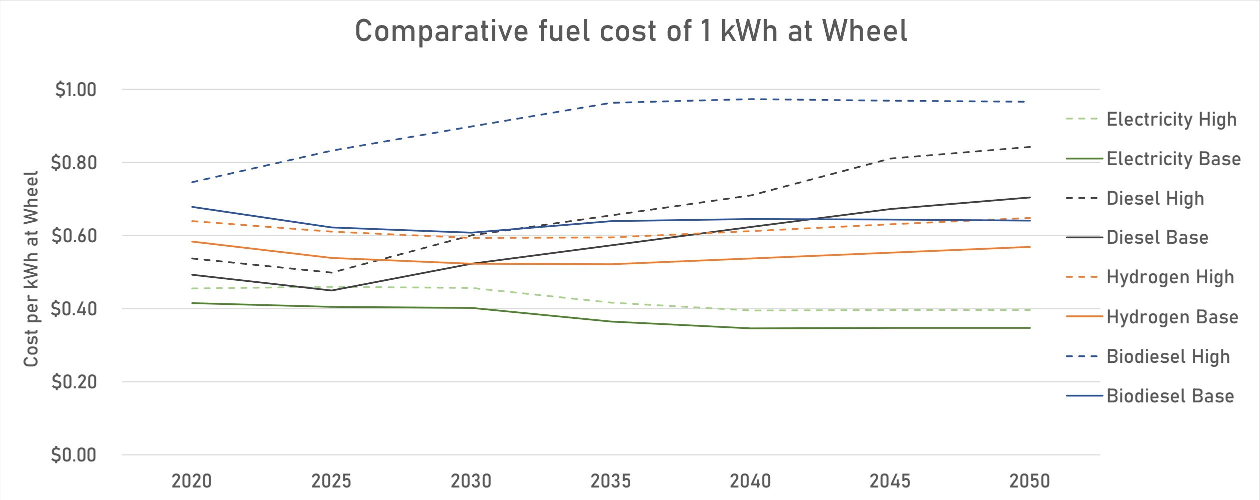


Figure 30: Comparative fuel cost of 1 kWh at the wheel

Source: Diesel and Electricity - MBIE real price curves, Biofuel - Hale & Twomey Feb 2021 Renewable Diesel (Class 1) Medium price path, Hydrogen - Beca Systra Hiringa Hydrogen Motive Power Options Study November 2022

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[97] Now Envisory, energy consulting.

[98] kWh ‘at the wheel’ is the energy that is left for driving the train, once inefficiencies, parasitic (non-traction) loads and transmission losses have been accounted for.

9.9. Benefits Assessment

The benefits listed in **Table 39** were assessed using both NZ Treasury and Waka Kotahi methods as set out in **Table 38** below. The benefits largely align with those included in the Value of Rail Report prepared by Ernst and Young for the Ministry of Transport.

All options were compared to the Base Option. The Base Option assumes:

- Maintenance and renewal of diesel-electric locomotive fleet and the refurbishment and eventual replacement of 15 EF class conventional electric locomotives.
- Scenario BAU freight volumes. This is the most conservative economic scenario as it does not assume any significant external interventions and represents a likely continuation of the current market share of rail freight. BAU assumes modest market share gain, generally agreed by the project team and stakeholders to be feasible and achievable. For more detail see 9.3.

Benefit	Rationale	Considerations
Emissions – carbon reduction	Rail freight produces lower carbon emission than road primarily through lower fuel usage per NTK. The differential between road and rail will change over time as the modes shift to low or zero-carbon motive power at a different pace. It is assumed savings are passed onto freight customers due to the competitive nature of the supply chain.	• Net differential in road vs rail emission factors. • Emissions factors have been adjusted for expected changes over time in locomotive fleet mix and heavy road freight fleet mix, and on when technology is adopted – refer to sections 9.10 and 9.16.
Air quality - PM2.5, PM10, NOx reduction	Particulate matter including PM2.5 from exhaust and PM10 from brakes and tyres, and NO_x emissions all have well-established detrimental effects on human health. Heavy vehicles emit a higher level of PM10 from brakes and tyres per NTK than rail and a higher level of PM2.5 exhaust emission from higher fuel use. New DM class locomotives have been designed to comply with the Stage V European Emission Standards.	• Net quantity (tonnes per NTK) differential in road vs rail PM and NOx • Price or cost per tonne per MBCM • Quantities per NTK have been adjusted for expected changes over time in locomotive fleet mix, the heavy road freight fleet mix, and on when technology is adopted
Reduction in fuel cost	Trucks use more fuel per NTK than Rail.	• Average fuel burn per 1000 NTK. • Forecast price of each fuel type • NTKs for each fuel type (road vs rail) by year • Adjusted for expected changes in the heavy road freight fleet mix

Benefit	Rationale	Considerations
Noise reduction	Road traffic noise is generally continuous and long-term exposure can have significant adverse effects on human health. These can be categorised as disruptive impacts, such as sleep disturbance and speech interference, and psychological impacts such as annoyance reaction and other behavioural impacts. There is a great deal of evidence to show that noise can cause adverse health effects in people, due mainly to stress-related factors.	• Noise changes from different locomotive power types are consider negligible.
Increased tunnel availability	Kaimai Tunnel potentially has a capacity constraint under significant growth scenarios due to the need to space trains to give exhaust emissions time to dilute. Options that produce no fumes remove this constraint.	• There is no constraint under Scenario BAU.
Time value benefits / disbenefits from motive power type	Some motive power options potentially could lead to a change in average journey time for some routes.	• No significant changes to journey time are expected. Further analysis will be conducted during the DBC to confirm.
Safety benefits	The 2021 EY Value of Rail report derived death, serious and minor injury per km/NTK from the NZTA Crash Analysis System (CAS). The Freight equivalent factor was determined by taking deaths, serious and minor injuries involving trucks divided by the total km/NTK travelled.	• Rate of injury by severity • Cost of injury by severity • NTK
Congestion benefits	Moving freight by rail removes or avoids further congestion. Based on travel time modelling for Wellington and Auckland.	• EY Value of Rail report • Benefit will increase with time as population and volumes grow.
Net saving on infrastructure maintenance	Rail is specifically designed for moving heavy loads compared to a road which is mixed-use. As such the maintenance cost of rail is lower per NTK than Road. The RUC paid by trucks is considered a proxy for the marginal cost of road damage incurred and is compared with the maintenance cost of rail (now funded through the RNIP programme) to determine the net maintenance saving from transporting heavy freight goods by rail.	• EY Value of Rail report • Benefit increases as freight volumes grow and trucks become heavier relative to payload.

Table 38: Benefits Assessment

To estimate the benefits, it is necessary to understand the likely rate of change for the heavy road freight fleet. This rate of change would influence the relative cost between road and rail, and therefore the relative attractiveness to customers.

The possible rate of road freight decarbonisation was explored through discussions with key stakeholders in this sector. These conversations indicated that transition is dependent on two things – a high carbon price, and carbon reduction emissions signals and policies from governments, with road freight moving to lower carbon alternatives when the economics justify it. It is expected that larger operators will be better able to take up emerging technology. Also, there is expected to be much higher take up of low carbon vehicles for first and last mile trips, which would support a faster modal share conversion to use rail as a zero emissions option.

Europe will cease internal combustion engine vehicle production in 2039, which will be a catalyst for the sector. It is not expected that there will be substantial take up of hydrogen until 2040.

These insights were used to develop a mid-range estimate of the percentage of the fleet powered by hydrogen, battery, biodiesel and diesel in 2021, as well as for projected future years. These estimates were tabled with sector stakeholders who indicated a level of comfort with these projections.

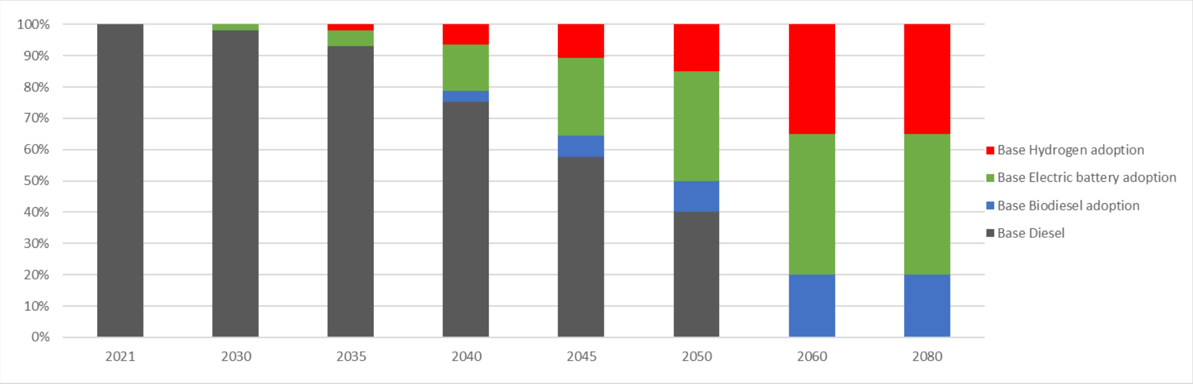

Figure 31: Possible road freight fleet low carbon technology adoption profile – mid range assumptions

Figure 32 shows the annual Air quality and GHG benefits relative to road. The benefits reflect the high emission standard the new DM diesel locomotives are designed too, and health value attributable to reducing PM and NOx exposure.

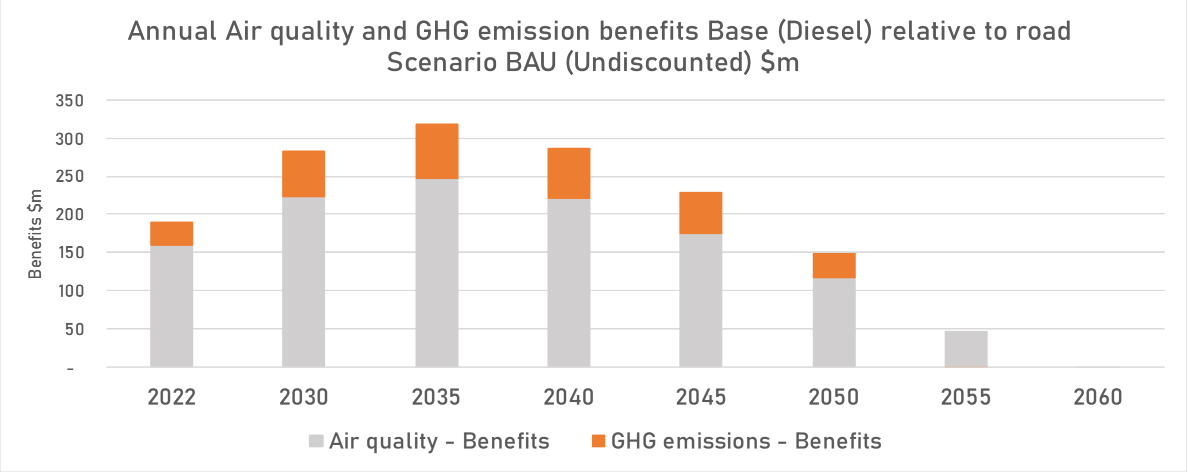

Figure 32: Air quality benefits of Base (Diesel) relative to road

Table 39 and **Figure 33** show the incremental 60 year discounted benefits relative to Base for motive power options evaluated. The three electric options and hydrogen deliver the highest incremental benefit, primarily through reduced emissions compared to diesel and improved air quality compared to Biofuel. Biofuel combustion still produces particulate matter and NOx similar to diesel.

PV(2022)$m	Option 1	Option 2	Option 3	Option 4	Option 5
Name	Battery	Biofuel	Hydrogen	Extend OLE	All mainlines OLE
Electrification	Existing OLE only			Existing + OLE P2H and H2T	OLE All main freight lines
Remainder	Electric Battery	Biofuel	Hydrogen	Electric Battery	Electric Battery
For Scenario BAU:					
Incremental benefits relative to Base					
Emissions - GHG reduction	403	403	403	403	403
Air quality - PM, NOx reduction	1,238	(157)	1,238	1,238	1,238
Reduction in fuel cost	-	-	-	-	-
Safety benefits	-	-	-	-	-
Congestion benefits	-	-	-	-	-
Net saving on infrastructure maintenance	-	-	-	-	-
Total	**1,641**	**246**	**1,641**	**1,641**	**1,641**
Total incremental benefits – other Freight Demand scenarios					
Scenario A	1,871	237	1,871	1,871	1,871
Scenario B1	2,203	242	2,202	2,203	2,203
Scenario D	2,597	268	2,597	2,597	2,597

Table 39: Incremental benefits - BAU scenario (60 year discounted cost at 5%)

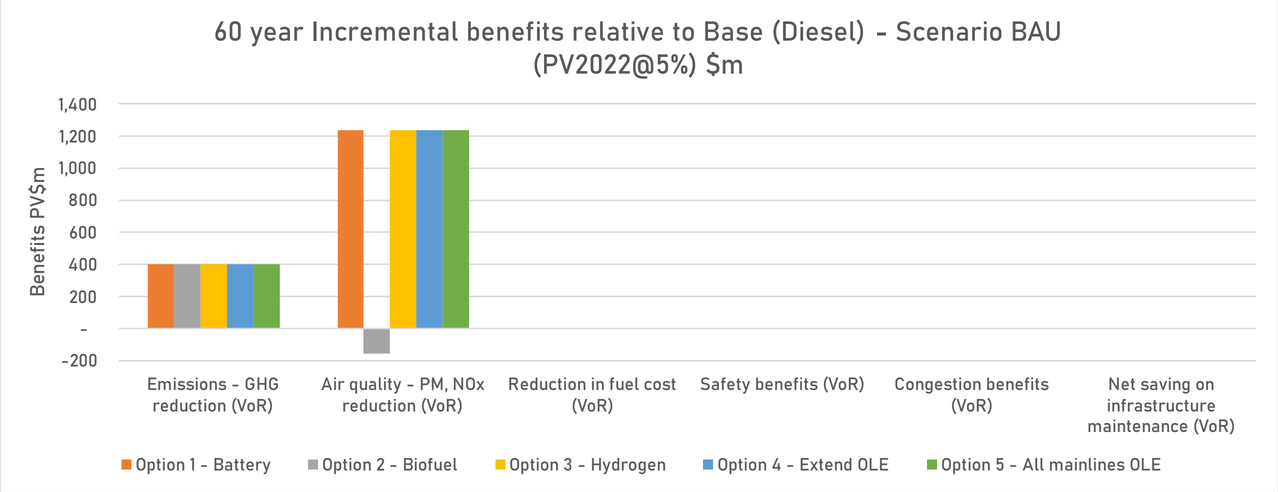

Figure 33: 60 year total incremental benefits, PV, KiwiRail Fleet Decarbonisation Economic Model

9.10. Emissions profile

The assessment shows that carbon emissions are one of the primary benefits. **Figure 34** shows the carbon emissions expected for each option, with the assumption that existing diesel freight fleet is retired or adapted at the mid-life overhaul date. This is the most pragmatic approach to take to achieve net zero take by 2050, given the lead in time required to source new rolling stock and ready the rail network with suitable infrastructure for a new motive power source.

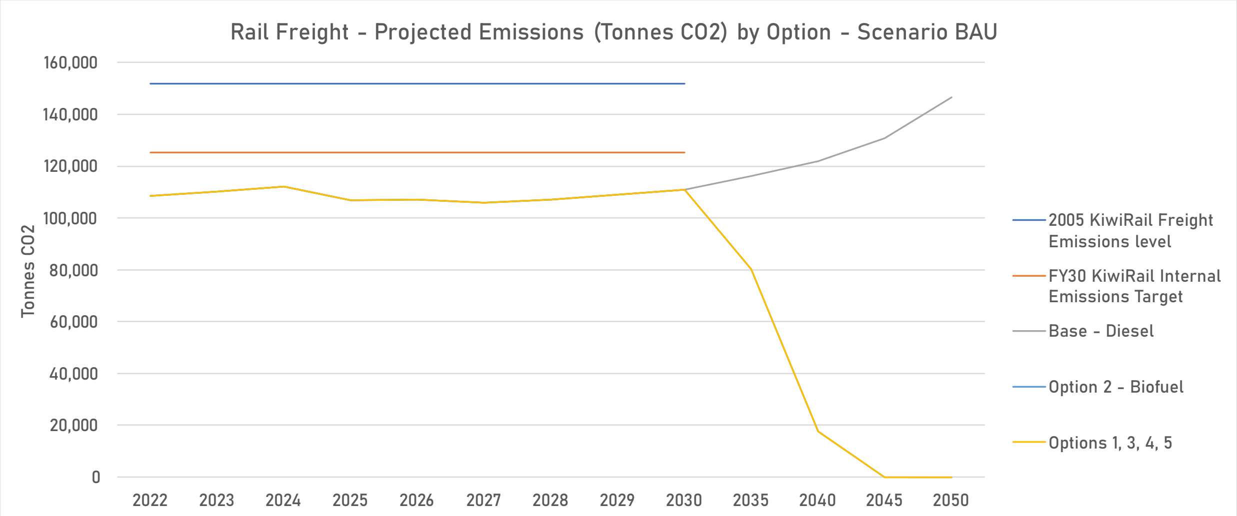

Figure 34: Emissions by Option

The graph shows emissions from the Base option (diesel fleet) increasing over time to 2050, by which time emissions match the 2005 KiwiRail freight emissions level.

The emissions profiles for all options are very similar as all fuel/motive power – electric battery, hydrogen and biofuels are zero emissions and change at the same time. All options reach their lowest emissions level in 2040-45. It is expected that some options retain a residual level of net emissions due to potential amelioration of dry year risk for grid supplied energy.

Based on the phasing in 9.5, **Figure 35** demonstrates how quickly rail can move to decarbonise, compared to long distance heavy road haulage[99].

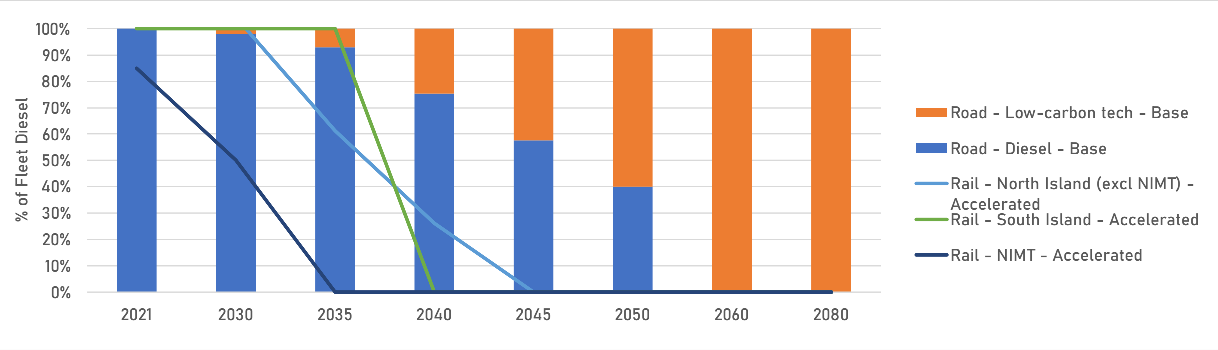

Figure 35: Heavy haulage road fleet zero carbon technology adoption profile compared to 'Accelerated' rail profile

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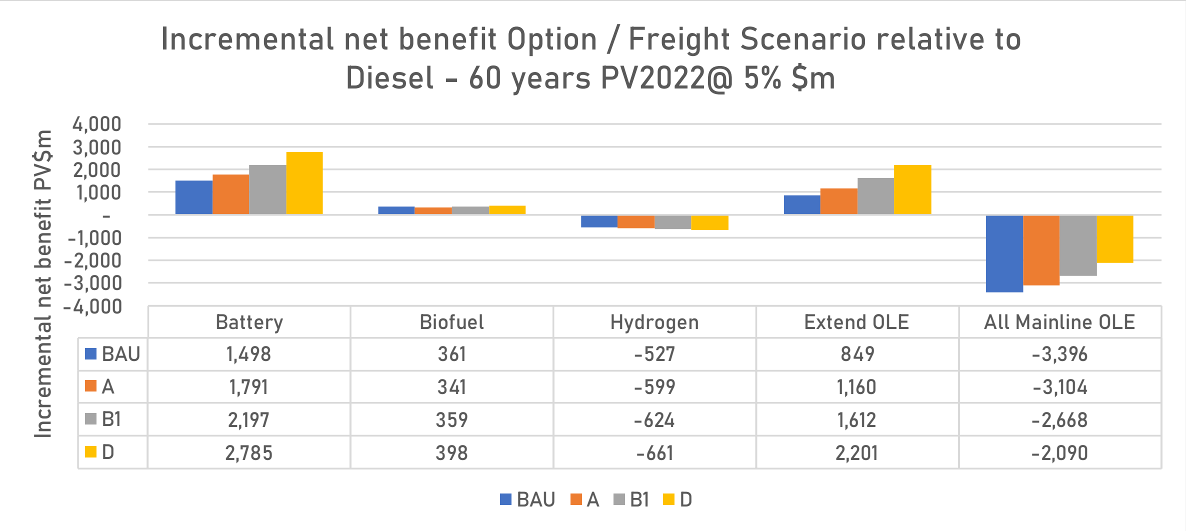
[99] Rail competes with the heavy end of the road freight market and complements the short haul and last mile delivery most likely to decarbonise early.

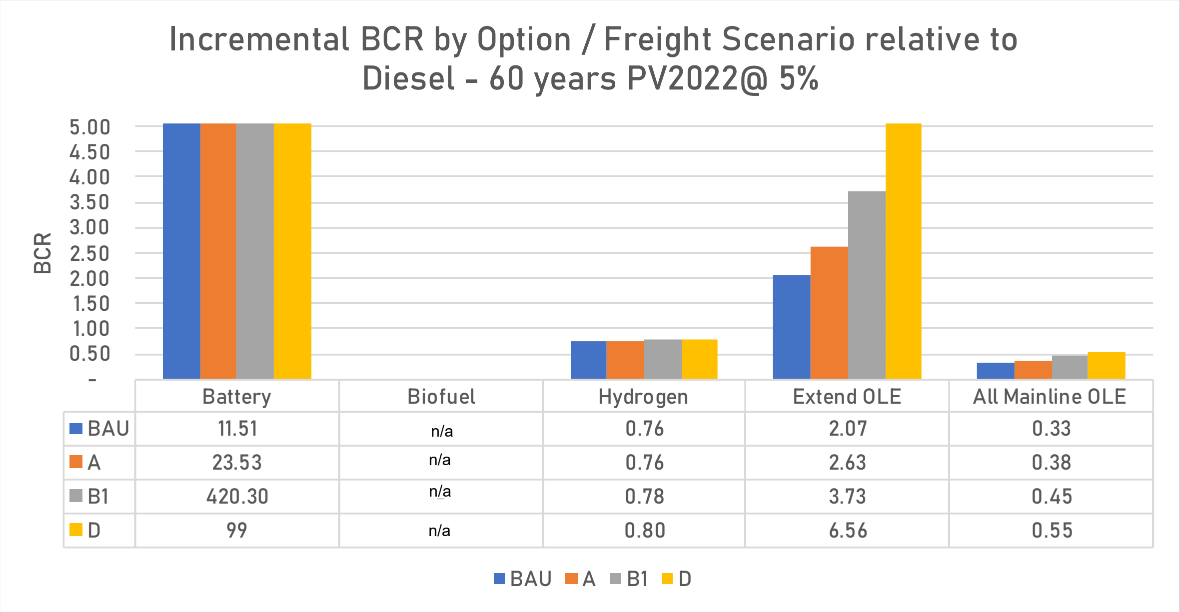
9.11. Benefit Cost Ratios and Sensitivities

Figure 36 and Figure 37 show the incremental net benefit and ratio of benefits to costs for each option, under each supply chain scenario relative to the Base (diesel). The lowest incremental BCR is for Option 5 (All mainlines OLE), where costs are far higher than the other options. All BCRs improve under high volume scenarios. From a net benefit perspective, Option 1 (Battery) is the best performing alternative fuel, followed closely by Option 4 (Extend OLE).



	Battery	Biofuel	Hydrogen	Extend OLE	All Mainline OLE
■ BAU	1,498	361	-527	849	-3,396
■ A	1,791	341	-599	1,160	-3,104
■ B1	2,197	359	-624	1,612	-2,668
■ D	2,785	398	-661	2,201	-2,090

Figure 36: Incremental net benefit to diesel by Option and Freight Scenario – 60 years



	Battery	Biofuel	Hydrogen	Extend OLE	All Mainline OLE
■ BAU	11.51	n/a	0.76	2.07	0.33
■ A	23.53	n/a	0.76	2.63	0.38
■ B1	420.30	n/a	0.78	3.73	0.45
■ D	99	n/a	0.80	6.56	0.55

Figure 37: Incremental Benefit Cost Ratio to diesel by Option and Freight Scenario – 60 years

For Biofuel in **Figure 37** and **Table 40**, the n/a reflects Biofuel has a lower cost than Base (Diesel) over the 60 years which leads to a negative BCR that is not meaningful. In comparing Biofuel to other options we have focused on the net benefit / (cost) and net benefit / (cost) per Tonne CO_2e removed.

Table 40 shows the change in ratio of incremental benefits and costs for each option for the range of sensitivities tested. The table shows that the discount rate, timing of changes and freight scenario are the three key variabilities that have the biggest impact on the BCR. The timing sensitivity illustrates that, under Scenario BAU, fiscally it is slightly more favourable to defer transition until locomotives retirement rather than Accelerate (transition at mid-life overhaul). Accelerate is supported for Battery and Extend OLE options where a combined high freight volume (Scenario D) and high fuel and carbon price environment occurs.

BCR	**Option 1**	**Option 2**	**Option 3**	**Option 4**
60 year period	Battery	Biofuel	Hydrogen	Extend OLE
Base assumption set				
Incremental Benefits PV2022$m	1,641	246	1,641	1,641
Incremental Costs PV2022$m	143	(115)	2,168	792
Incremental Net Benefit/(Cost) $m	**1,498**	**361**	**(527)**	**849**
BCR	**11.5**	**n/a**	**0.8**	**2.1**
▲ *= Cost lower/equal to Base*				
Net benefit / BCR change by test variable:	$m / BCR	$m / BCR	$m / BCR	$m / BCR
Freight Scenario A	+293 / +2.1	▲ -20 /	-71 / 0.0	+311 / +0.4
Freight Scenario B1	▲ +699 / +4.9	▲ -2 /	-97 / 0.0	+763 / +1.0
Freight Scenario D	▲ +1,287 / +9. 0	▲ +37 /	-134 / -0.1	+1352 / +1.7
High Fuel Price	+126 / +0.9	-295 /	+72 / 0.0	+123 / +0.2
Low Fuel Price	-38 / -0.3	▲ +41 /	+21 / 0.0	-35 / 0.0
High Carbon Price	▲ +466 / +3. 3	▲ +466 /	+466 / +0.2	+466 / +0.6
Low Carbon Price	-340 / -2.4	-340 /	-340 / -0.2	-340 / -0.4
Low Fuel price + Low Carbon	-378 / -2.7	-298 /	-319 / -0.1	-374 / -0.5
High Fuel price + High Carbon	▲ +592 / +4.2	▲ +170 /	+537 / +0.2	+589 / +0.7
2% discount rate	▲ +3,332 / +23.4	▲ +840 /	+471 / +0.2	+3,213 / +4.1
6% discount rate	-477 / -3.3	▲ -112 /	-11 / 0.0	-445 / -0.6
Haulage performance – +44%	▲ +142 / +1.0	▲ 0 /	834 / +0.4	+42 / 0.1
Haulage performance – +35%	+120 / +0.8	▲ 0 /	707 / +0.3	+36 / 0.0
Timing of changes - Slow	-818 / -5.7	▲ -106 /	191 / +0.1	-777 / -1.0
Timing of changes – Ambitious	+199 / +1.4	▲ -6 /	-121 / -0.1	+177 / +0.2
Road Freight transition faster	-$572m. Impacts Base and Options by same amount, no net change.			
Road Freight transition slower	+$980m. Impacts Base and Options by same amount, no net change.			

Table 40: Summary of sensitivity tests

Option 5 – All Mainline OLE excluded from table, as none of the sensitivity tests bring it into contention.

Figure 38 and **Figure 39** present a scatter graph showing the relationship between costs and benefits for each option under the sensitivities tested above. BCR trend lines of 1:1 and 4:1 are included for reference. The results show that under a range of sensitivities the incremental benefits and costs of battery and extend OLE options deliver high benefits and BCRs above 4. Battery is also lower cost than diesel under a number of scenarios/sensitivities. Biofuel is a low benefit / low cost option, while Hydrogen and All Mainline OLE mostly deliver BCRs below 1. Overall battery and extend OLE perform best under most sensitivities.

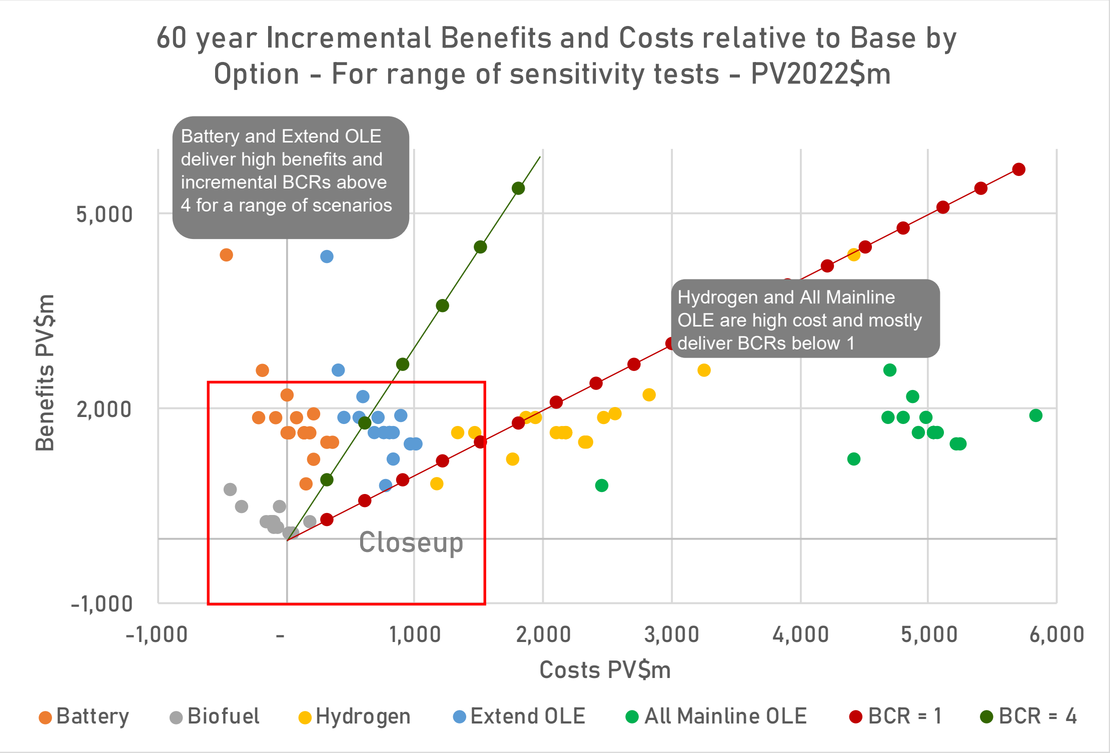


Figure 38 Incremental Benefit vs Costs relative to Base under different sensitivities

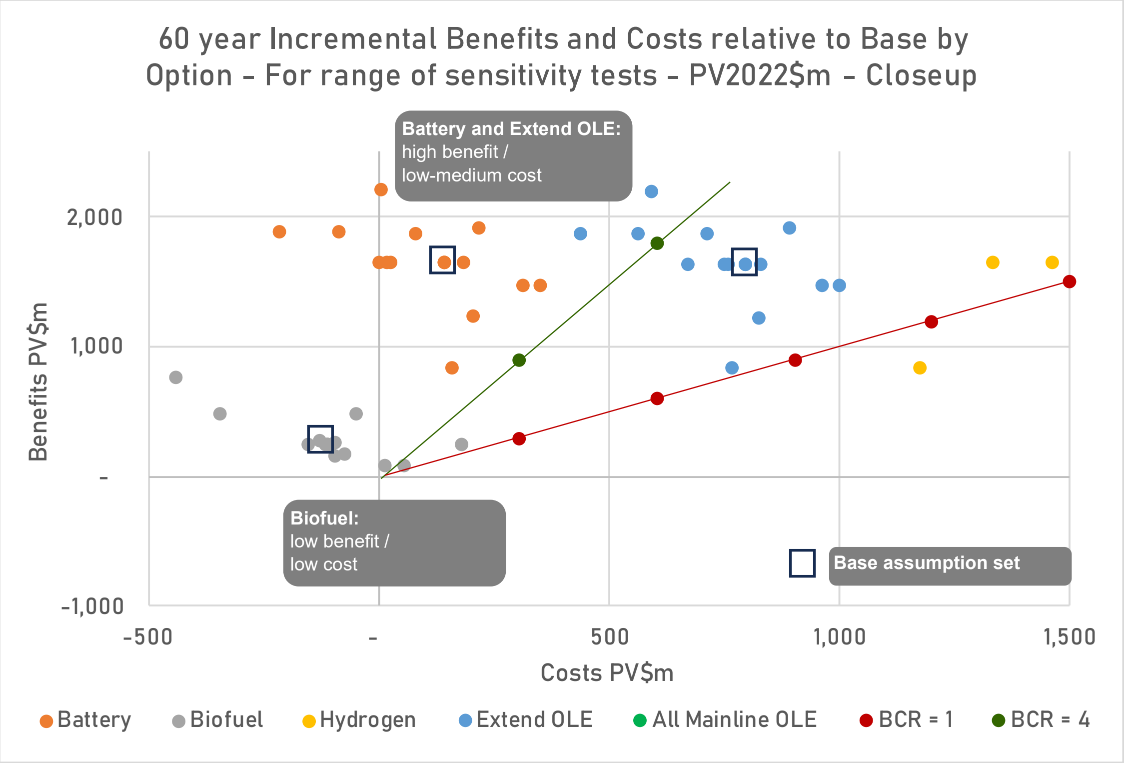


Figure 39: Closeup of Incremental Benefit vs Costs relative to Base under different sensitivities

Further details of the sensitivity parameters used are included below.

9.12. Fuel Price sensitivity

Fuel (energy) price directly impacts locomotive fuel costs; and indirectly the reduction in fuel cost benefit. As fuel price increases the reduction in fuel cost benefit also increases.

High and low fuel price curves were developed for each fuel type: Diesel, Biodiesel, Electricity and Hydrogen.

The low fuel price curve was a flat 15% lower than base across the 60 year period. The high fuel price curves as a % above the base curves is as follows:

Fuel type	2020	2025	2030	2035	2040	2045	2050
Diesel	10%	14%	20%	20%	20%	30%	30%
Biofuel	10%	34%	48%	51%	51%	51%	51%
Electricity	10%	14%	14%	14%	14%	14%	14%
Hydrogen	10%	14%	14%	14%	14%	14%	14%

Table 41: High fuel prices relative to base fuel prices by fuel type by time period

The biofuel high price curve was sourced from Hale and Twomey (now Envisory) biofuel price Feb 2021 report – Renewable Diesel (Class 1) High price path.

The electricity price curve was derived from Energy Link – RETA data provided by EECA being the relative difference between High and Central curves. As the proposed hydrogen solution primarily uses grid supplied energy, the % above the base electricity curve was also used for the high hydrogen price curve.

9.13. Carbon price sensitivity

The high and low shadow carbon price curves were sourced from The Treasury's CBAx Guide October 2022 and are graphed below.

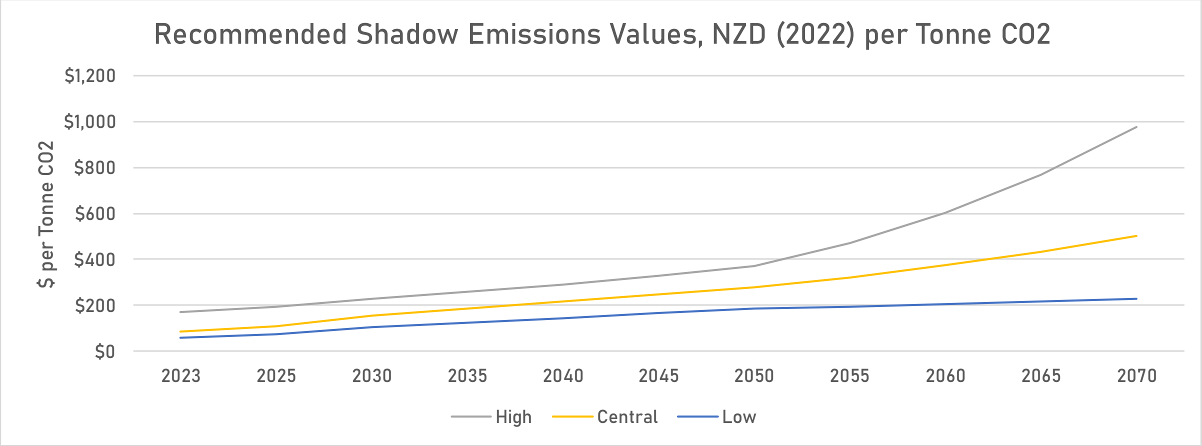


Figure 40: Shadow emissions values

Carbon price indirectly impacts the cost of diesel, and electricity to the extent power is generated using fossil fuels. That cost of carbon passed through to KiwiRail from energy suppliers is include as part of *Locomotive operating costs – Fuel*.

The *Emission – GHG reduction* benefit increases / decreases as cost of the carbon increases / decreases.

9.14. Haulage performance

For the base economic assumptions, the X-64 pair and hydrogen full width body twin unit are conservatively treated as being equivalent to the DM class locomotive. However, as shown in **Table 42** the power and continuous traction effort (TE) specifications of the X-64 pair and equivalent hydrogen twin unit have around 44% more power (3600kw/2500kw) and around 35% more continuous tractive effort (500kN/370kN). These higher performance characteristics should allow these locomotives to pull greater loads reducing operating costs and capital costs per NTK[100]. For the two sensitivities we have tested the BCR if the comparative haulage performance of the X-64 pair and Hydrogen full width body twin unit was 144% and 135%.

Loco	Power (kw at wheels)	Continuous TE (kN)
X-66	2500	370
X-64	1800	250
X-64 pair	3600	500
Hydrogen full width body twin unit	3600	500
DM	2500	370

Table 42: Locomotive power and tractive effort specifications

9.15. Timing of Changes

The model was used to test three different timing options: Accelerated, Slow and Ambitious, which are defined below. This is because if changes can be fast tracked, benefits will be delivered more quickly and accumulate over time. This is particularly important when considering zero carbon goals.

Accelerated (Base assumption) – transition occurs as locomotives reach mid-life overhaul or retire, whichever is earlier, as that is the natural point to change given lead times and capacity to deliver those changes.

Slow – transition occurs as locomotives retire, reducing need to retrofit new technology into existing or recently ordered locomotives, allowing more time for fuel supply and technology development/supply chains to become established.

Ambitious - as soon as possible taking into consideration lead times for infrastructure build and locomotive build and manufacture – these lead times are normally around 2 years for procurement and 2 years for production.

The transition will happen at different times for the South Island, North Island and North Island Main Trunk, as the locomotives for each of these regions reach end of life at different times. The locomotives have been split into these three regional groupings for modelling purposes. **Table 43** shows the % of fleet that are zero or low carbon by timing options by region by period:

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[100] But excess pulling performance NOT used in base assumptions, rather the pair is held back to be equivalent to a single DM and the surplus unused power stays in batteries as extra range. In the real world, short hauls may have heavier and fewer trains using pair to its maximum and more lighter trains on routes where range is critical.

Region	2020	2025	2030	2035	2040	2045	2050
Accelerated							
NIMT	32%	60%	60%	100%	100%	100%	100%
Rest of North Island	0%	0%	0%	47%	76%	100%	100%
South Island	0%	0%	0%	18%	100%	100%	100%
Slow							
NIMT	32%	60%	60%	100%	100%	100%	100%
Rest of North Island	0%	0%	0%	14%	14%	14%	14%
South Island	0%	0%	0%	0%	0%	0%	0%
Ambitious							
NIMT	32%	60%	60%	100%	100%	100%	100%
Rest of North Island	0%	0%	31%	61%	100%	100%	100%
South Island	0%	0%	0%	92%	100%	100%	100%

Key:

🟦	**50<90%**	🟩	**>90%**

Table 43: % of locomotive fleet that is zero or low carbon

9.16. Road Fleet Transition

The assessment of the likely Heavy Haul Road Fleet pathway to net zero carbon is explained in 9.9. **Table 44** shows the % of Heavy Haul Road Fleet that are expected to be zero or low carbon by timing scenario by period.

Road Fleet Adoption Scenario	2020	2025	2030	2035	2040	2045	2050	2060
Base assumption	0%	1%	2%	7%	25%	42%	60%	100%[101]
Faster adoption	0%	1%	4%	15%	37%	58%	80%	100%
Slower adoption	0%	0%	1%	3%	15%	28%	40%	85%

Table 44: % of heavy haul road fleet that is zero or low carbon

The pace of Road Fleet transition impacts the Emissions – GHG reduction and Air quality – PM, NOx reduction benefits. Rail currently emits significantly less GHG, PM and NOx than Road therefore as Road transitions the relative advantage would decrease.

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[101] Assumption updated to 100% from 80% to reflect the biofuel price as used for modelling falls below diesel (including carbon pass-through) by this date and therefore it would be economic to transition, subject to supply and market risk.

9.17. Recommended Way Forward: ECONOMIC basis only

From a strictly economic analysis perspective Option 1 (Battery), Option 2 (Biofuel) and Option 4 (Extend OLE) should be taken forward to the next stage.

Table 45 summarises the economic assessment for the three options. These options all have an incremental BCR, relative to diesel, above 1 across a range of sensitivities, with Battery delivering the highest incremental net benefit.

Battery and Extend OLE have high benefits relative to Biofuel. This difference is caused by Biofuel combustion still emitting NOx and PM reducing the air quality benefit relative to Battery and Extend OLE and produces higher NOx emissions than Diesel combustion. Operational savings on fuel, road maintenance, congestion and crash savings are the same as they are directly related to freight volume, as the model assumes the same volume of freight is transported by rail for each option. Biofuel has the lowest cost as transition costs are minimal. Battery is lower cost than Extend OLE, primarily because of the infrastructure cost for additional overhead lines in Extend OLE. Under higher volume freight scenarios (B1 and D), Extend OLE closes most of the differential to Battery.

	Economic Options to take forward		
Scenario BAU Present value 2022 $m	**Option 1 Battery**	**Option 2 Biofuel**	**Option 4 Extend OLE**
Incremental Benefits	1,641	246	1,641
Incremental Cost	143	(115)	792
Net benefit	**1,498**	**361**	**849**
BCR (60 year period)	11.5	n/a[102]	2.1

Table 45: Economic Summary – Option 1 (Battery), Option 2 (Biofuel) and Option 4 (Extend OLE) ($m)

To meet the zero carbon goal by 2050, the preferred timing scenario from an economic perspective is the Accelerated adoption profile which produces significantly higher net benefits than the Slow adoption profile. While the Ambitious timing scenario generates a higher net benefit, the technology development risks are significantly higher, with the potential to compromise achievability and reduce net benefits to a level below the Accelerated adoption profile.

The Accelerated timing scenario involves:

- electrifying the Pukekohe to Hamilton to Tauranga sections of the NIMT and ECMT lines by 2030 (under Option 4)
- replacing DL class gen 1 and 2 in late 2020s/early 2030s with new locomotives
- mid-life motive power swaps or replacement in mid 2030s of the DL class gen 2.2, 2.3 and 2.3ii[103]
- mid-life motive power swaps for the DM class locomotives at their first scheduled overhaul (10 years – late 2030s/early 2040s).

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[102] The negative incremental cost results in a BCR which is not meaningful.
[103] Refer to Table 31 (and Glossary) for a tabulation of locomotive sub types.

The appropriateness of suggested timing will be reassessed to account for any new information on technology and operational risks, asset strategy and ZGHG journey, gathered as part of the detailed business case.

Based on the economic analysis only, the recommended way forward (RWF) short-list for further assessment in the detailed business case is:

RWF 1: Existing OLE and battery-electric for other routes (**Option 1**) with timing aligned with locomotive retirement or midlife overhaul, whichever is earliest

RWF 2: Extend OLE between Pukekohe to Hamilton and Hamilton to Tauranga, and battery-electric for other routes (**Option 4**), with timing aligned with locomotive retirement or midlife overhaul, whichever is earliest

RWF 3: Existing OLE and biofuel for other routes (**Option 2**) with timing aligned with locomotive retirement or midlife overhaul, whichever is earliest

10. Commercial Case

Is the proposed deal commercially viable? Who will deliver it?

The Commercial Case describes the commercial viability and market conditions that will impact the project and outlines the proposed procurement arrangements for the preferred option.

10.1. Battery locomotive situation

Major locomotive and prime mover suppliers (OEMs) were engaged as part of the study. All confirmed that battery locomotives and their support systems formed part of their future offerings. Battery locomotives are already available from these suppliers, although not yet in a form suitable for the constraints of the New Zealand network.

KiwiRail was able to gain some confidence that battery technology and the locomotive industry will be able to provide locomotives that could meet the needs of a pilot implementation and are on a trajectory that should be able to meet production requirements by the early 2030's.

A concern is that demand is expected to ramp up very rapidly, leading to very long lead times with constraints on production capacity.

Figure 41: EMD (Progress Rail) GT38J 1.5-2.1 MW / 4.0 MWH "Joule" battery electric locomotive

Source: Progress Rail brochure. Note: Overweight and oversize for New Zealand in 2023 form, but improving battery performance will allow both to be addressed.[104]

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[104] https://s7d2.scene7.com/is/content/Caterpillar/CM20230103-cf67a-ad066?_ga=2.46775460.220730784.1681962841-1884599534.1669848677

Figure 42: Wabtec FLX drive battery locomotive

Source: Wabtec datasheet[105]. A North American sized locomotive but work has started.

But the significant point is that battery locomotives with the performance of an X-64 pair cannot yet be purchased off the shelf and there cannot be complete certainty when or if they will become available as a product able to be procured conventionally.

This requires a sophisticated approach to procurement.

10.2. Locomotive Procurement factors

Beyond highly standardised markets like North America, any new locomotive purchase and delivery is complex and requires lead times of several years. Factors influencing this are

- Fleet purchase is a significant investment, requiring lead time for securing finance.
- Any locomotive is a sophisticated technological product produced in small quantities.
- Even modular designs require customisation for markets where there are weight and size restrictions and special equipment is required for compatibility with the existing operation and facilities.
- Main line locomotives are not produced for stock. There are lead times for the scheduling, set up and operation of the production line. Even where a modular design has been selected, production rates are low and an order will enter the supply chain behind orders already in progress.
- In the case of battery locomotives KiwiRail and other railways are seeking technology which is changing and improving rapidly but is not yet a stable product.
- The early production designs available are to suit heavy duty railways, and a variant capable of operating in NZ falls well short of the performance required and assumed for the X-64 concept. Locomotives of this performance are likely coming but cannot be ordered today.

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[105] https://www.wabteccorp.com/FLXdrive-Battery-Electric-Locomotive?inline

A conventional locomotive procurement approach requires some development to make it suitable for the procurement of an emerging technology battery locomotive fleet.

10.3. Procurement Approach

In summary, the procurement of a ZGHG locomotive for New Zealand conditions:

- Is high value
- Complex and partly custom, requiring an engaged and informed purchaser
- Involves lead times of several years even once product becomes a production item
- Is seeking a product that is currently in the development phase and may be a decade away from stability
- Will require maintenance procedures to evolve and will need a profound shift in how operations are conducted
- Will require significant supporting infrastructure: charging and depots

This requires a customised procurement approach that takes account of these factors.

The previous, also transformational, transition of rail from steam to internal combustion (petrol then diesel) had these characteristics and remains helpful in guiding today's equivalent transformation.

This involved a staged approach, with early experimentation, mostly around passenger vehicles, adoption for small, then full sized shunt locomotives, including a pilot implementation, and completed by a prioritised steady conversion of mainline operations by region or route. New steam locomotives were purchased during the conversion to maintain some operations ahead of dieselisation having progressed sufficiently and the best displaced steam locomotives were cascaded to areas scheduled to be dieselised last, to in turn displace less capable steam locomotives.

Applying the steam to diesel lessons to the decarbonisation transformation:

- Motive power experimentation was appropriate in a railway that for over 100 years designed and built its own locomotives and passenger railcars. Today prototypes are only appropriate for manufacturers developing a product.
- However, a pilot implementation allows a user to gain familiarity with new products from a supplier and begin the process to new way of doing things. Full introduction on a limited scale forces the process of adapting its operation, facilities and people without full commitment. It also allows time for a developing product to evolve without "betting the business" on it.
- Shunt and other lower performance duty cycles are good places to start a "micro pilot", where demands are not too much of a stretch for technology early in its development.

Therefore the initial procurement exercise is for the pilot operations.

10.4. Micro Pilot – Shunt Locos

For an immediate micro-pilot involving a sub fleet of battery powered shunt locomotives at one fixed location it is proposed that the existing in progress "Operational Shunt"[106] procurement be adapted to deliver the small fleet of battery shunt locomotives.

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[106] Shunt locomotives in the class of current DSG/J/H diesel-electric heavy shunt locomotives, but lacking the extended range that comes with a fuel tank full of diesel, so confined to yard operations.

For this first “toe in the water”, the supply will preferably be for a turn key system of locomotive and charger(s). KiwiRail would assume responsibility for the supply of power to the chargers, unless the locomotive supplier subcontracts the charger element to an NZ based electrotechnical company with strong experience in working with local lines companies.

10.5. Full Scale Mainline Pilot

The lead time for locomotives can vary between three to four years, depending on complexity – up to 24 months for procurement, with 24 months more for manufacturing and commissioning. Longer is easily possible if there are any delays in the business case phase. Serious procurement would need to commence before the end of FY24 for there to be any chance of a pilot in this timeframe.

For the full scale pilot proposed for 2027/28, a dedicated procurement is proposed. Special arrangements are expected to be necessary for the pilot scheme, in view of the in developmental nature of the product, but the same general competitive procurement approach used for the in delivery Stadler DM is proposed.

This is a performance specification followed by a joint project involving technical and commercial experts for the duration. Conduct of the procurement and project would need to take account of this being a development project involving risk for both parties. High levels of supplier support would be required for the agreed duration of the pilot.

Responsibility for the supply of the pilot charging system is recommended to be determined at the time but power supply to the chargers to be a KiwiRail responsibility, in view of the risks (very limited cost effective control available to the locomotive specialist) around connection. Refer below.

With the steady advances in performance and affordability, commitment to the battery is best made as late as possible in the design/build process, so the cheapest and best battery is fitted.

10.6. Probity and process

KiwiRail has voluntarily adopted the Government Rules of Procurement (GRP) and will follow the rigorous procurement processes required of these.

As an SOE, KiwiRail also has rigorous processes in place for managing and reporting the Crown (public) funding being used to invest in its railway infrastructure and equipment. These align with Waka Kotahi requirements and meet their requirements of the RNIP funding administered by them. Any locomotive procurement would follow equivalent processes.

10.7. Electric locomotives

The OLE electric locomotives are conventional products, albeit subject to the general challenges set out earlier in this section. The fitting of a traction battery for “last mile” operation away from wires is a recent development but no longer novel, certainly not by the time these locomotives are required in the later 2020’s. A conventional competitive procurement against performance requirements as employed for the DM locomotive is the assumed model.

The EF electric locomotive life extension is being managed by KiwiRail, with integration and assembly at its own workshop and electric locomotive depot using in house engineering resource. Specialist suppliers provide services and equipment. The existing project and supply chain is targeting delivery of 15 refurbished locomotives.

10.8. DFT locomotives

The proposed DFT life extension[107] can either be based on refurbishment of the existing legacy traction package or by substitution of the legacy equipment with a completely new package. Locomotive and prime mover OEMs offer kits for the former or complete packages for the latter. Which route is taken is a matter for a detailed business assessment followed by a conventional, but very tightly specified, competitive procurement for the preferred option, or to separate the options.

There is always an element of risk in a refurbishment that cannot be economically assumed by a supplier. Only the engineering and new equipment can be a quoted and competitive fixed price. In view of the nature of such work, ideally KiwiRail would carry out the upgrade itself, applying its own expert resources, supported by the supplier kit and engineering, and KiwiRail managing the variability in the donor locomotives.

10.9. Battery charging connections

This study has identified significant risks, variability and cost associated with the high capacity power supply connections to charging stations, which suggest that KiwiRail manage this element.

The battery locomotive OEMs are increasingly able to provide charging stations, although this does not include any special competence in the connection of these to grid or lines power supplies that would negate the challenges here.

It is recommended that the shunt “micro pilot” be an integrated package of locomotive and charging station (single location), with KiwiRail taking responsibility for the power supply.

It is recommended that the more detailed study phase investigate options for the provision of charging stations for the mainline pilot. Specialist electro-technical companies spoken to during the study confirmed that the supply of such stations and the development of MW range chargers formed part of their developing business, so procurement separate from the locomotives is probably the preferable option, each element being supplied by a specialist in the field.

This also gives the option of the specialist electro-technical company with local presence managing and delivering these connections on KiwiRail’s behalf. While the risk around the capacity and cost of the supply on the lines/grid side would remain with KiwiRail, this delivers advantages of their expert staff, existing relationships with the electricity industry and integration of charger and supply.

10.10. Biofuel

Air New Zealand in conjunction with MBIE are advancing a project intended to establish a SAF industry in New Zealand. This project is at the stage of short listing supplier technology proposals ahead of a procurement to “buy”. KiwiRail has entered into a Non Disclosure Agreement with ANZ and has been following progress in this project.

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[107] Proposed in the discussion section of this study.

It is recommended at KiwiRail continue this relationship with a view to deciding whether to become more closely involved and to better understand the biofuel option. Certainly ANZ is interested in having a significant diesel user involved.

10.11. Other

Major upgrades of electrical equipment and changes to inventory, tools and workforce will be required at KiwiRail's maintenance sites.

While the battery locomotive supplier may provide tool and support equipment as part of their package, KiwiRail will manage the facility upgrades. Accountability for the procurement will rest with the Capital Projects and Asset Development (CPAD) team, under a Programme Director: Mechanical Facilities.

This work will primarily be delivered by external parties. KiwiRail's procurement processes align with the Government's procurement policies, and conventional GETS competitive processes will be appropriate for most elements of the mechanical maintenance and network service facilities build and fitout.

Figure 43: Battery shunt locomotives are not new. NZR Eb class battery – electric shunting locomotive (fleet entered service 1925 and 1929). Considering the subject of this report, it is perhaps ironic that this class of five battery locomotives were converted to diesel-electric from 1953, running as diesel locomotives until the end of their lives. [108]

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[108] A P Godber Collection, Alexander Turnbull Library. APG-0329-1/2-G

11. Financial Case

Is the investment proposal affordable? How will It be funded?

This section sets out the indicative financial implications of the recommended way forward short-list.

11.1. Recommended Way Forward Short-list Cost Estimates

The cost estimate breakdown table for Option 1 (Battery), Option 2 (Biofuel) and 4 (Extend OLE) is shown in **Table 46**.

For Option 1 Battery the incremental investment cost above Base (diesel) is PV$0.1bn. Assuming Lineside charging infrastructure is treated the same way as OLE, the incremental investment split between Above Rail and Below is less than PV$0.0bn and PV$0.2bn respectively. For Option 2 Biofuel there is net cost saving of $0.1bn all attributable to Above rail. For Option 4 Extend OLE the incremental investment cost is PV$0.8bn and is mainly attributed to Below Rail with Above Rail receiving a cost reduction relative to Base of PV$0.2bn.

		Incremental cost over Base			Total cost		
60 year discounted cost for BAU ($m's)		**Option 1 Battery**	**Option 2 Biofuel**	**Option 4 Extend OLE**	**Option 1 Battery**	**Option 2 Biofuel**	**Option 4 Extend OLE**
Locomotive operating costs – fuel		9(2)(i) - Commercial Activities	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Locomotive maintenance costs	motive power	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	non motive power	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Infrastructure maintenance costs		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Fuelling and storage costs		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Business change costs		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Total operational costs		**(572)**	**(116)**	**(518)**	**2,568**	**3,025**	**2,623**
Locomotive purchase costs	motive power	9(2)(i) - Commercial Activities	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	non motive power	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Network infrastructure construction costs		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Storage and fuelling infrastructure costs		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Mechanical and Network Services facilities		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Total Capital Costs		**715**	**1**	**1,309**	**1,711**	**996**	**2,305**
Total Investment Cost		**143**	**(115)**	**792**	**4,279**	**4,021**	**4,928**
Comprising: Above Rail Investment		9(2)(i) - Commercial Activities	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Below Rail Investment		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 46: Cost Estimate Breakdown for Option 1 (battery), Option 2 (Biofuel) and Option 4 (Extend OLE), compared to Base (diesel)

11.2. Spending Profile

The capital and operating spend profile for Base, Option 1 (Battery), Option 2 (Biofuel) and Option 4 (Extend OLE) are shown in **Figure 44, Figure 45**, **Figure 46** and **Figure 47** respectively. Detailed cash flow projects for Base and each option are included in Appendix 2.

The Option 1 Battery profile shows a peak above rail funding gap of $0.7bn in 2035, which reduces to nil by 2055, and with lower fuel and operating costs, eventually delivers an overall lower above rail cost relative to Base of around $2.5bn by 2082. See **11.4** for potential funding pathways to manage current funding gaps.

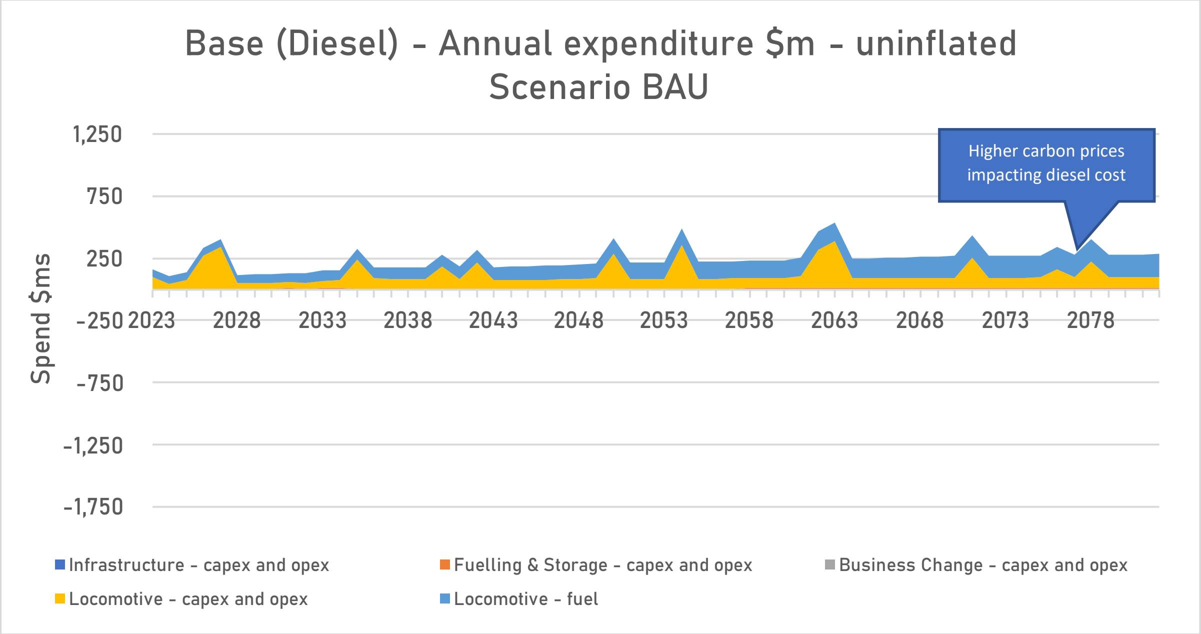


Figure 44: Annual cash flow profile for Base (diesel) - Scenario BAU

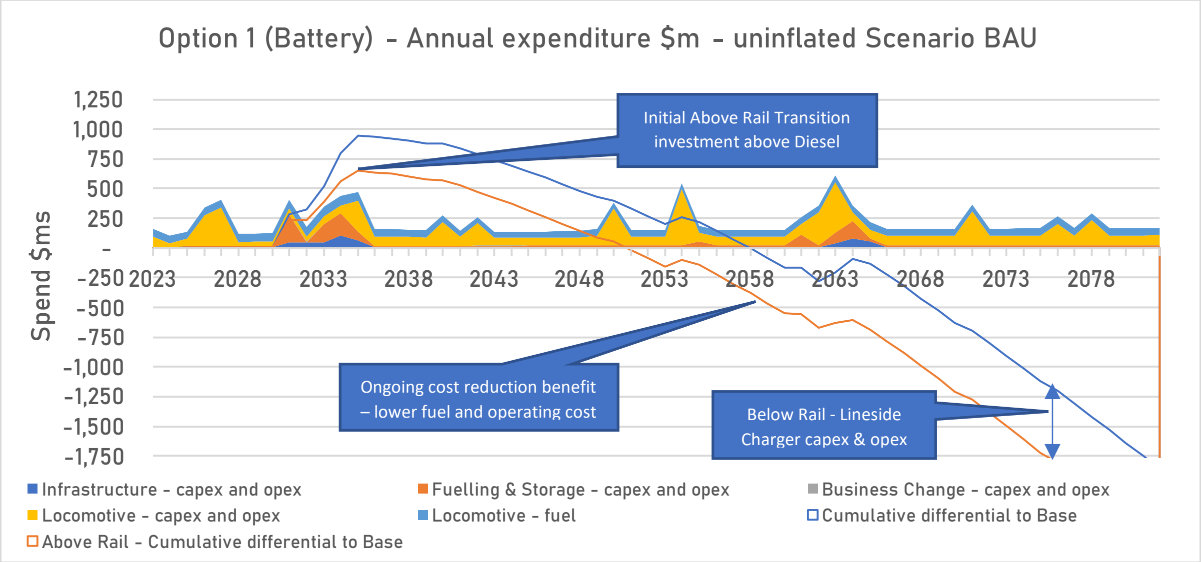
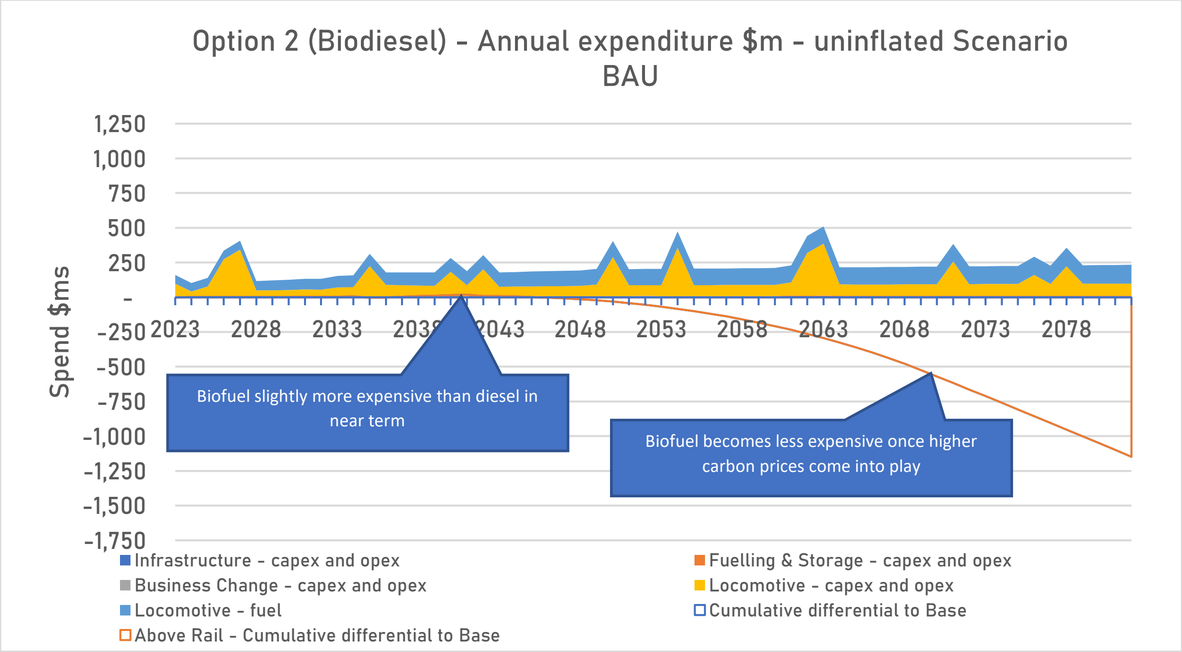


Figure 45: Annual cash flow profile for Option 1 with cumulative comparison to Base (diesel) - Scenario BAU

The Option 2 Biofuel profile shows a peak above rail funding gap of less than $0.1bn in 2040, which reduces to nil by 2050, and with lower fuel and operating costs, eventually delivers an overall lower above rail cost relative to Base of around $1.1bn by 2082.

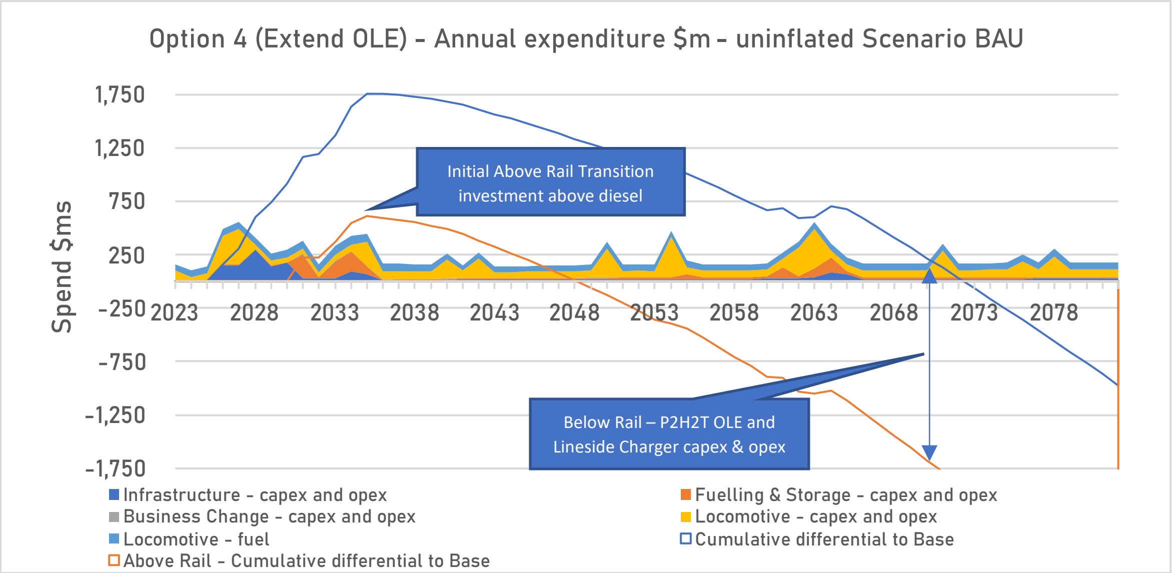


Biofuel slightly more expensive than diesel in near term

Biofuel becomes less expensive once higher carbon prices come into play

Figure 46: Annual cash flow profile for Option 2 with cumulative comparison to Base (diesel) - Scenario BAU

The Option 4 Extend OLE profile shows a peak above rail funding gap of $0.6bn in 2035, which reduces to nil by 2050, and eventually delivers an overall lower above rail cost relative to Base of around $3.1bn by 2082.



Initial Above Rail Transition investment above diesel

Below Rail – P2H2T OLE and Lineside Charger capex & opex

Figure 47: Annual cash flow profile for Option 4 with cumulative comparison to Base (diesel) - Scenario BAU

Table 47 shows the total spend by Option by year and the difference to Base (Diesel) with split between Above and Below Rail. The figures are based on 2022 real prices and undiscounted.

Annual Cash flows – Opex and Capex	2023	2024	2025	2026	2027	2028	2029	2030	2031-35 Ann.avg	2036-40 Ann.avg	2041-45 Ann.avg	2046-50 Ann.avg	2051-55 Ann.avg	2056-60 Ann.avg	2061-65 Ann.avg	2066-70 Ann.avg	2071-75 Ann.avg	2076-82 Ann.avg	Total
	$m	$m	$m	$m	$m	$m	$m	$m	$m	$m	$m	$m	$m	$m	$m	$m	$m	$m	$m
Base (Diesel)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	14,903
Option 1 (Battery)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	13,043
Option 2 (Biofuel)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	13,755
Option 4 (Extend OLE)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	13,930
Cumulative difference vs Base (Diesel)	2023	2024	2025	2026	2027	2028	2029	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2082	Peak diff
Option 1	1	1	2	3	4	5	5	6	946	875	642	396	221	(164)	(131)	(630)	(1,123)	(1,860)	946
Above Rail	1	1	2	3	4	5	5	6	651	570	318	53	(143)	(550)	(686)	(1,208	(1,723)	(2,493)	651
Below Rail	-	-	-	-	-	-	-	-	295	306	324	344	364	386	555	577	600	633	633
Option 2	-	1	1	1	1	2	2	2	(4)	16	2	(31)	(100)	(207)	(361)	(570)	(807)	(1,149)	16
Above Rail	-	1	1	1	1	2	2	2	(4)	16	2	(31)	(100)	(207)	(361)	(570)	(807)	(1,149)	16
Below Rail	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Option 4	1	1	2	155	307	602	745	917	1,762	1,686	1,478	1,237	1,012	670	679	215	(267)	(973)	1,762
Above Rail	1	1	2	3	4	5	5	6	608	489	204	(125)	(443)	(890)	(1,116)	(1,680)	(2,264)	(3,119)	608
Below Rail	-	-	-	152	303	597	739	911	1,154	1,197	1,274	1,362	1,455	1,560	1,795	1,895	1,997	2,145	2,145
	🟨	Peak diff		🟩	Break-even														

Table 47: Locomotive and Infrastructure operating and capital spend by year for Option 1, Option 2 and Option 4 compared to Base (Diesel) – Scenario BAU.

11.3. Financial appraisal

Option 4 (Extend OLE) provides the best financial result for Above Rail with net cash flow being $3.1bn lower than diesel over the 60 year forecast period, followed by Option 1 (Battery) and then Option 2 (Biofuel). Option 4 (Extend OLE) lowers KiwiRail's Above Rail operating cost from early 2030s enhancing KiwiRail's competitiveness relative to Road in the domestic freight market.

While Option 4 (Extend OLE) has a higher Below Rail cost than Option 1 (Battery) and Option 2 (Biofuel), under the higher rail freight volume scenarios (B1 and D), Option 4 is significantly better than Option 2. Further, the financial risk associated with this option compared to Option 1 is lower as the OLE and conventional electric locomotive technology is mature, currently in use and electrification of Pukekohe to Papakura in progress and NIMT substation renewals completed.

11.4. Funding Sources

KiwiRail's current funding sources are a combination of Crown and NLTP Funding through RNIP, EBITDA cash reserve, and partial external debt financing.

Table 48 shows, for each major cost element, the mix of possible funding sources.

It is expected that capital investment required for up to 263 single track km of OLE under Option 4 would be included in the Rail Network Investment Programme (RNIP), as would the network of battery chargers required in both Option 1 and Option 4.

Capital for rolling stock replacements would be from the cash reserve and external debt financing, or, if an accelerated path is agreed, from a Budget Bid, in recognition of the social benefits delivered. Potentially, a mix of a grant to cover increased costs due to acceleration, and a loan to cover cash flow timing.

Existing and possible funding	Funding methods currently available to KiwiRail			Ministry & Minister dependent		EECA & CERF Application
Cost component	**RNIP**	**EBITDA KiwiRail Cash reserve build from 2027**	**Partial external debt financing or third-party investment**	**Budget Bid - Loan to cover cash flow timing.**	**Budget Bid – Grant to cover pilot programme**	**Contestable funding – pilot, feasibility, tech trials**
Above Rail						
Locomotive replacements and motive power swaps – Slow		Options 1,2,4 (Battery, biofuel, extend OLE)	Options 1,2,4			
Locomotive replacements and motive power swaps – Accelerated		Options 1,2,4	Options 1,2,4	Options 1,4	Options 1,4	Options 1,4
Fuelling and Storage (Depot infrastructure)		Options 1,2,4	Options 1,2,4	Options 1,4	Options 1,4	Options 1,4
Business change		Options 1,2,4	Options 1,2,4	Options 1,4		
Below Rail						
Infrastructure – OLE	Option 4					
Infrastructure - Lineside chargers	Options 1, 4					

Table 48: Possible funding sources

KiwiRail considered leases but this resulted in a higher overall cost. Given KiwiRail's capital structure and implicit credit rating this is not considered an option to investigate further.

These possible funding sources would be investigated further in as part of the detailed business case.

11.5. Overall Affordability

This is a significant programme. **Table 49** shows Options 1 (battery) and 4 (extend OLE) require between $0.9bn to $1.8bn of funding between 2025 and 2040 to deliver the initial stage. Option 2 (biofuel) does not require any significant funding above Base, however, that assumes KiwiRail can access a reliable supply at scale within the estimated price range.

Peak funding required above Base for initial stage to 2040	Above Rail $m	Below Rail $m	Total $m
Option 1 (Battery)	9(2)(i) - Commercial Activities		946
Option 2 (Biofuel)			16
Option 4 (Extend OLE)			1,762

Table 49: Peak funding required

KiwiRail's cash reserve – 9(2)(i) - Commercial Activities Those funds are required to support KiwiRail's future asset renewals and growth. A portion of this forecast cash reserve would be accessible to contribute towards transition. The amount accessible will be firmed up as part of the detailed business case.

External Debt funding - 9(2)(i) - Commercial Activities

RNIP investment - The existing 10-year RNIP programme is focused on core renewals, maintenance with limited improvements, and has been funded for the next four years. With the focus on delivering core network reliability and resilience within an already constrained funding level, there is limited capacity to reprioritise existing RNIP funding to support rail decarbonization within the next RNIP triennium (1 July 2024 to 30 June 2027). However, we would seek to include the following funding requirement in the third and fourth RNIP triennium. Funding approval would be subject to completion of the detailed business case, KiwiRail Board, Waka Kotahi advice to Ministers and Ministerial approval. NLTF Top up funding via Crown Budget process would likely be required.

Below Rail Investment profile	Current RNIP triennium	Next RNIP triennium (Under development)	Third and Fourth RNIP triennium	10-30 years	30-60 years
2022 prices, no inflation	1 July 2021-30 June 2024 $m	1 July 2024-30 June 2027 $m	1 July 2027-30 June 2033 $m	1 July 2033-30 June 2053 $m	1 July 2053-30 June 2082 $m
Option 1 (Battery)	9(2)(f)(iv) - Active consideration		133	224	277
Option 4 (Extend OLE)			990	418	728

Table 50 Below rail investment profile

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[109] Subject to review following IREX termination.

Budget bid – The Crown's fiscal capacity is under pressure. With deficits and New Zealand's Crown debt to GDP ratio growing to 49%, bids need strong alignment to key policies and high benefit cost ratio.

This programme delivers significant emission benefits for New Zealand through the acceleration of diesel fleet replacement / motive power swaps. Options 1 (Battery), 2 (Biofuel) and 4 (Extend OLE) provide a net benefit relative to Base of up to $220 per Tonne CO_2-e, cost effective zero carbon solutions for New Zealand to decarbonise over 17% of New Zealand's Freight NTKs. These solutions also lower New Zealand's overall supply chain costs relative to the status quo. Bringing Option 1 or 4 to market earlier than what KiwiRail could otherwise, has significant benefits and builds a strong case for Crown support.

Subject to completion of the detailed business case and KiwiRail Board approval, KiwiRail would require Above Rail funding through Crown Budget 2026 9(2)(f)(iv) - Active consideration [redacted] to cover the incremental cost of the accelerated zero carbon transition programme through to 2040.

Grants from Energy Efficiency and Conservation Authority (EECA) or the Climate Emergency Response Fund – EECA has a Low Emissions Transport Fund – up to $25m a year in funding is available to support the demonstration and adoption of low emission transport technology, innovation and infrastructure to accelerate the decarbonisation of the New Zealand transport sector. The CERF has $20 million of funding for Decarbonising Freight Transport - Resourcing and Seed Funding. This initiative provides funding for activities that support decarbonising the freight and supply chain sector. This includes funding for business cases and research programmes, capability and capacity, and contestable funding for low emission freight solutions. Certain components of the proposed transition programme, such as the pilot study and adoption or testing new motive power technology and charging/energy storage systems, may be eligible for contestable funding. As part of the detailed business case we will gauge agencies appetite to invest.

Third party investment – There are opportunities for upfront Electricity and Hydrogen infrastructure to funded by third parties and recovered from KiwiRail through a tariff arrangement providing a better cash flow match between transition costs and ongoing expenditure savings. This would reduce the amount, if any, sought through a Crown budget bid. We will explore these options, including the implicit finance charges and margins, in further detail as part of the detailed business case.

Overall, Above Rail affordability is mainly a timing consideration. A slower adoption/transition gives time for KiwiRail's cash reserve and debt capacity to increase to a level that would allow the Above Rail components of the programme to be funded by KiwiRail. This needs to be balanced against an accelerated transition, which requires additional funding support, but achieves KiwiRail's emission targets, enhances and sustains rail's emissions competitive advantage over road, lowers supply chain costs per NTK and contributes materially to lowering NZ greenhouse gas emissions. This will be explored further as part of the detailed business case.

12. Management Case

Are the necessary arrangements in place for successful delivery?

The purpose of the management case is to describe the arrangements that will be put in place for to ensure successful delivery of the project and to manage project risk.

12.1. Governance

KiwiRail has typical large organisation corporate governance arrangements, with activities authorised and implemented by management levels having the necessary delegated financial authority for the size of that decision or transaction.

Upward reporting and downward supervision is in place at progressively higher levels of management. Programme Governance Boards (PGB) are the forum for supervision below the full Executive team. They include Executive representation. All this activity is overseen by the company Board of Directors, including Board Subcommittees, reporting in turn to its main shareholding Minister.

The Statement of Corporate Intent also sets targets, overseen and evaluated by the KiwiRail Board and Executive, and the Treasury Commercial Operations team and Commercial Performance Unit

The proposed investment programme is an integral part of the KiwiRail capital programme, which comprises a portfolio of projects for the delivery of a resilient, reliable and safe rail network.

KiwiRail has put in place specific governance arrangements for these mostly government funded investments to satisfy the funding organisations. This is now primarily Waka Kotahi, funding via the RNIP programme, but also includes arrangements for earlier Crown funding initiatives that are still in the delivery phase. This includes the NZ Upgrade Programme. RNIP funding currently includes "below rail" (infrastructure) and separate Crown equity SOE funding for "above rail" (rolling stock) investment.

The RNIP and SOE governance arrangements would continue in place for any RNIP infrastructure, or rolling stock, investments to support the recommended decarbonisation pathway.

In summary, KiwiRail has comprehensive and appropriate processes in place for the governance of public funding. These include reporting and the involvement of representatives of funding organisations. Business as usual RNIP processes or acceptable adaptations would be proposed to cover below rail decarbonisation investment.

12.2. Programme and Project management strategy and framework

The initiative will be delivered through KiwiRail's CPAD group. The CPAD group is set up to deliver infrastructure and rolling stock upgrade investment programmes of this type, across NZ's rail network.

The CPAD manual sets out comprehensive formal processes for the structuring, monitoring and general management of major capital procurement and delivery. These processes align with typical practice for other government agencies or large corporate entities.

For current major rolling stock programmes, a dedicated Programme Director for Rolling Stock Procurement has a group of Project Managers and Procurement Managers engaged for the procurement of each asset class. Each Project Manager has end-to-end accountability for the project and each Procurement Manager is responsible for tendering. The Programme Director reports to the Chief Operating Officer, CPAD. This model would likely be applied to the procurement phase of the new locomotive programmes.

12.3. Programme Level Governance (current)

This study phase project is being overseen under the Rolling Stock Programme Governance Board. The project sponsor is the KiwiRail Chief Operating Officer – CPAD, who chairs this PGB.

Its current portfolio includes a shunt locomotive procurement, the DM mainline locomotive (now in design and delivery phase), the early stages of procuring a replacement for KiwiRail's medium weight diesel locomotives, the EF locomotive life extension and a number of wagon procurements.

This Rolling Stock Board includes representatives of CPAD and the Rolling Stock Asset Services team.

The current Mechanical Facilities[110] programme has a dedicated PGB and others cover a variety of infrastructure programmes. The KiwiRail Chief Operating Officer – CPAD, also chairs this PGB, ensuring coordination.

It is proposed that the recommended follow-on investigations and planning during FY24 would continue to be under the aegis of the Rolling Stock Programme Governance Board

12.4. Programme Level Governance (follow on phases)

This is a strategic programme recommended to be made up of three large sub programmes, each of which in turn is made up of multiple projects. While the programmes and projects within it are covered, the overall control of this programme or programmes over 25 years sits well above the coverage of the CPAD Manual.

Due to the wide scope; rolling stock, infrastructure, facilities and operations, the scale of investment, the timeframe and the transformational significance of the decarbonisation endeavour, it is proposed that an early action of the next stage of work be a review of the governance arrangements. It may be necessary to formulate a customised PGB to provide the necessary coverage and authority.

The current KiwiRail ferry and terminal replacement project (IREX) provides an example of a where customised governance regime has been implemented in a project of high strategic impact and complexity.

This solution is likely to include members covering infrastructure, rolling stock, maintenance, finance, sustainability, commercial and operations. The transformational nature of the proposals and the need for those impacted to embrace the change makes this as much an operational and commercial programme as a technical one.

KiwiRail has an interest based problem solving initiative (High Performance High Engagement or HPHE). This can be combined with modern Programme Management approaches to ensure that business as usual operations are engaged throughout and "own" the changed way of doing business as the project is delivered.

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[110] Refurbishment and upgrading of rolling stock depot and workshop facilities.

Finally, with a structure of thirteen major projects deliver in sequence required to deliver the decarbonisation programme (Refer **12.5**), it comprises a “system of systems”. The application of modern Systems Engineering to the programme is recommended.

KiwiRail has gained some early experience with Systems Engineering in its IREX and Train Control System projects and is adopting the approach in full for the Wellington Resignalling and ETCS project. It is recommended that the capability built here is applied to ensure the decarbonisation effort is properly coordinated and delivers against its objectives.

12.5. Programme Structure

The recommendations require that 12 material initiatives be successfully advanced in parallel and in the correct sequence over a period of 15 years or more:

1 DM loco procurement and entry into service (existing project).
2 DFT loco life extension (redirect existing project).
3 Te Rapa – Pukekohe OLE design, build and commission.
4 Hamilton – Tauranga OLE design, build and commission.
5 EF loco successful life extension (all 15 units) (complete existing project).
6 New Generation electric locomotive procurement and entry into service.
7 Battery shunt loco micro-pilot (adapt existing project).
8 Battery locomotive pilot and then fleet deployment.
9 Charging and power supply issues and development.
10 Facilities adaptation.
11 16 tonne axle load route upgrade to 18 tonnes[111] (focus existing initiative).
12 People and operations.

Other actions such as continuing to advance the backup option of biofuel are additional lines of activity. The implementation of distributed power and electric braking as an essential adjunct to full future battery locomotive operation could itself be a major activity. **The significant shifts required to implement the growth scenarios A, B1 and D are also excluded from this list**.

It is tentatively proposed that the above be grouped into three staged and parallel programmes, each under the direction of a Programme Director:

1-3. Diesel rolling stock engineering and procurement. Continued and expanded diesel locomotive modernisation programme. Expanded DM procurement and DFT life extension.

4-7. Conventional electrification programme. Power supplies, overhead line and signalling for the two new routes, expanded EF life extension, new generation electric locomotive procurement and revised maintenance facilities and organisation. Business case, justification, design and then delivery.

8-12. Battery electric locomotive programme. Shunt loco micro-pilot, full scale mainline pilot, business case and justification leading to procurement and deployment, including facilities and some of the organisational transformation. Possible new generation high efficiency trains and braking. Strong elements of technical development and organisational transformation.

These would then be coordinated by the overall governance board, which would also take responsibility for 13, the people and operations transformation.

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[111] May not encompass all routes. Some other motive power solution will be required for these very low use routes

The significance of the human and organisational change required to implement this transformation cannot be overemphasised.

12.6. Capability

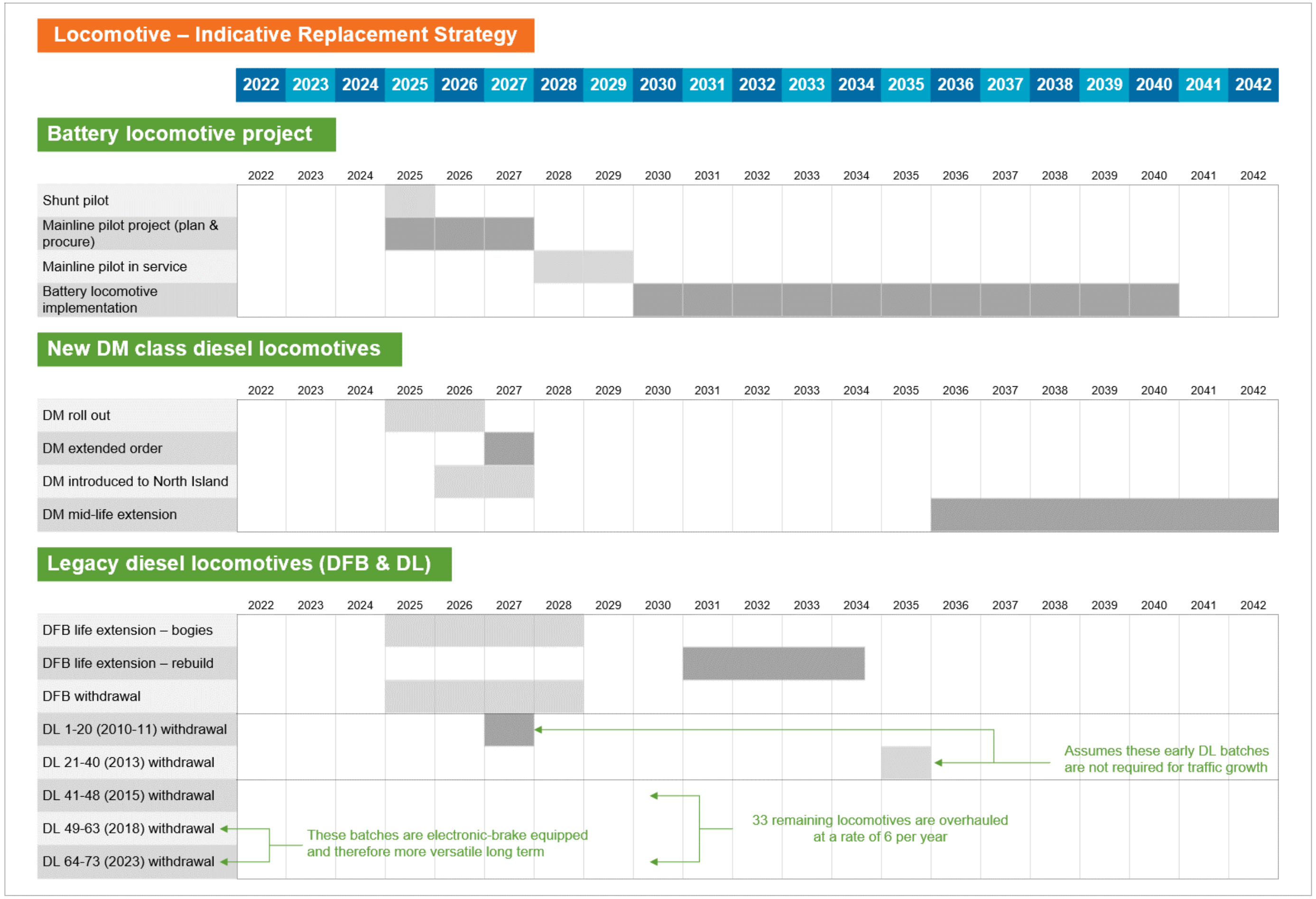
KiwiRail employs or contracts specialists in the areas of:

- Rolling stock engineering and procurement
- Mechanical Service Facilities
- Rail infrastructure, including OLE electrification
- Sustainability
- Operations

and these experts would be used to advance the streams of work that make up the decarbonisation programme.

Figure 48: Modern diesel locomotive, Class DM on order Modern diesel locomotives, like the DM on order, can significantly assist with decarbonisation through superior fuel efficiency during the period of transition to ZGHG.

12.7. Outline Project Plan (Indicative)



Assumes these early DL batches are not required for traffic growth

33 remaining locomotives are overhauled at a rate of 6 per year

These batches are electronic-brake equipped and therefore more versatile long term

Figure 49: Indicative Project Plan (Excluding “Golden Triangle”)

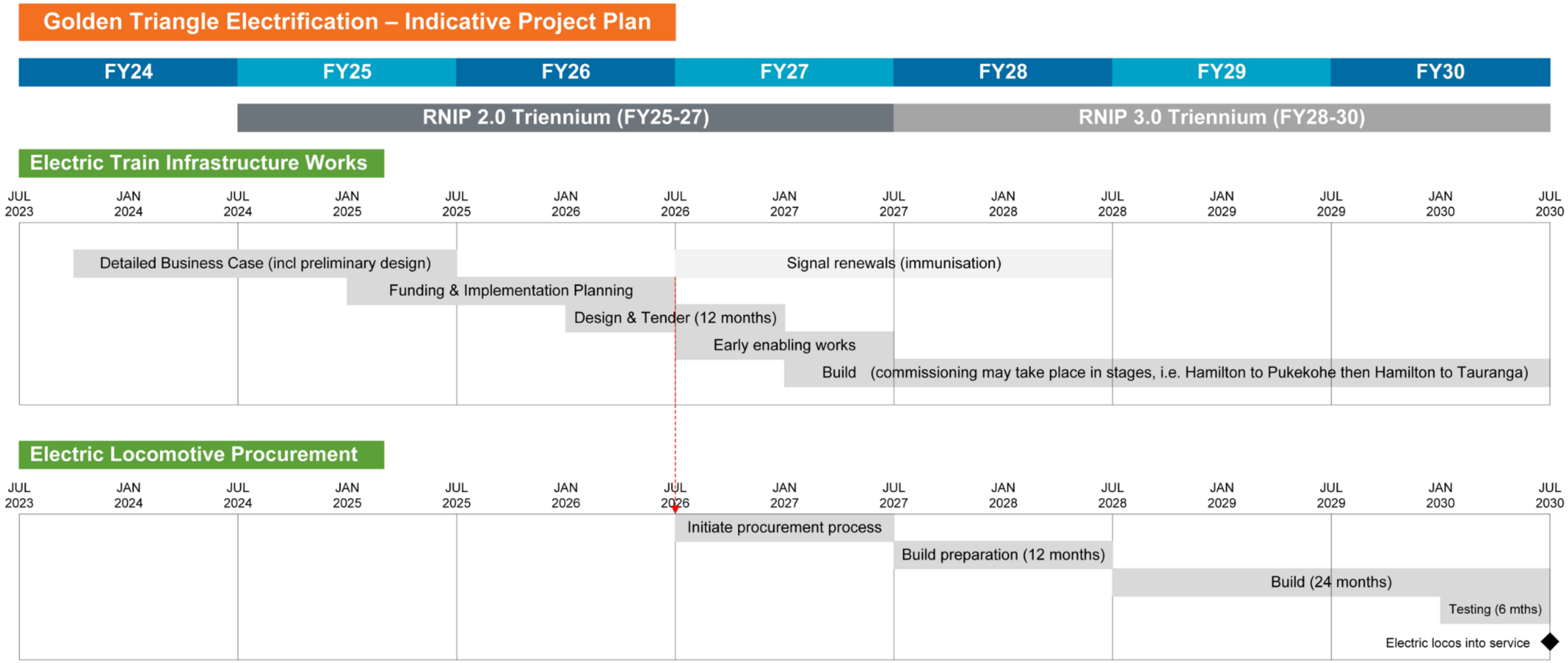


Figure 50: Indicative “Golden Triangle” OLE Project Plan

12.8. Partnerships

No formal partnerships are proposed for the recommended next phase of work, beyond the continuation of collaboration with Air New Zealand.

The next stage of work should investigate the possibility of and need for a collaboration with the key elements of the electricity industry, with the objective of finding a way to address the supply/transmission/lines challenge. This includes Government (regulatory) agencies and policy settings[112].

12.9. Benefits realisation management

The key benefits and tracking are explained in **Table 51**.

Key Benefits	Quantum and Timing	Team tracking and monitoring
Reduce rail freight emissions	KiwiRail freight achieves net zero carbon by early 2040s through change to electric locomotives and decarbonisation of grid electricity	Sustainability Team reporting to KiwiRail Executive
Increase rail's share of the total freight task and associated social benefits	Potential carbon price changes over the next 30 years impact heavy long-haul trucks significantly more than rail, creating an opportunity to increase rail's share of the freight task from 12.5% at FY21 to 17% by 2035. The key social benefits include: • Environmental sustainability - 70% fewer carbon emissions per tonne by rail than by road. • Healthy and safe people – rail eliminates at least 277 safety incidents a year compared with road • Economic prosperity – saves on road maintenance spend, reduces road congestion, and provides critical links from regions to ports for exports. [113]	Markets and Pricing Team reporting to KiwiRail Executive and Sustainability team
Reduce overall supply chain emissions	NZ's electricity generation is expected to be lower emission than continuing to use diesel. NZ imports diesel, and a significant amount of energy is used in the exploration, production, refining and shipping of diesel.[114]	Sustainability Team reporting to KiwiRail Executive

Table 51: Benefits Tracking

Accountability for benefits management and assessment will be at PGB level. The benefits realisation assessment will then allow lessons learnt and mitigation plans to be developed by KiwiRail. Key Performance Indicators will be developed during the detail phase.

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[112] The issues are covered in the Boston Consulting report "The Future is Electric": https://www.bcg.com/publications/2022/climate-change-in-new-zealand

[113] Value of Rail Report prepared by Ernst and Young, 2021

[114] New Zealand fuel and electricity total primary energy and life cycle greenhouse gas emission factors 2019 prepared by Andrew Barber and Henry Stenning, September 2019

12.10. Change management

The technical, operational, organisational and people change from this investment is profound. This is reflected in the narrative above and all governance arrangements take this into account.

KiwiRail is committed to utilising the principles of HPHE to involve the workforce and union representatives in appropriate phases of the procurement process, including defining asset requirements and evaluating tender submissions. This approach will help ensure the buy-in of critical stakeholders, enabling assets to be introduced to service smoothly and investment benefits realised quickly.

12.11. Risk Management

Risks, opportunities and issues will be implemented, tracked, updated at regular intervals and assessed monthly by the Programme Directors and their Project Managers as part of their responsibilities as set out in the CPAD Manual. KiwiRail maintains a dedicated system for recording and manging risks – ARM.

Key project risks are outlined in **Table 52** below.

12.12. Risks

Risk	Impact	Proposed mitigation
Parallel demands for significantly increased passenger services consume network capacity.	Existing freight service levels unable to increase or even have to be reduced. Increased rail freight scenarios impossible. Reported GHG improvements not achieved.	Retain clear visibility of risk. Investment in improved network capacity has to go hand in hand with introduction of new or increased passenger services.
Battery technology may not evolve as quickly as anticipated, with less than expected range. Higher cost. General uncertainty around proposed solution.	Increased cost and or reduced performance. Reduced availability of suitable battery locos. Increased number of enroute charging points required.	Continue to explore and investigate during detail phase and pilot schemes to gain greater certainty. "Buy time" by advancing modern diesel and OLE options in parallel.
Performance levels of locomotives in initial stages may adversely impact OTP.	Reduced service standards and increased costs.	As above.
Generation, transmission and lines system may not be adequate for distributed charging network.	Increased cost or impact on overall feasibility.	As above. Electricity industry and their regulatory bodies identified as key stakeholders to be engaged, brought along with KR plans, and supported in their reform efforts.

Risk	Impact	Proposed mitigation
Organisation and people do not adapt and embrace the change required for success.	Battery locomotive "system" is not operated as required and the solution fails.	The staged incremental introduction above provides more time. The need for this human change identified as a critical element of programme. Application of proven HPHE approach. Programme accepted as essential and high priority and driven from KiwiRail Board.
KiwiRail organisation not organised and equipped to deliver a transformational programme of this size, duration, complexity and importance.	Programme fails, costs rise, benefits erode and railway fails to contribute to NZ economy or decarbonisation efforts to full potential.	Report recommends a strategic level examination of organisational fitness for this challenge with the view of organising and resourcing so success is likely.
Facilities do not suit	New generation locomotives suffer low availability and reliability.	Battery locomotives recognised as being a system. This system includes appropriate new facilities (and trained people) and these are identified as a critical element of programme. The staged incremental introduction above provides more time for identification of needs and delivery.
Normal major programme risks.	Track access, availability of resources, land acquisition, management of multiple stakeholders, consents and so on.	Managed by KiwiRail major programme processes.
Integration of decarbonisation into an overall transformational programme	Full benefits not achieved	Develop integration plan and operate the three recommended streams as a coordinated effort strongly focussed on achieving the overall objectives.

Table 52: Major Risks, Impacts and Mitigation

12.13. Project and business assurance arrangements

The project management will follow KiwiRail's stage-gated delivery process, as documented in the CPAD Programme Manual. This project is currently in the Pre-Project Stage of the project lifecycle.

This includes comprehensive processes for assurance of all key project indicators.

Identified project benefits will be monitored as the project progresses through detailed design, construction and operation, with the PGB accountable for benefits management and assessment.

A set of Key Performance Indicators to assess options against the Investment Objectives and to determine the level of "benefit" that could be derived will be developed as part of the DBC.

13. Analysis

This section brings together the foregoing work, provides some analysis and then draws conclusions.

13.1. Overview of study

The purpose of this study is to identify the preferred option for decarbonising the KiwiRail mainline locomotive fleet by 2050.

This is an indicative study. While a preferred and practical route for decarbonisation has been identified, it requires detailed analysis of the recommended path, ahead of being adopted. Feedback from stakeholders also needs to be gauged before confirming the route to decarbonisation. The areas requiring further work are identified in this analysis and discussion section.

The general format of a Better Business Case[115] "Indicative Business Case" was adopted to ensure the approach was rigorous and was in a format that would be familiar to decision makers. The output is a recommended path and the proposed next step is detailed confirmation of some of the elements within this as well as early moves on design and procurement for others.

The modelling depends on assumptions, projections and simplifications and as such cannot be relied on to be absolutely correct. But as an initial study, the main objective was to sort or screen the options to identify those worthy of detailed study, with a view to adoption. As such, ranking the relative performance of the options was of primary importance. A lack of complete precision or certainty in some of the inputs is less critical when seeking to rank relatively.

However, the study team has confidence that the absolute costs and benefits are also reasonably representative and provide sufficient direction for decision making.

In answering the question above, this study looked at the problem in three ways:

- A quantified or "dry" assessment of the costs and financial benefits of each option with an economic model.
- An assessment of the feasibility and risks of the options using experience and expert advice.
- Consideration of the practicalities of fleet renewal and opportunities to avoid sunk investment

This section discusses the outputs of these three approaches and then combines them in a recommended mainline locomotive decarbonisation approach.

13.2. Future Rail Traffic

Rail freight traffic could increase substantially in the future, mostly in the northern North Island, and KiwiRail needs to be prepared for it.

As set out in **Table 10** and **Table 30**, seven traffic scenarios, including BAU (base year) were developed for this analysis. From these, four were selected for modelling: Business as usual/do minimum ("BAU"); Scenario A, Scenario B1 and Scenario D.

- BAU is the current "resilient and reliable" investment programme.
- Scenario A assumes that rail has the extra equipment required to carry the available future demand.

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[115] Better Business Cases™: Overview of the five-case model (treasury.govt.nz)

- B1 adds on top of Scenario A, all Ports of Auckland growth beyond current levels, which in the model is assumed to be transferred to Tauranga.
- Scenario D models the impact of strong policy moves to increase rail traffic, through an enhanced carbon price.

Most detailed results in this report are presented for BAU, to avoid complexity. BAU alone will see a 32% rise in traffic relative to the 2020/21 base. However, Scenario B1 is a very likely scenario, given moves to share Ports of Auckland growth with adjacent ports. Full closure is still a possibility (which was another scenario, Scenario B), so just keeping volumes static seems conservative.

In Scenario B1 volumes are estimated to grow by 65% by 2035. Most of this will take place on the Auckland-Hamilton-Tauranga corridor, which will be placed under serious pressure without investment in upgrading it, including electrification.

13.3. Mineral (fossil) diesel is favoured under current conditions

The following summary output of the economic model shows that under current policy settings (and model inputs and assumptions), early action to reduce and eliminate GHG is not strongly favoured, on strictly commercial grounds.

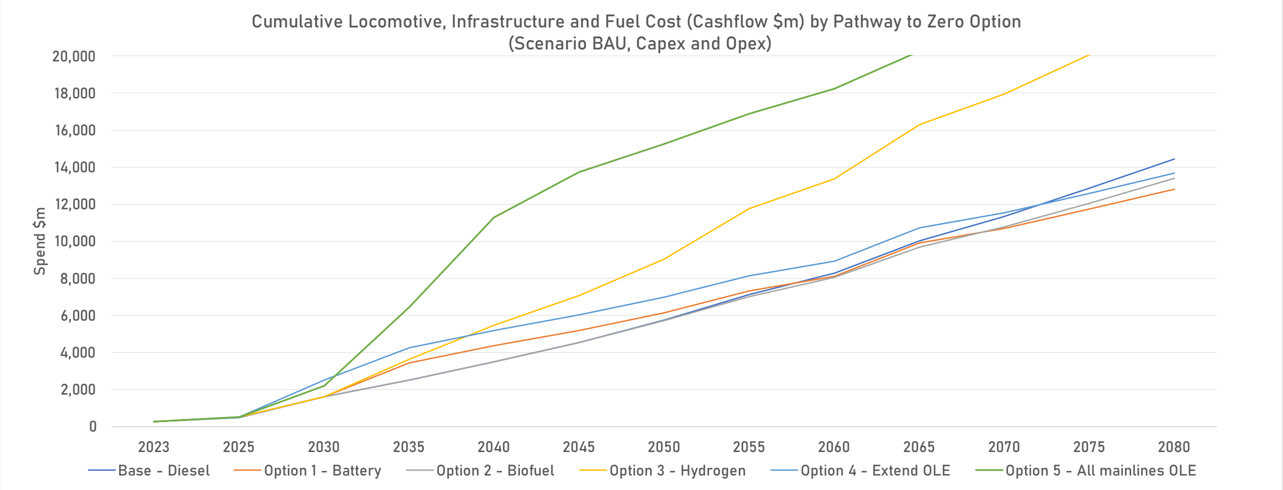

Figure 51: 60 year cumulative locomotive, infrastructure and fuel costs by option under BAU Scenario

The uncertainty, development risks, surrounding the innovative options favour diesel even when they offer a small economic advantage over it from around 2050.

Ignoring the “risk” that policy levers will shift, mineral diesel remains the favoured option until at least 2050, in this economic model and analysis.

However, a recommendation to remain with the status quo of mineral diesel does not lead to the overarching objective of reducing and eliminating net greenhouse gas emissions by 2050, with significant reduction milestones along the way (e.g. KiwiRail’s current near-term carbon reduction target is a 30% reduction of emissions by 2030). Nor does it allow this study to explore and report the implications of changing to other energy sources.

Therefore this report assumes that policy and economic conditions will change so that mineral diesel does not remain favoured.

13.4. Discussion of other outputs from economic model

The economic model:

- Shows how mineral diesel is the commercially favoured option until 2050, but only just.
- Eliminates electrification of the complete network and hydrogen from serious consideration.
- Places battery as the preferred economic option (with benefits of near zero GHG, NOx and PM emissions exceeding the incremental financial cost over diesel and biofuel).
- Has busiest route electrification and battery-electric as the second most favoured option until late in the 21st century, where it becomes most favoured.
- Has biofuel as the third most favoured option.

But the economic model does not provide a complete basis for decision making:

- As above, the relative cost of fossil diesel is not congruent with current GHG reduction targets. If the objective is to encourage shift to low or zero greenhouse gas fuel, the relative cost of diesel will have to rise over that assumed.
- Official cost curves are used for biofuel (and other energy). These do not take into account the likely challenges in supplies of acceptable biofuel in volume over the period of the study.
- The conclusion of the study is that it will be very difficult to establish sufficient local or imported supplies of 2nd generation or better biofuel. The land use is significant, the technology is still developing, EROI is very poor and there are users without other options who will require what supplies are available. This does not appear to be reflected in current official cost curves. In the absence of 3rd or 4th generation supplies, which are many decades away, biofuel is likely to be a specialty energy supply only, for users lacking other options.
- Rail is a user that does have other options.
- Biofuel does not change any other aspect of railway operation. The economic model is not able to fully account for some of the advantages of the transformational change that electrification will bring. These include reduced or zero local emissions, reduced maintenance, reduced use of lubricating oil and the ability to minimise or avoid turn around servicing.

There are some significant risks around the battery-electric solution not reflected in its cost curve. It assumes:

- a good rate of progress in battery performance increase and price reduction.
- that generation, grid and lines capacity will be available to support MW range charging at a range of locations throughout urban and provincial New Zealand.
- That locomotive suppliers will make battery locomotives suitable for a selected duty on the New Zealand network available by 2028 (pilot) and high performance battery locos able to match the assumptions of this study from the early 2030s (full scale implementation)

Finally, while its high capital costs are front and centre, the relatively low technical risk of overhead line electrification is not really rated. Decarbonising a route by OLE uses well proven commercially available technology which KiwiRail has long experience with. The relative ranking of the battery - OLE mixed option would be improved if this risk was able to be sensibly quantified.

13.5. Biofuel

Biofuel will be distributed through the national liquid fuels supply chain.

KiwiRail uses a very small proportion of the national liquid fuel volume in its locomotives[116]. KiwiRail will continue to take its diesel locally from the bulk supplies and supply chains intended mainly for all other users.

In the event KiwiRail, with other users, supports the establishment of a 2nd generation or later biofuel industry, the resulting volumes are unlikely to warrant independent distribution throughout the KiwiRail network. The resulting product will be mixed with mineral diesel in the national distribution chain. The blends must also be of consistent characteristics, as locomotives, and all conventional diesel prime movers, have only limited ability to cope with fuel that varies between locations and period of uplift. This further supports biofuel being mixed with the main mineral diesel flow early in the local supply chain.

Regardless of a conscious KiwiRail decision regarding biofuel, it will be used in remaining diesel locomotives if, decided by others, it forms part of the national bulk diesel supply, either pure or more likely a blend. The implications of this for rail are remaining alert to this happening and ensuring that remaining diesel locomotives are modified to use whatever product type and blend percentage results. Suitable blends of up to 20% can be handled by existing locomotives, suitably adapted with plenty of notice and with increased maintenance.

For 2nd generation biofuel KiwiRail has identified potential concerns regarding; the limited and delayed supply (well into 2030's), the adverse effects of securing supply, the practicalities of nationwide distribution, the continued emissions of GHG from using biofuels, albeit not net emissions, and the missed opportunity to improve local emissions, maintenance and operations. The likely effect is to make battery/electric operation as good or better than biofuel in real as opposed to modelled conditions.

But biofuel remains, at the least, a backup to battery/electric and a potential way to reduce the through life net emissions of the diesel locomotives remaining in service till 2040. It should be taken to the next stage of study, to ensure options are not prematurely closed off.

13.6. Hydrogen

Hydrogen is an energy carrier between electricity generation and electricity use that is suited to niche applications that other options are not viable for. If electricity can be used directly without hydrogen as an intermediate carrier then this is generally favoured on financial, energy efficiency, emissions and complexity grounds.

Duty cycles on the KiwiRail network appear to lie well within the lengths and loads amenable to battery electric. Some routes also appear suitable for direct use of electricity through overhead lines. Assuming the assumptions and approximations underlying these assessments are sound, hydrogen is not required to decarbonise the bulk of the New Zealand rail network.

This aligns with the Aurizon conclusion that routes below 800km in length and not warranting OLE are best suited to battery electric. They identify a role for hydrogen on longer routes but through a

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[116] Oil statistics | Ministry of Business, Innovation & Employment (mbie.govt.nz). KiwiRail locomotives use approximately 1.2% of New Zealand's annual diesel consumption and 0.6% of total liquid fuel consumption.

range extending tender paired with standard battery locomotives. The tender generates electricity to charge the battery locomotive, using hydrogen fuel cells.

While the Hiringa proposal for the supply of hydrogen is plausible, the hydrogen fuel cell locomotive concept is less convincing, being complex, currently existing only in prototype form and assessed as unlikely to be satisfactory this decade or more.

There are routes requiring significant energy where battery charging is likely to be expensive to provide. Assuming that the most economical solution is not simply assigning an additional standard battery locomotive to provide sufficient consist battery capacity, hydrogen may have a niche role in these routes. This would likely be a range-extending tender, as envisaged by Aurizon.

However, most busy non OLE routes are proposed to be operated by the new generation DM diesel locomotives for at least the next ten years, possibly until 2040. Alternatively, DM locos can be concentrated on the routes “resisting” early conversion to battery. This allows any decision on alternative operation to be deferred, allowing time for battery performance, local lines capacity, hydrogen fuel cells and the hydrogen supply chain to have evolved significantly, allowing for a more informed decision.

The long timeframes for hydrogen development, the availability of positive alternatives and the distant window for a final decision mean it can be set aside and reopened only if there are significant developments positive for hydrogen, and/or major challenges with the recommended solutions.

13.7. Hybrid locomotives

Hybrid locomotives, locomotives incorporating diesel and battery operation in one body or unit, were eliminated from consideration during the feasibility stage and were not considered in the economic model. It was concluded that such hybrid locomotives, requiring significant new development for what was only a transitional contribution, were a distraction to the main goal.

Hybrid consist operation, standard diesel locomotives and standard battery locomotives running together in multiple, does however offer a very useful way to begin battery operation and gain benefits in the period before batteries reach full performance and a complete charging network is in place. On board management systems, under development by locomotive suppliers, would optimise battery use and energy recovery, using the diesel locomotive only to the extent needed to complete the duty.

13.8. Locomotive fleet strategy

13.8.1. Overview

Ideally the decarbonisation project actions would be efficiently merged with KiwiRail's existing locomotive fleet asset management plans.

The KiwiRail loco fleet has units ranging from on order, just been life extended through to imminent retirement.

A locomotive's useful life can be extended by periodic refurbishment and upgrade, typically on a 10 - 15 year cycle. This can amount to a complete rebuilding above the underframe, and its cost can approach the cost of a new locomotive. The mid-life overhaul date is therefore a natural point to consider replacing locomotives.

To avoid waste, a renewal programme is ideally timed to replace locomotives as they come due for life extension or retirement. This is unless the benefits of early replacement is demonstrated to exceed the costs of discarding the older locomotive.

Locomotive class	Number of locomotives	Main operating area	Midlife overhaul (preferred date)	Retirement
DX	47	South Island (SI)	N/A	2027
DF (Medium duty)	27	North Island (NI) and SI	N/A	Last 12 2040
DL G1	20	NI	N/A	2028
DL G2	20	NI	2024-27*	2035
DL G2.2	8	NI	2033-34	2054
DL G2.3 – 2.3ii	25	NI	2034-38	2054
EF	15	NIMT Te Rapa to Palmerston North	N/A	2042
DM	66	47 Units - SI from 2025 19 units - NI from 2027	2036-40 2041-42	2061-63

Table 53: Midlife Overhaul and Retirement Dates for each Rolling Stock Type

*DL G2 (21-40) older platform not considered economic / suitable for motive power swap, will operate to retirement using diesel motive power. Note: this table excludes the remnants of the DC class because of their imminent retirement. DL G2.3 includes 10 locomotives recently (April 2023) delivered.

13.8.2. Key Decisions

Recent key decisions around KiwiRail's locomotive fleet are summarised below, and are consistent with the longer term decarbonisation strategy:

Decisions made are:

- To retire 20 DL G1 locomotives in 2028
- To retire 15 DF locomotives between 2025-2031
- To acquire 66 new Stadler DM locomotives, with lower fuel consumption and emissions, to:
  - replace all legacy diesel locomotives in the South Island (47 units)

    - replace some legacy locomotives in North Island (19 units)
- To life extend 20 DL G2 locomotives (diesel motive power), retirement deferred to 2035
- To life extend 12 DF "medium duty" locomotives (diesel motive power), retirement deferred to 2054
- To seek proposals for a new generation replacement heavy shunt locomotive

The following sections provide a brief summary analysis class by class.

13.8.3. Stadler DM locomotives

The decision has been made to acquire 66 new Stadler DM class diesel locomotives to replace all South Island and legacy diesel locomotives and some North Island diesel locomotives. These locomotives are in the manufacturing and prototype testing stage. This replacement of legacy locomotives on its own delivers a useful reduction in GHG emissions. Combined with a series of network wide operational management improvements, it delivers a good further step along the decarbonisation journey, using available conventional technology and techniques. The model assumes the DM fleet operates as diesel locomotives until late 2030's/early 2040's.

The model also assumes that battery performance and price has advanced sufficiently to allow the DM class to be converted to (or replaced by if lower total cost) battery-electric locomotives of the X-66 type when they fall due for life extension then.

13.8.4. Heavy Shunt Locomotives

While not a mainline duty, the other current project that is relevant is an active procurement to replace operational or heavy shunt locomotives, of the DSC/DSG/DSJ/DH classes.

Options for reduced or decarbonised operation are being sought.

Due to the less demanding duty cycle, this procurement offers an opportunity to gain experience in the operation, charging and maintenance of battery electric locomotives on a local (pilot) scale[117]. The required battery capacity and charging demands all lie within the reach of current practice and the local allocation of such types means the innovation can be confined to one yard and depot. This will require a significant change in direction for this procurement.

13.8.5. DL locomotives

The first generation DL locomotives have only limited potential and an option that allows them to be economically retired rather than expensively life extended from the late 2020's would be attractive.

Later DL locomotives are of improved performance but the same argument applies to a lesser extent. An option that allows them to be economically retired rather than life extended will be of interest. Likely only the 25 Gen 2.3 electronic brake equipped units warrant life extension, if a role exists for them. The 8 Gen 2 units have more in common with Gen 1.

Finally, the obsolescent DL platform offers little for a battery electric conversion. Very little would be reused. A sound policy is to remove these locomotives from service as they fall due for heavy work.

The exception is if policy and mode shifts considerably increase rail market share from the mid-late 2020's under Scenarios A, B1 and D. The best withdrawn legacy diesel locomotives will always need

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[117] A sub-fleet only large enough to convert a small shunting operation to battery – like Wellington.

to be retained longer to cover this increased demand, pending the arrival of zero carbon replacements. Even legacy diesel locomotives considerably reduce emissions relative to road.

13.8.6. DFT locomotives

The DFT is a legacy medium duty design. It is a sound design capable of being useful for many years but its legacy prime mover has relatively high emissions and fuel consumption relative to work done.

Its key uses are on light axle load lines, passenger services and miscellaneous duties. It is of peripheral importance to the majority of KiwiRail's haulage task and decarbonisation project, but of critical importance to the tasks that require a loco of its characteristics.

Of the duties requiring a DFT, most passenger services are anticipated to be replaced by self-propelled trains by the early 2030s and KiwiRail's asset management plan should see all remaining 16 tonne axle load main lines[118] upgraded to 18 tonnes or beyond by the mid 2030's.

There is an opportunity to delay the replacement of the DFT for another life cycle by life extending it and apply the freed up resources more effectively. In particular, any new generation locomotives are best employed on main routes where energy required is high and absolute savings in fuel use are maximised.

Conversely, light axle load routes and secondary duties are where the least energy is required and where legacy locomotives waste the least fuel and create the least emissions.

Whether the DFT life extension is best accomplished by means of refurbishing the existing power train (minimal improvement in fuel efficiency emissions) or a new generation power package delivered "turn key" by one of the OEMs is best determined by a dedicated project and analysis.

The life extension of the DFT avoids a significant new locomotive investment to cover what is a low energy use transitional duty which is not a route to zero carbon emissions.

NOTE: KiwiRail subsequently decided in mid/late 2023 that it would life extend 12 DF locomotives to continue operating through to 2054. The other 15 DF locomotives would be progressively retired as operational demand permits.

13.8.7. Electric locomotives

The surviving EF conventional OLE locomotives are being refurbished to enable reliable operation of the existing Palmerston North - Hamilton freight electrification. While the first refurbishments remain under development, KiwiRail is confident the resulting locomotive will deliver at least ten years' good service.

With all 15 locomotives life extended[119] this would be sufficient to displace many or all DL locomotives from the Auckland – Hamilton section, if the 83km gap in wiring was closed.

A new generation electric locomotive is required to provide a fleet large enough to service a Hamilton – Tauranga/Mount Maunganui electrification and (via a follow on order) to replace life expiring EF's in 2035. Work needs to be done to determine if additional electric locomotives would be required to eliminate diesel haulage Auckland – Hamilton[120].

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[118] The short Invercargill to Bluff and Napier to Wairoa lines are the only lines anticipated to remain light axle load and special arrangements can be made for their working.

[119] At the time of writing steps were being taken to extend the refurbishment to all 15 units.

[120] Excluding Mission Bush branch services. Early purchase of NG electric locos will also allow yard electrifications to be avoided.

13.9. Introduction of mainline battery locomotives

The introduction of battery electric locomotives to displace all remaining diesel locomotives represents a transformation not much less significant than the change from steam to diesel.

- Maintenance facilities will change and engineering teams will need to adapt. While a significant change, existing locomotives are electric drive, meaning less of a step here than was necessary in the steam to diesel transition. Maintenance requirements will reduce, further easing the adaptation.
- Lineside chargers, high capacity electrical installations equivalent to traction substations, will spread over the entire network and require a specialist electrician workforce for support.
- Servicing will change completely and likely move the point of “refuelling” into the operational yards and terminals.
- Time will have to be allowed in turnarounds and journeys for charging.
- Sophisticated planning will be necessary to ensure locomotives are not overcharged or undercharged for their next duty. Overcharging will prevent energy recovery early in the journey, waste time and unnecessarily degrades batteries. Undercharging results in delays later in the journey or a train running out of power enroute.
- With the low energy density of batteries and the high cost of all sustainable alternatives compared to diesel, energy efficiency is going to become very important. This will drive large steps in further reducing train tare mass, avoiding wasted haulage and developing more efficient (electric) wagon braking systems.
- Similarly, energy recovery through dynamic braking is an essential component of success. This will drive trains with distributed power (X-64 loco pairs spaced apart), to overcome the limits to regenerative braking with all locomotives placed at the head of the train.
- Trains will have to be handled very carefully enroute following a precisely calculated strategy designed to maximise energy recovery and avoid energy waste. While OEMs are developing on board software to advise and automate this and KiwiRail has experience with Driver Advisory Systems, strict adherence to this planned strategy will make the difference between reaching a destination or running out of battery power in some cases. “Advice” is replaced by mission critical.
- The combination of these can be imagined as a future where trains are made up of short semi-permanently coupled rakes of standardised light weight electrically braked container or bulk wagons, not designed for the high longitudinal loads of today, matched to a single medium sized locomotive driven automatically for most of a journey. Longer trains might be made up of multiples of 2-3 such units.

Overall the picture is one of eventual transformation for facilities and designs, an even more planned and consistent operation and, even more significantly, widespread change for KiwiRail’s organisations and people.

All this is combined with the uncertainty around the:

- development of batteries of sufficient performance in the timeframes envisaged
- the availability of suitable locomotives in quantity
- the supply to and economics of charging stations

Combining these risks with the transformational change required of organisation and people means it would be most unwise to fully commit to battery locomotives at scale, this early. Time is needed for the technology to develop, for KiwiRail to gain confidence and for the organisation to progressively learn how to adapt to the change and take advantage of it.

An in service pilot of battery electric operation is recommended, as the most effective way of introducing and exploring the change, gaining comfort with the technology and buying time for its capability to develop. It is recommended this pilot comprises three parts:

- Gain early technical, organisational and people experience by ensuring that at least one small sub fleet of the new heavy shunt locomotives are pure battery operated, using proven (near) bus scale technology, and are assigned to one location as early as possible.
- Next, introduce a pilot fleet of battery locomotives to one group of routes. Fleet sized to be able to cover most duties from this depot, after an initial proving exercise with some units delivered in advance of the main batch. By inspection, the Palmerston North Depot and Napier/New Plymouth/Wellington routes would appear to be a good prospect for a pilot application employing in the order of 10 - 12 locomotives.
- Develop and provide the charging infrastructure for the limited geographical range of the battery loco deployment. While any gap in the charging network exists, use hybrid consists to allow early productive deployment.

Note that the parallel development of a charging network is required and the challenges of this probably equal those of the locomotive due to systemic limitations in the NZ generation, transmission and distribution system. The pilot will provide the focus and drive to tackle these locally and insights into how to do this nationally.

Demonstration of a prototype will be a distraction. Only planning and preparation for a full, but limited deployment, forces the commitment and focus required for success (and is likely to interest OEMs).

As the pilot fleet will employ the battery technology available at the time of their construction[121] rather than the forecasted 2030+ batteries used in modelling, these locomotives will likely have a compromised performance compared to that assumed for the X-64 loco in this report. This is an unavoidable consequence of the essential early piloting but can be worked around. The routes and duty cycles selected for the pilot, along with charging locations and hybrid consist operation will all be matched to pilot locomotive performance.

It should also be noted that the pilot locomotive battery packs will be substituted with battery packs of contemporary (higher) performance when they reach the end of their useful life in the mid 2030’s, significantly increasing the usefulness of this fleet.

The pilot will immediately begin reducing GHG emissions and once settled, the pilot fleet will be able to displace a number of DL Gen 1 locomotives.

13.10. Conventional overhead line electrification

This has, unsurprisingly, been ruled out as a preferred solution for network wide electrification of services, due to high capital costs relative to traffic density. New generation battery locomotives are a game changer for lighter traffic railways. They allow electrification of services without the unaffordable capital cost of lineside equipment.

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[121] Note that, with battery technology under rapid development, the battery supply contract is best finalised as late as possible during the design and build of the locomotives.

However OLE electrification has a significant point in its favour. Locomotives and power supply are conventional and proven technology with the only delivery risks being those normally associated with major infrastructure construction projects. These are able to be predicted and managed, whereas there are elements of development risk with battery locomotives and charging and these are largely outside the control of KiwiRail or New Zealand.

KiwiRail also has up to 15 electric locomotives potentially available[122], sufficient for more trains than are presently electrically hauled.

The pure economic analysis shows that Option 4, battery locomotives with application of OLE to allow electric operation over the two busiest KiwiRail routes, is third ranked of the three decarbonisation options and not far from them. But if the matter of risk is considered subjectively, the gap is not material.

Battery and charging development may be delayed or may not live up to expectations and time is required to be certain. But if decarbonisation targets are to be achieved, the mainline locomotive decarbonisation project has to get under way promptly and deliver gains ahead of 2030/35. A conventional electrification will take 6 years to deliver but can be planned from now with confidence.

The Pukekohe – Te Rapa electrification is clearly a "no regrets" investment. There would be value in this section even if battery locomotives become viable faster than assumed. 83 route km of wiring[123] and a single substation[124] allow one of two of the busiest freight routes in New Zealand to be electrified and the existing electric locomotive fleet to be used to full capability. Planning work could commence with reasonable confidence that the business case would be successful. Construction could be plausibly phased to allow opening by either 2027 (mobilisation ahead of the end of the current Papakura to Pukekohe OLE project) or 2028, albeit this would be challenging.

The single track Hamilton – Tauranga electrification is a similar undertaking, fewer STK (110 km) but a longer route (104 km), and the business case is less open and shut. But planning would commence late in the planning stage of the Pukekohe – Te Rapa project, allowing time for this review to be completed. Planning should determine if Tauranga or Mount Maunganui[125] is the optimum terminal. This project can be phased to allow opening as soon as 2029.

Early dates are plausible if the combined project is fast tracked[126].

Installing OLE on the two busiest lines, using conventional electric locomotives, results in just under half of all KiwiRail traffic being electric hauled. This is proven technology with the only risks being normal project delivery ones.

In addition, there is a sequence of milestones:

- Business case milestones (above)
- Detail design
- Procurement and contract
- Construction

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[122] Not all are in service, although a refurbishment programme is under way to correct this.
[123] 83 route km and 153 STK, with all but 13km double track
[124] Exact power supply arrangements to be confirmed. The interface with the non-auto-transformer Auckland Electrification Area introduces some complexity, albeit solved by appropriate design.
[125] Most likely Te Maunga, the junction serving the 7 km branch to Mount Maunganui, or a few km beyond this. The Port area would thus be served using the "last mile" battery capability of new generation electric locomotives.
[126] The 409 route km NIMT project was delivered in 5 years from start of design and procurement.

- Commitment to new generation electric locomotives

These decision points between 2023 and the late 2020’s, allow planning work to start immediately while serious commitment can be staged. If battery locomotive solution progresses faster and better than anticipated, or other factors intervene, the project can be paused, stopped or reduced in length to suit, before the next jump in financial commitment.

In particular planning and design work should commence with the assumption that this is one combined project warranting investment in staff and equipment to ensure high productivity. There is an opportunity to reduce the cost, disruption and time for electrification over the last 15 years of metro experience.

Together these projects would decarbonise 46% of the entire Kiwirail freight task with proven technology able to be delivered to a predictable schedule.

There is also the opportunity for new passenger rail to add economic benefit to investment on these new OLE sections, particularly between Auckland and Hamilton. Note however that new trains would be required, and double track for anything but the lowest frequency service.

13.11. Battery – electric locomotive economics

The standard duty cycle used in performance modelling was a train sized to be hauled by a single DM class diesel. All alternative locomotives had to (virtually in the simulation) haul the same train on a given route, allowing direct performance and economic comparisons.

The primary driver for the battery-electric locomotive trailing biofuel in the model is the concept design decision to have the standard single diesel locomotive duty cycle met by TWO battery locomotives. Two medium power locomotives have significantly more total battery capacity on board, for the required power rating, than a single high power locomotive. Using 2030 assumed battery performance, this provided, for the purposes of the study, what was judged a workable balance between the delay and cost of lineside charging and the cost of cheaper but more locomotives.

The impact of the larger fleet size is significant in:

- Capital cost
- Unit maintenance costs
- Battery replacement costs (10 years)

but expected to be offset to some extent by reduced charging costs, fewer enroute chargers.

Like all aspects of the study, assumptions and forecasts had to be used, such as developments in battery technology, the practicality of high output charging stations, and the ability of local lines networks to deliver the required power. In the case of the more numerous medium size battery electric locomotives more detailed study may:

- Enable the 2:1 ratio to be reduced or eliminated
- Allow the slightly more capable X-64 pair to move a greater load than a single DM equivalent, further offsetting the extra costs
- Be able to be matched to significant savings in charging infrastructure cost by optimising the provision

- Determine that battery performance at the time these majority of these locos are constructed is sufficient to service a single high power unit.

It is recommended there be a focus on the validity of this 2:1 assumption in any follow on study. The performance of batteries by the early 2030's is a key variable, as is the extent and cost of the charging network.

13.12. Human and organisational factors

The transformational impacts of electrification will be felt throughout the railway, not just in motive power. Maintenance will be simpler, and facilities can be smaller and fewer. Skillsets will need to evolve or change, for example in locomotive engineers, maintenance and back-office staff. Cleaner, lighter and potentially simpler jobs will widen the pool of talent that KiwiRail can draw on.

Operations will need to be managed in a more precise and rigorous way, from active monitoring of energy use and reserves on the locomotive, careful management of battery stress to maximise life, through more precise load planning, to minimising the tare weight of wagons, and reducing unnecessary haulage of empty wagons. Just as in society at large by 2050, the railway will have to be much more conscious of wasted energy.

13.13. Other

While not investigated in depth, the opportunity for KiwiRail to produce some of its own electricity e.g. through renewable options and an electricity storage system using its own land and building roofs was identified. Most likely, this would occur with an energy industry partner.

This would help reduce the risk of increasing KiwiRail's electricity demand, and with its desire to reduce carbon emissions, could reduce operating costs and susceptibility to price fluctuation, reduce demand on the national grid, and help KiwiRail reach net zero as any remaining carbon emissions could be offset through electricity generation.

At this stage of screening, embedded carbon was not investigated in detail, although it was a criteria in the MCA analysis. The next stages of work must take account of this, not because it is expected to tip the balance in a decision, but with the intention of guiding design to reduce or optimise this. This is likely of greatest importance for the OLE projects. The lineside masts and wires embody considerable carbon[127] and there are high and low carbon options so sophisticated analysis is warranted.

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[127] Copper alloy and aluminum alloy wires, steel or concrete masts and (usually) concrete and/or steel foundations

13.14. Putting it all together (synthesis)

Subject to more detailed study, justification and funding, this recommended approach is:

1. In general, investment in solutions that are transitional (hybrid locomotives, new types of diesel locomotive) is not recommended, as these are avoidable distractions from the main goal. The exceptions are set out below.
2. Electrification is recommended as the method for decarbonising the majority of the KiwiRail mainline locomotive fleet.
3. Battery electric is recommended as the way of achieving this for the majority of routes.
4. This assumes that battery and charging technology will develop as assumed in this study.
5. There are risks around this assumption and they are out of the control of KiwiRail. It is therefore recommended that battery electric and OLE electrification on selected busy routes be progressed in parallel to buy time for confidence to be gained while guaranteeing significant decarbonisation progress by the end of this decade.
6. Therefore, begin planning immediately to fill the two key gaps of Pukekohe – Te Rapa and Hamilton – Tauranga in the North Island OLE electrified network by 2029, with the projects being staged to allow progress on the battery alternative to be assessed before committing to each next higher phase of expenditure and works.
7. While only two routes, 46% of the entire KiwiRail freight task will be decarbonised by this initiative, using proven technology able to be delivered to a planned schedule. These two routes are where most of the traffic growth will occur, so this proportion will grow towards 60%.
8. Maintain a watching brief on the progress of battery-electric and charging technology and authorise each next step in the OLE projects based on this progress. If battery technology advances rapidly this may alter the extent of OLE electrification committed.
9. Refurbish the EF fleet now and then procure new generation electric locomotives to service this expanded electrified network.
10. Battery electric must be considered a system comprising locomotives, charging and operational changes to best maximise the strengths of the solution and minimise weaknesses. Therefore, introduction must be considered as a transformation programme involving far reaching change to our organisations, operations, facilities, and people.
11. Use the current heavy shunt locomotive procurement to gain early technical and organisational experience by means of a small pilot fleet of battery electric shunt locomotives based at a selected single yard and depot.
12. Engage with the market for the supply of a pilot fleet of approximately twelve battery electric mainline locomotives (accepting reduced performance) that can be trialled from 2027/28 onwards, to provide focus, test assumptions and allow the organisation to gain experience with a battery locomotive "system".
13. Assuming the success of the pilot and the commercial availability of superior battery locomotives matching the assumptions in this study, commence conversion of remaining North Island routes to battery electric operation from the early 2030's.
14. Extend this to the South Island as the new DM fleet begins to fall due for life extension. Consider DM locomotive battery conversions.
15. Use the pilot project to help spur the policy and investment focus needed to overcome the limitations in the NZ generation, transmission and distribution system that could prevent widespread transport and industrial electrification in the coming decades.

16. Combine the DFT replacement, DM, OLE and battery pilot initiatives to avoid the need to life extend any of the first 40 DL locomotives commencing late this decade.
17. Use production battery locomotive deployment from the early 2030's to avoid the need to life extend any of the 8 remaining non electronic brake DL locomotives as they fall due.
18. 2nd generation or later biofuel should be considered as a fall back against delay to the battery option and/or as a way to decarbonise the long-life DM fleet. Active engagement to continue, to keep this option open.

Transitional investments that are recommended are:

19. Continue with the DM diesel locomotive procurement to:
    a. replace all legacy diesel locomotives in the South Island with lower emission and higher efficiency diesel units.
    b. displace high emission and lower efficiency North Island legacy locomotives on the busiest routes.
20. Life extend the DFT fleet by rebuilding or re-engineering rather than replacing with new diesel locomotives.
21. Plus, continue with infrastructure investment to eliminate all remaining light axle-load routes requiring DFT locomotives, by the end of their extended life
22. Retain reserve pools of some legacy diesel locomotives[128] against mode shift increases in traffic ahead of decarbonised locomotives being available.

Most diesel locomotives can and should be removed from service by around 2040 if the assumed performance battery improvements are delivered and suitable products become available.

Reaching the locomotive decarbonisation objective requires delivery of these initiatives as a series of tightly interconnected projects over the next two decades. Each step must be delivered on time and enable the following step.

The recommended approach can be efficiently packaged into three sub programmes as follows:

- Continued diesel locomotive modernisation programme – DM procurement, DFT life extension and legacy DX, DC, DF and DL retirements.
- Conventional electrification programme. Power supplies, overhead line and signalling for the two new routes, EF and electrification life extension and new generation electric locomotive procurement. Business case, justification, design and then delivery.
- Battery electric locomotive programme. Shunt loco micro-pilot, full scale mainline pilot, business case and justification leading to procurement and deployment, including organisational transformation.

These programmes require coordination at Executive or Board level, to ensure the overall objective of ZGHG by 2040 is achieved. The overarching imperative of transformational organisational and people change sits above the individual technical activities.

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[128] Most likely late production electronic brake equipped DL's.

13.15. Implications for policy makers

This study has identified some areas of interest for agencies of Government:

- The opportunity to achieve a significant reduction in transport GHG emissions by encouraging mode shift to rail, where it is a practical option, even while legacy diesel locomotives remain the main motive power. The gains will be significantly improved as reduced and ZGHG locomotives replace legacy diesel units.
- The B1 scenario[129] appears to be a useful and practical scenario to target.
- Note that the KiwiRail analysis still indicates fossil diesel to be the cheapest option for rail, for the next 25 years. Current pricing signals do not seem to strongly justify change.
- The need to consider the development of policies and programmes that overcome the NZ generation, transmission and distribution system limitations that could hinder widespread transport and industrial electrification in the coming decades.

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[129] A “Resilient, Reliable and Substantial” scenario increasing 2035 market share from 15.2% to 18.7%. Refer to Table 10 and Table 11.

14. Summing up and recommendations

14.1. Summing up

The railway faces two interlinked issues: substantial growth and the need to decarbonise.

The proposed approach proposes taking low risk actions first, to make material early progress while becoming more comfortable with the less certain battery electric route to decarbonisation. Commitment is staged, providing the flexibility to adapt the plan if assumptions or conditions change over the next decade. For locomotive decarbonisation, three parallel lines of activity are recommended:

1. Develop and run a mostly new build fleet of diesel locomotives of the highest efficiency and performance on all non OLE routes until progressively displaced by battery electric locomotives during the 2030 – 2040 period. Retain a small fleet of upgraded lightweight legacy diesel locomotives to operate low axle load routes until this infrastructure is upgraded. Utilise biofuel or blends to further reduce GHG emissions, as/if these become available in the NZ supply chain.

2. By 2030 extend the existing 25kV AC OLE networks to provide complete coverage of the Auckland – Hamilton – Tauranga and Palmerston North routes and enable operation by existing and new conventional electric locomotives. This initiative decarbonises nearly half of all KiwiRail freight traffic using proven off the shelf technology. Advance these projects methodically and cautiously, with a review before each increased level of commitment. Be prepared to adjust or abandon if battery locomotive technology has advanced such that the objective is better accomplished without OLE.

3. Use the time made available by the above initiatives to allow battery, charging and battery locomotive technology to advance and to gain experience with battery locomotive operations. Use a shunt locomotive micro-pilot followed by small fleet mainline pilot in 2027/28 to focus and drive this process. Begin progressive replacement of all remaining diesel locomotives with production battery locomotives from the early 2030's and complete by 2040.

Recommended short to medium term actions: Move with a purpose

While further study is needed to confirm the conclusions of this report, justify investment and source funding, KiwiRail should work from a position that the report's recommendations form a firm action plan for development and decarbonisation of the mainline locomotive fleet, starting in 2023.

- Establish a budget and programme team to confirm the above recommendations and commence early work during 2023 and 2024.
- That work start early and that the objectives be pursued with a purpose, with a focus on practical coordinated action.
- As part of this next year of activity, review programme leadership, organisation and governance and put in place arrangements suited to the breadth and strategic importance of the endeavour, with consideration being given to the structure of three programmes: immediate, end of this decade and 2030's.
- Work with Government on the policy settings, mode shift, funding and electricity industry issues.
- Consider the organisational implications of the substantial growth implicit in adopting the B1 growth scenario[130].
- Ensure the operational shunt procurements is concluded in a way that enables a small scale battery pilot.
- Review preferred battery option in detail and, if confirmed, prepare a detailed plan for funding and delivering a battery mainline loco pilot later this decade. Review also to examine the challenges of power supply to charging facilities.
- Develop a detailed plan and case for the recommended OLE, including funding sources, power supplies and locomotive refurbishment and procurement.
- Adopt a policy of not life extending DL1 - 40 and arrange the decarbonisation programme to enable this.
- Continue with the DM project and assign any locomotives not needed in the South Island to the North Island to displace legacy diesel locomotives.
- Review DFT replacement with a view to converting DK proposal to a lesser number of additional DMs, and a suitable number of life extended DFTs. Convert review to action.
- Continue to work with Air New Zealand and Government agencies on the options for 2nd generation biofuel for reducing DM emissions and as a battery locomotive fall back.
- Connect the findings from these parallel initiatives in a Detailed Business Case justifying execution of a comprehensive locomotive decarbonisation plan over the next two decades.
- Begin analysis and planning for a railway transformed by these changes.

It should be noted that at the time of finalising this report, funding has been approved and a project team formed to prepare a Detailed Business Case to further explore in more depth electric locomotive options (and associated infrastructure) and develop a staged roll-out plan. The size of the investment plus quantified benefits will be determined as part of the Detailed Business Case.

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[130] A "Resilient, Reliable and Substantial" scenario increasing 2035 market share from 15.2% to 18.7%. Refer to Table 10 and Table 11.

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Extend OLE - Electric Railway Concept