Minimising carbon emissions and energy expended for the New Zealand transport sector through to 2050

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ABSTRACT

Carbon Emissions Pinch Analysis (CEPA) and Energy Return on Energy Investment (EROI) analysis are combined to investigate the feasibility of New Zealand (NZ) reaching a 1990 emission levels for transport in 2050. The transportation sector traditionally has been a difficult area to transition to high levels of renewable energy because of the strong dependency on fossil fuels. Multiple scenarios for reducing transport emissions are analysed. With NZ's unique mix of renewable energy resources the analysis demonstrates that NZ is in a very good position to sustainably meet their future transport needs provided substantial commitment is made to transition light vehicle fleet to hybrid vehicles, plug-in hybrids vehicles and electric vehicles by 2050. Electrification of rail within and between major centres will also require major political commitment. The resulting increase in electricity demand for transport is 3.6 TWh (or 4.8 % of electricity generation in NZ). We show the minimum amount of biofuel renewable production to achieve the goal of 1990 emissions level in 2050 is 46 PJ. Delivering 46 PJ is expected to be well within the potential biofuel production capacity of NZ. The delivery of economically competitive renewable liquid biofuels will also require close cooperation and system integration with other energy systems like the electricity sector and industrial process heat sector.

1. INTRODUCTION

One of the biggest challenges facing the world is the replacement of traditional oil and natural gas based transport fuels with alternatives that are both technically and economically viable and environmentally, socially and politically sustainable. As transport energy demand rises, especially in developing countries like China and India, and as oil and gas reserves become increasingly difficult to find and exploit, energy companies and nations are turning more and more to unconventional energy resources, like tar sands, shale oil, agricultural crops and silver culture forests, to try and solve the emerging energy replacement problem.

Increased motivation to address the transports fuels challenge is derived from the need to lower environmentally harmful emissions and to reduce air pollution in many of the world's major cities. In particular, carbon and like emissions have been identified as a possible accelerant to global climate change providing increased political will to seriously look for alternatives to traditional fossil fuels. At present unconventional energy sources, even after considerable research effort, are more technically difficult and more costly to transform into usable liquid fuels compared to oil or natural gas. In general they require much higher levels of energy to be expended to deliver the same amount of useable fuel. In turn this can result in a contraction of the rest of the economy, which can potentially affect industrial production, employment and general economic well-being of citizens [1]. Careful energy sector planning using engineering analysis tools such as Carbon Emissions Pinch Analysis (CEPA) and Energy Return on Investment (EROI) analysis is therefore needed, on a country by country basis, to ensure that the inevitable transition to a low fossil fuel transport energy sector occurs in a way that minimises the increase in energy expended to meet the desired demand within the nation's carbon emissions targets.

One potential solution proposed by Danish researchers is to use renewable electricity to power as much of the future transport fleet as possible, while using any excess to generate hydrogen to combine with biomass to produce liquid fuels for transport operations such as aeroplanes and ships [2]. The idea has merit for countries like New Zealand and Denmark that have the natural resources to produce large quantities of excess renewable electricity at reasonably high Energy Return On energy Invested (EROI) ratios and with reduced carbon emissions. Maintaining high EROI levels for transport fuels and electricity for transport will help minimise the economic and environmental effects of transitioning from fossil fuels to other energy alternatives.

Electricity powered transport vehicles such as electric trains, trams and trolley busses are well established technologies. Electric light passenger vehicles (LPV) and electric light commercial vehicles (LCV) are recently commercialised technologies; however the issues of low travel distances and long battery charge times have limited their usefulness and restricted their uptake. A way around this problem that is growing in popularity is to use plug-in hybrid vehicles (P-HV) with a hybrid electric and internal combustion engine system. Automobile manufacturers now make this type of vehicle and the associated production costs are decreasing as the technology continues to mature and the scale of manufacturing increases. Under the Danish approach synthetic liquid fuels from biomass is required to power heavy vehicles like trucks, ships and planes, and for LPV and LCV that are run by hybrid engines.

The aim of this paper is to apply CEPA and EROI analysis to planning how NZ can slowly transition away from fossil fuels to best meet future transport demand for a population that is anticipated to reach 5.8 million around 2050, while also meeting the goal of 1990 emissions and lower environmental impacts in terms of carbon footprint. Energy generation methods are analysed using CEPA and EROI analysis to determine the 2050 generation mix that best meets 1990 emissions levels, while minimising energy expended.

1.1. Background information for the New Zealand Case study

NZ is an isolated country in the South Pacific that is well endowed with energy resources. Both renewable and non-renewable energy resources are used for electricity generation, industrial process heat and liquid fuels production. Renewable resources such as hydro, geothermal, wind and biomass accounted for a little less than 80% of electricity generation in 2013. Coal, natural gas and biomass are used for process heat and thermal power generation. Currently imported crude oil accounts for 33.78% of NZ's primary energy needs and 99.85% of NZ's transport fuel needs [3].

NZ has a current population of 4.4 million that is anticipated to reach 5.8 million about 2050 [4]. Overall energy demand is therefore anticipated to plateau sometime after 2050. There is strong political will within NZ for continued growth in the renewable generation sector as a strategy for reducing NZ greenhouse gas (GHG) emissions and for creating a sustainable energy future for NZ in general. Numerous studies have been commissioned by the NZ government into alternate transport fuel options for NZ [5] and on-going research is being supported in the bioenergy and biofuels areas.

NZ has the natural resources to support a high renewables target for NZ's entire energy sector including the transport, process heat and electricity sectors. However, achieving high renewables content in transport fuels is technically and economically challenging, especially as the most favourable renewable energy sites or sources are used up, and the energy expended to generate the next useful quantity of renewable energy gets progressively higher resulting in a declining EROI. More analysis of the actual effect of a returning to 1990 emissions levels target stretching out to 2050 for the NZ transport energy sector on the generation mix, GHG emissions levels, environmental impact/footprint, economic costs and security of supply is needed. Consideration of various scenarios needs to also include the declining EROI for each renewable and non-renewable resource [6].

2. THEORY AND METHODS

2.1. Carbon Emissions Pinch Analysis

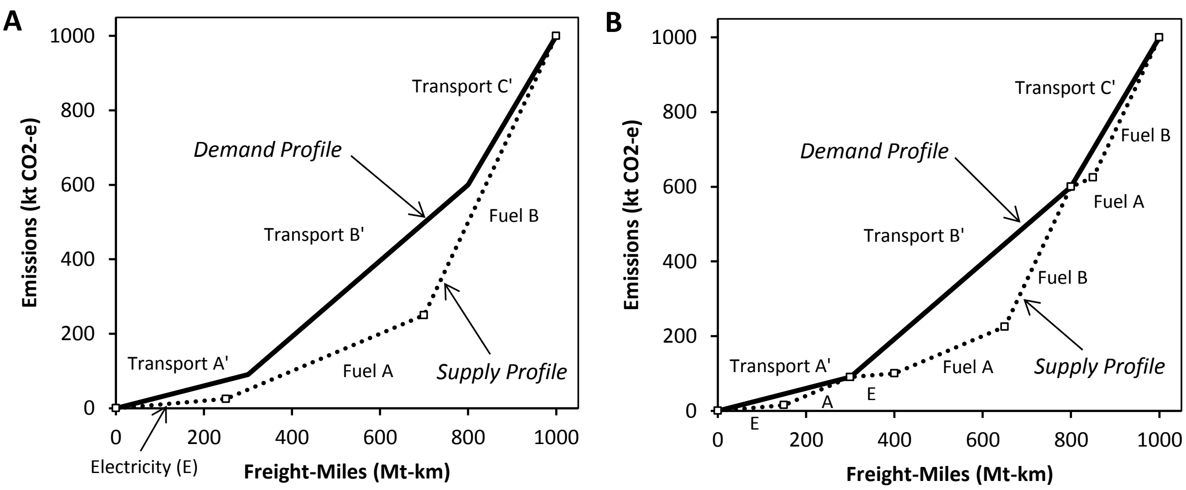
Carbon Emissions Pinch Analysis (CEPA) was first developed by Tan, Foo, and co-workers [7], and is based on the application of traditional Pinch Analysis techniques beyond Total Site to broader macro-scale applications such as the electricity generation sector [8]. Sectorial and regional studies have been conducted for power systems emissions constraint planning [9] with CCS [10] including retrofitting [11] and for multi-period scenarios [12] and variable CO_2 sources and CO_2 sinks [13]. In the New Zealand context, CEPA has been applied to national electricity sector [14] and how increased electricity demand in 2050 can be met and the generation mix optimised for minimised energy cost [15]. However, the method has not been applied to the transport sector as the authors are aware and some degree of modification to the standard method is required to extend CEPA to analysis of a transport system.

A major aspect of CEPA applied to the transport sector involves the construction of multiple supply and demand composite curves that plot cumulatively the quantity of useful transport output that occurs by fuel sources (supply) and by transport method (demand) against total equivalent carbon emissions (CO_2-e) from those sources and methods. The fuel source and transport method with the lowest Emissions Factor (EF) (the amount of emissions produced per unit of useful transport output, i.e. kt CO_2-e/Mt-km for freight transport or kt CO_2-e/passenger-km for passenger transport) is plotted first, followed by the next highest and so on. The slope of the supply profile is equal to the emissions factor. The overall Transport Emissions Factor (TEF) is simply the average total emissions factor or specific emissions for the entire system.

An example of the method is presented in Table 1 and Figure 1 for the freight transport demand class (expressed as Freight-miles in Million tonne kilometre [Mt-km]). Figure 1a presents the overall supply and demand with the associated emissions of 1000 kt CO_2-e. Figure 1b gives a breakdown of the supply and demand for each transport mode and the demand profile now meets the supply profile at the beginning and end of each transport mode. If the new emissions target is 700 kt CO_2-e, emissions can be reduced through transport switching to lower emitting transport modes (Figure 1c) or by fuel switching to a lower emitting fuel within a transport mode (Figure 1d). There are many combinations of transport modes and fuels that can achieve the target, but options 1c and 1d identify important limits bounding the various combinations. Option 1c shifts transport demand from mode C' to mode A' and thereby takes advantage of the lower average emissions of mode A' relative to mode C'. It is assumed that the fuel mix within the transport modes for this scenario stays the same. Option 1d shifts demand by switching from Fuel B to Electricity (E) with a much lower emissions factor. Electricity generation in NZ has a low Grid Emission Factor (GEF) due to a high proportion of renewable generation from hydro, wind and geothermal. The GEF is the overall average emissions from the generation of electricity and in analogous to the TEF. Either option 1c or 1d meet the target, however further consideration of fuel costs, supply limits and transport mode limits are needed. Although not illustrated in the example, it is important to note that the EF is specific to a combination of transport mode and fuel type. For example, a cargo ship may use diesel and a truck may also use diesel, but their efficiency of transporting freight from one location to another is substantially different.

Table 1. Example transport and emissions scenario.

	Quantity [Mt-km]	Emissions [kt CO_2-e]	Emissions Factor [kt CO_2-e/ Mt-km]
Demand			
Transport Mode A’	300	90	0.3
Transport Mode B’	500	510	1.0
Transport Mode C’	200	400	2.0
Total Demand	**1000**	**1000**	1.0
Supply to A’			
Electricity	150	15	0.1
Fuel A	150	75	0.5
Fuel B	0	0	2.5
Total Supply to A’	**300**	**90**	0.3
Supply to B’			
Electricity	100	10	0.1
Fuel A	250	125	0.5
Fuel B	150	375	2.5
Total Supply to B’	**500**	**510**	1.0
Supply to C’			
Electricity	0	0	0.1
Fuel A	50	25	0.5
Fuel B	150	375	2.5
Total Supply to C’	**200**	**400**	2.0
Total Supply	**1000**	**1000**	1.0



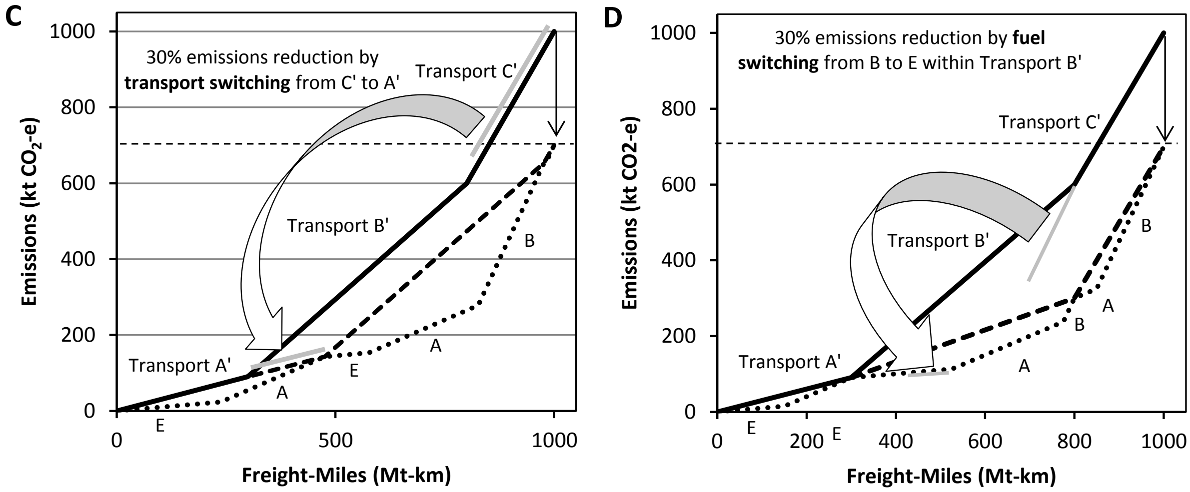


Figure 1. Example demand and supply composite curves (a) overall (b) within transport modes and (c) after emissions reduction by transport mode switching and (d) fuel switching within a transport mode.

Liquid fuel efficiency values in PJ/Mt-km or PJ/passenger-km can also be used to represent the two demand classes of freight transport and passenger transport in terms of fuel heat content in PJ or equivalent mechanical work in GWh. For this calculation three units of heat energy can be assumed equivalent to one unit of mechanical work as a first approximation.

2.2. Energy Returned on Energy Invested Analysis

Fuel switching to reduce emissions makes sense provided the replacement fuel is in good supply and is available at an economical price, which cannot be predicted by CEPA analysis alone. Energy Return on Energy Invested (EROI) principles are also needed in the analysis to ensure conclusions are economically relevant. The concept was first proposed over 40 years ago by American systems ecologist Charles Hall [16]. With rising fuel cost and concerns about limits to economic growth in the developed world the concept is of increasing importance [17].

EROI is essentially the ratio of the amount of useful energy produced for society to the amount of energy that has to be expended by society to get the useful energy in the first place. The useful energy for society may be in the form of a *primary energy source* such as natural gas (NG), crude oil or coal, or in the form of a refined energy carrier such as electricity, gasoline or briquettes [18]. When calculating EROI ratios it is advised that energy qualities (e.g. heat, work and electricity) be arranged to be equivalent by converting all energies into thermal units or into units of work [19]. Typically three units of heat energy are assumed equivalent to one unit of mechanical work or electricity, but this is a simplification of a more complex situation and more detailed heat to work conversion formulas can be used if there is a need to be highly accurate with EROI values.

For an energy project involving liquid fuels generation EROI is defined by Eq. 1 where E_{use} is the amount of useful or gross liquid fuel energy in PJ produced per year, t_{life} is the expected lifetime of the extraction and refinery plants and E_{exp} is the energy expended for extracting (E_{ex}) and processing (E_{pro}) the natural resource (e.g. oil, NG or biomass) to the desire liquid fuel product in PJ including construction (E_{con}) and decommissioning (E_{dec}) of the plants.

$$EROI = \frac{\dot{E}_{use}}{\sum \dot{E}_{exp}} = \frac{\dot{E}_{use}}{\sum \left(E_{con} + E_{dec}\right) / t_{life} + \dot{E}_{ex} + \dot{E}_{pro}} \tag{1}$$

Processing conversion loses are not included in useful energy produced. Energy resources with high EROI potential, like oil and coal, are desirable and these resources are typically first to be exploited. Where the EROI is less than unity (e.g. some agriculture crops), it means the fuel has a net energy consumption rather than generation. It has been suggested that for economic sustainability that the EROI of an energy source needs to be greater than five [1].

When transport fuel production is considered we can further define an EROI for the primary energy resource ($EROI_R$) as in Eq. 2 and an EROI for the liquid fuel after refining at the point of use ($EROI_{pou}$) by the consumer as in Eq. 3a. The total energy expended (E_{ED}) is the sum of all the inputs needed in the extraction, processing and distribution operations of the primary energy source (e.g. Crude Oil) to the refinery, which includes the direct use of the energy product (E_{pro}), direct use of external energy (E_{ext1}), and indirect use of external energy (E_{ind1}).

$$EROI_R = \frac{\dot{E}_R}{\dot{E}_{ED}} = \frac{\dot{E}_R}{\dot{E}_{pro} + \dot{E}_{ext1} + \dot{E}_{ind1}} \qquad (2)$$

When liquid fuels like petrol and diesel are made additional energy is required for running the refinery (E_{PP}) and for distribution of the product to consumer outlet points (E_{DIS}). Refinery energy includes internal electricity (in PJ) use (E_{para}), direct fuel inputs (E_{dir}), direct external energy inputs (E_{ext2}) and indirect energy inputs (E_{ind2}), some of which is the embedded energy of construction and decommissioning that must be spread over the expected lifetime of the plant. Distribution energy included energy for transporting (E_{trs}) and imbedded energy in the distribution equipment (E_{net}), such as pipelines, pulps road tankers and storage facilities. Expanding Eq. 3a to include these factors individually yields Eq. 3b.

$$EROI_{pou} = \frac{\dot{E}_{use}}{\dot{E}_{ED} + \dot{E}_{PP} + \dot{E}_{DIS}} \qquad (3a)$$

$$EROI_{pou} = \frac{\dot{E}_{use}}{\left(\dot{E}_{pro1} + \dot{E}_{ext1} + \dot{E}_{ind1}\right) + \left(\dot{E}_{para} + \dot{E}_{pro2} + \dot{E}_{ext2} + \dot{E}_{ind2}\right) + \left(\dot{E}_{trs} + \dot{E}_{net}\right)} \qquad (3b)$$

EROI is a dynamic ratio that can vary over time especially as non-renewable energy resources become scarce and as new technology and innovative practice improves utilisation efficiencies (Figure 2). Where renewable resources are used (e.g. Biomass), $EROI_R$ values may vary over time due to changing climatic conditions, rather than because of resource depletion. In the early stages of developing a new energy product (e.g. biofuels from biomass and renewable electricity) the EROI will be low, even less than one. However, as the new technology develops and matures more efficient extraction and energy generation techniques become available, the EROI can vastly improve [20] within the thermodynamic limits of the resource.

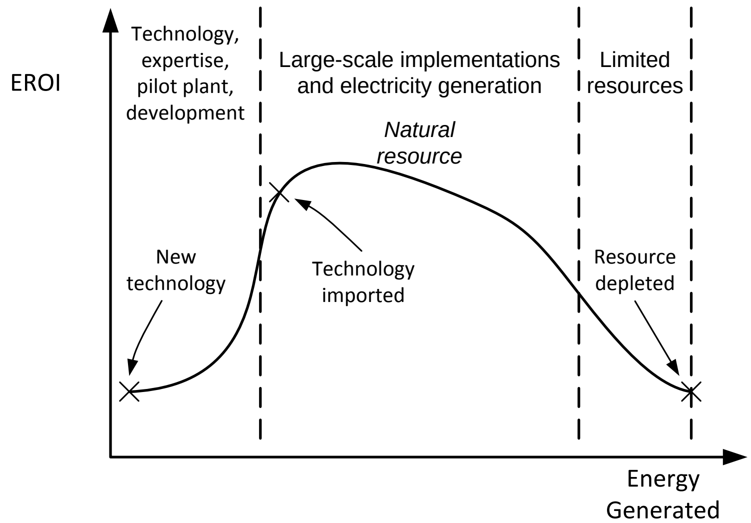


Figure 2. The influence of technology development and availability of natural resource on EROI.

EROI for fuels used for transport can vary greatly depending on the type and quality of the natural resource and the technology used for extraction and conversion [21]. Hall et al. [17] discusses these issues and the EROI ranges presented in their review paper have been used to create Figure 3. To date, there has been little work on EROI of liquid fuels in the context of the New Zealand transport energy sector.

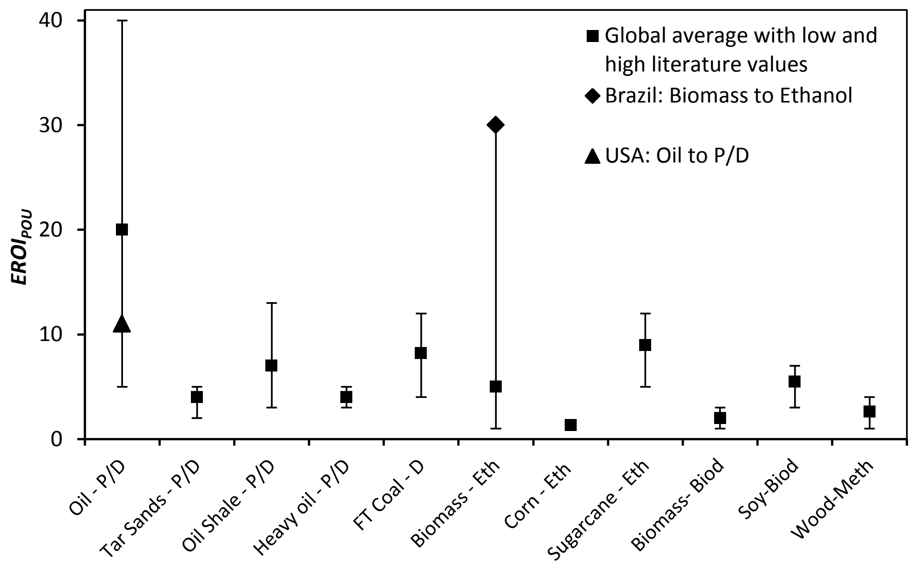


Figure 3. EROI values for liquid fuels production from fossil and renewable energy sources [17], where P is petrol, D is diesel, Eth is ethanol, Biod is biodiesel, and Meth is methanol.

3. RESULTS AND DISCUSSION

3.1. New Zealand Transport Sector Fuel and Emissions Growth Analysis

The transport sector in NZ has experienced significant growth in fuel demand from 1974 to 2008 as illustrated in Figure 4. Petrol and diesel fuels dominate the growth in fuel use, followed by aviation fuels and LPG. Fuel oil declined in the 1980's and again increased in the 1990's. Responses to global recessions, oil price hikes and/or periods of economic restructuring are also evident in the fuel use data. As global oil prices rose in the late 1970's, economies like NZ we forced to spend more on foreign imported oil, which affected their balance of trade, which in turn forced other changes on the economy. The economic restructuring that took place in NZ in the 1980's was in many ways precipitated by the oil crisis of 1979.
The large increase in diesel fuel use and to a lesser extent petrol fuel use, as seen in Figure 4, is related to the large increase in light passenger and light commercial vehicles that occurred during the 1990's and beyond when import regulations were relaxed in the early 1990s, along with road freight transport rules. Light vehicle numbers soared, especially diesel powered vehicles, and cheap imported vans and trucks increased freight tonne-miles at the expense of any growth in rail (Figure 5a).

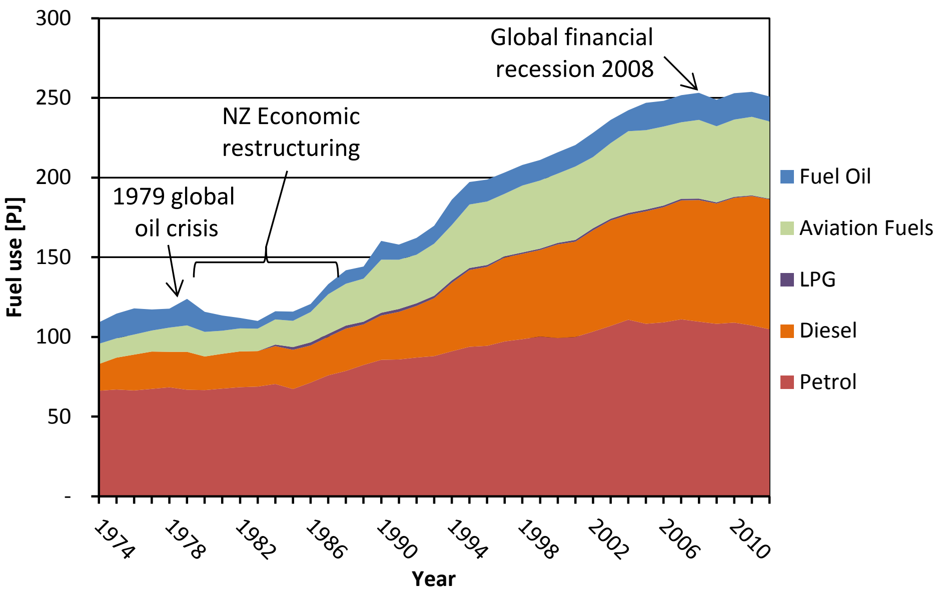


Figure 4. Transport fuel growth in NZ by fuel type from 1974 to 2013.

The contribution of each transport mode to fuel use and emissions from 1990 to 2012 is illustrated in Figure 5. As discussed previously, road transport has dominated the growth in both fuel use and emissions. International air and international marine have also risen most likely as a result of global tourism increases. Domestic air, domestic marine and rail, have experienced only small increases. Significantly, about half of the international transport emissions are not formally included in NZ's emissions for this study. Only trips that fuel and begin in NZ, e.g. departing international flight, are counted.

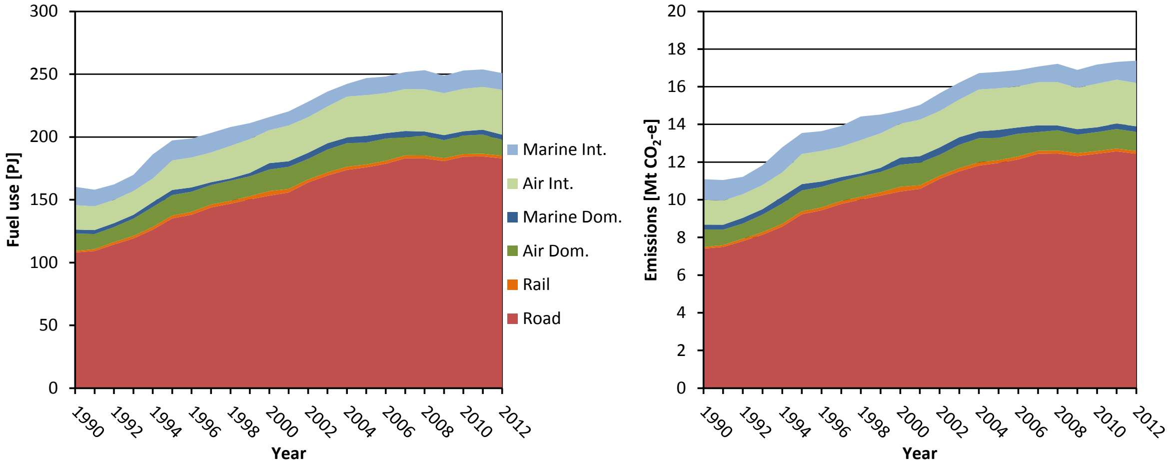


Figure 5. Transport fuel (a) and emissions (b) in NZ growth by transport mode from 1990 to 2012.

Since 2005 annual growth has slowed with negative growth in 2009 after the 2008 recession, and growth rates are expected to return to traditional levels from 2013 due to a continued rising population and the continued reliance on fossil fuels for transport (Figure 6). Population is rising because of positive net migration and a higher than replacement birth rate of 2.1 [22]. It is predicted by Statistics NZ, the country's population is most likely to peak between 6 and 7 million after 2050. The increase in population will put pressure on energy, land and water resources; however, economies of scale and productivity gains will help offset some of these limitations, and for the transport sector, it may result in transport mode switching to more efficient options.

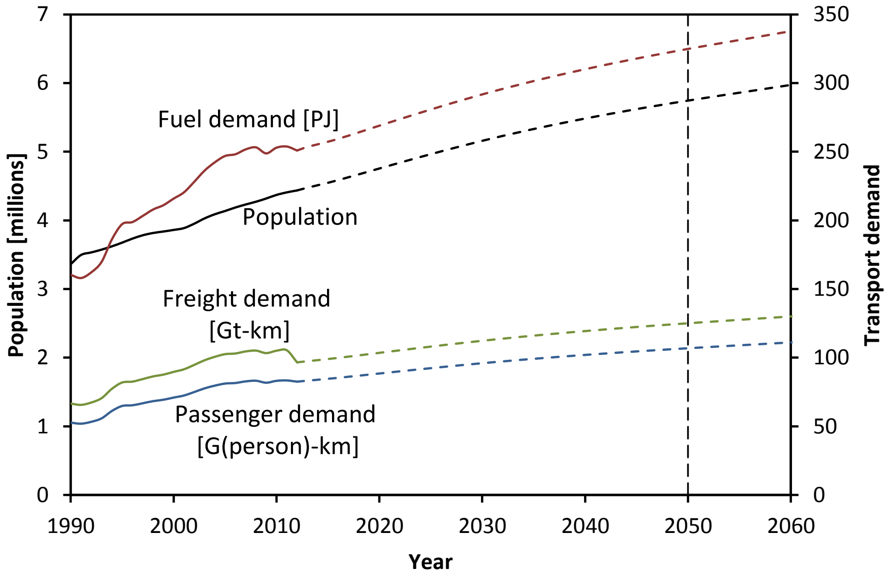


Figure 6. Projected population and transport demand growth in NZ to 2050 for business as usual.

For this study we have taken a conservative 'business-as-usual' approach and assumed passenger and freight transport demand, and fuel demand, will increase proportional with population through to 2050. This gives 2050 targets for CEPA of 107 G(passenger)-km for passenger transport demand and 126 Gt-km for freight transport demand, and 326 PJ thermal equivalents for fuel use.

3.2. Transport mode analysis

NZ's transport energy use is dominated by road transport (Figure 5) with Light Passenger Vehicles (LPV) and Light Commercial Vehicles (LCV) making up to 92% of the vehicle fleet in 2013 [23]. The growth in light vehicle numbers without reductions in any other mode, explains the consistent growth in diesel and petrol consumption, and the corresponding rise in emissions observed.

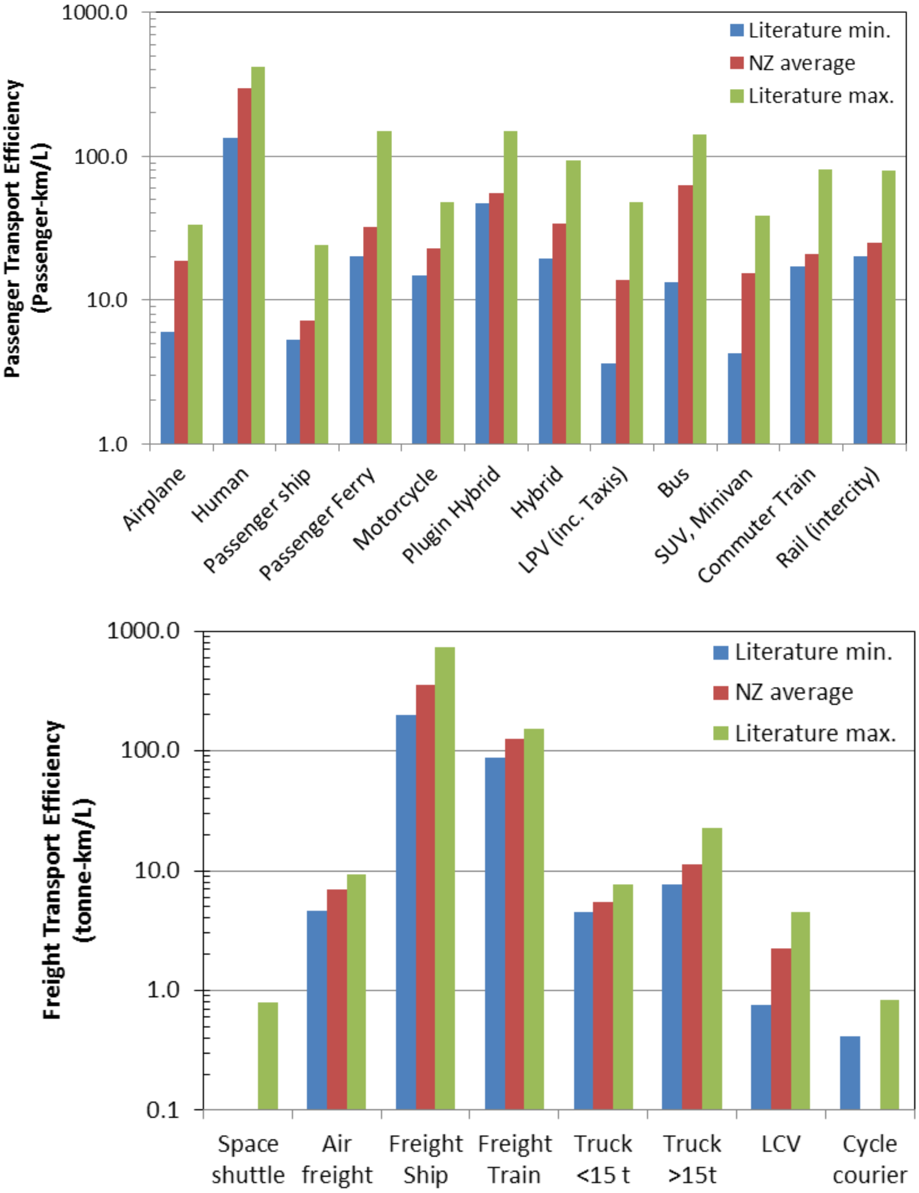


Figure 7. Passenger (a) and freight (b) transport efficiency by transport mode and class for NZ transport [3,23] compared to literature values [24].

There are a wide variety of transport modes (Marine, Air, Road, and Rail) and many classes of vehicles or vessels within these modes. For example, within the Marine transport mode there are cruise ships, cargo ships, oil tankers, barges, ferries, tug boats, submarines etc. and within these classes, there are further subclasses of specific vehicle or vessel models made to common specification and/or performance. At the vehicle model level, transport efficiencies can be calculated with a reasonably degree of accuracy, and numerous data are available from auto companies and government agencies if required. At the higher subclass, class or transport mode level overall fuel consumption, emissions and passenger or freight demand data can be combined to derive average transport efficiency figures. Similar data is available for determining vehicle emission factors and overall transport mode emission factors.

Using transport data published by the NZ Ministry of Transport [23] and the Ministry of Business, Innovation and Employment [3], and literature values, suitable average transport fuel efficiencies in passenger-km/L and tonne-km/L have been determined and are presented in Figure 7a for passenger transport and 7b for freight transport. A log scale has been used to enable a wider range of transport modes to be displayed on the same graph. For passenger transport human powered methods, like cycling, running and walking, are very efficient from an extra fuel (food) consumption point of view, over normal metabolic activity. Other methods like ferry, bus and rail potentially have good efficiencies provided passenger fill rates are high. Unfortunately NZ public transport fill rates are poor and bus and rail efficiency values are thus low. Standout modes for passenger transport are ferries, plug-in hybrids, hybrids, bus and rail provided fill rates are good.

Freight transport exhibit similar trends (Figure 7b) with ship and rail being the most efficient methods, followed by truck and air. LCV is convenient and so is cycle package delivery within the city centre, however relatively they are much less efficient methods from a fuel consumption point of view, comparable to the space shuttle delivering satellites to space [24].

Transport class emission factors used in this study were calculated based on data from NZ's Ministry of Business, Innovation and Employment energy data set [3] and are presented in Table 2.

Table 2. Transport emissions factors for fossil fuel energy supply.

Transport Mode	**Transport Class**	**Passenger Emissions Factor [g CO_2-e/ vehicle- km]**	**Freight Emissions Factor [g CO_2-e/ tonne- km]**
Air	Air Domestic	173	
Air	Air International	120	
Marine	Cargo Domestic		9
Marine	Cruise Domestic	401	
Marine	Ferry	120	
Marine	Cargo International		11
Marine	Cruise International	401	
Rail	Inter-City Rail	90	
Rail	Intra-City Rail	109	
Rail	Freight Rail		18
Road	Bus	36	
Road	LCV		1013
Road	LPV	174	
Road	MC	159	
Road	Truck (<15 t)		414
Road	Truck (>15 t)		200

3.3. Carbon Emissions Pinch Analysis for the New Zealand Transport Sector in 2012

Using the CEPA composite curve method the freight transport mix and passenger transport mix in NZ for the year 2012 are illustrated in Figure 8. The total freight transport demand and emissions for NZ in 2012 were 95.9 Mt-km and 5.0 Mt CO_2-e respectively (TEF = 0.0518 Mt CO_2-e/Mt-km), and the transport mode mix was 83.8% marine international and domestic, 7.2% heavy truck, 2.4% light truck, 1.7% LCV, and 4.8% rail. The total passenger transport demand and emissions for NZ were 82.5 G(passengers)-km and 12.4 Mt CO_2-e respectively (TEF = 0.150 G(passengers)-km/Mt-km) and the transport mode mix was 56.1% LPV, 23.2% air international, 10.4% bus, 7.1% air domestic, 1.7% domestic and international cruise, 0.8% inter- and intra-city rail, 0.5% motorcycle, and 0.3% ferry. In both cases the amount powered from renewable fuels was negligible.

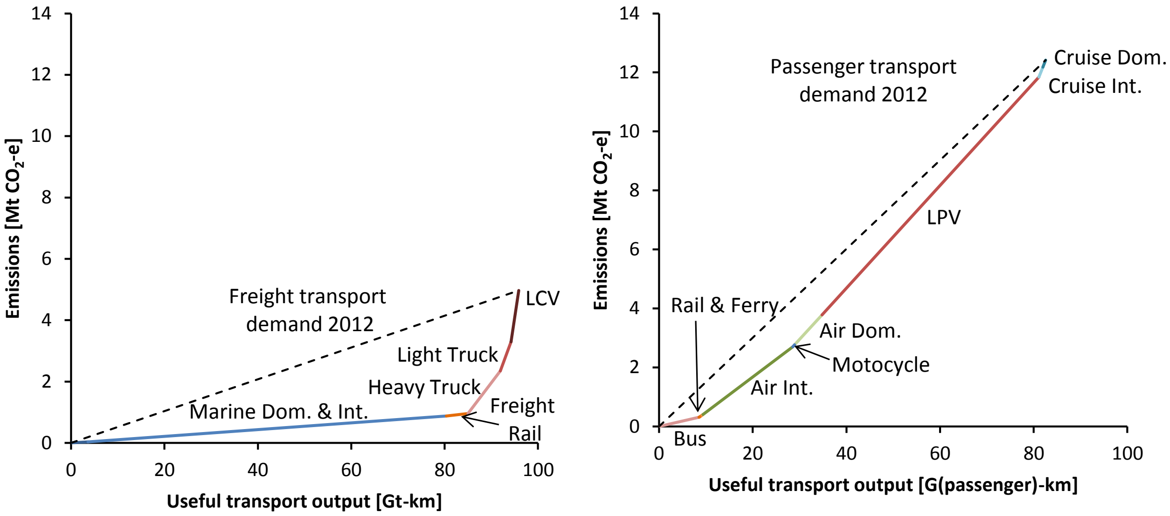


Figure 8. Comparison of emissions composite curves for freight (a) and passenger (b) transport demand in New Zealand for 2012.

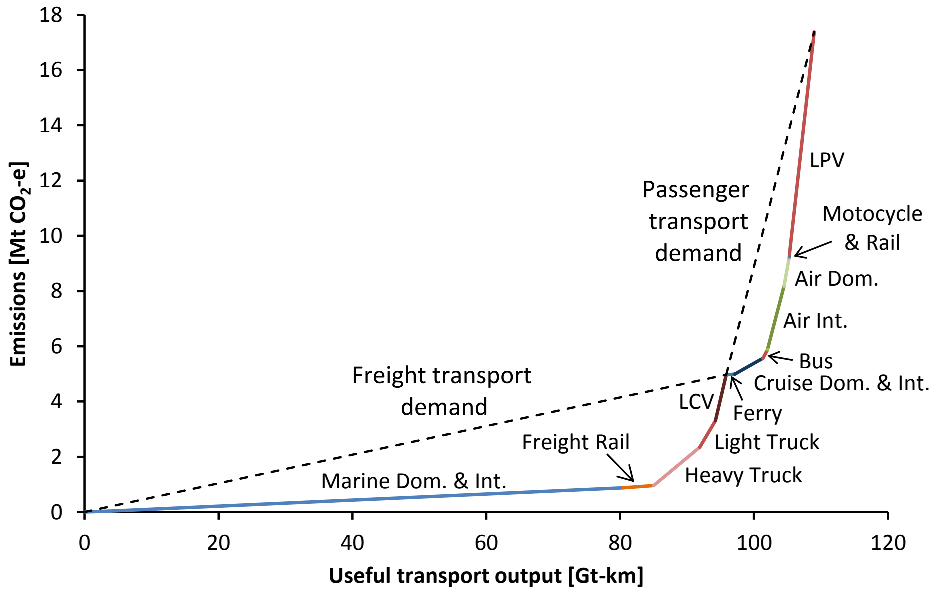


Figure 9. Combined emissions composite curve for freight and passenger transport demand in New Zealand for 2012.

Each useful transport output is combined to a common mass basis by assuming passengers have an average mass of 75 kg. The combined emissions composite curve is presented in Figure 9. Emission factors vary because of freight or passenger load factor, engine technology and tare weight differences rather than fuel differences. Marine transport is clearly very efficient at transporting both freight and people with marine vessels having the lowest emission factors in both demand classes. Freight rail is equally a low emissions transport method and road freight methods are the highest. It is important to note that although road freight methods have the highest emissions factors, they have additional cost benefits of being flexible giving point-to-point delivery with minimal handling stages. This flexibility clearly suits NZ's current low population density situations outside of Auckland and the underdeveloped rail and water transport infrastructure.

With passenger transport, air international is a significant contributor to emissions, exceeded only by LPV. Tourism growth to NZ is contributing to large air international emissions, while a relatively old vehicle fleet, convenience, relatively cheap petrol prices, low population densities outside Auckland (NZ's only >1 million population city), underdeveloped public transport infrastructure, general NZ topography and the freedom-to-travel culture of New Zealanders is behind the high LPV emissions. High emissions for rail and bus are principally caused by low participation rates as a result of high LPV use.

3.4. Approaches to Reducing CO_2 Emissions in Transport Energy Sectors

Renewable Liquid Fuel Production

The production of renewable liquid fuels will be specific to a country's local resources. The transition to liquid biofuel in NZ is most likely to involved second generation biofuels from woody biomass, grown in sustainable rotation forestry. Additional afforestation of low productivity or marginal land not suitable for dairy pasture or other crops would be needed. It has been estimated that with the use of marginal land to produce woody biomass, NZ could produce up to 483 PJ or 14.7 billion litres of petrol equivalent biofuel [25] and could be economically competitive with conventional liquid fuels at an oil price of around US$200 per barrel. Conversion technology is currently in the pre-commercialisation stage and, therefore, the efficiency of biofuel production and its cost competitiveness is expected to increase in time. Production of biofuels will be necessary for NZ, as with other countries, to lower emissions from transport.

Improved Vehicle Transport Fuel Efficiency

In the last decade the fuel efficiency of LPVs, LCVs and buses has been significantly improved by hybrid engine technology. The hybrid vehicles intelligently use a battery and electric motor in conjunction with an efficient combustion engine to achieve high fuel efficiency. In this study, we estimate a 40 % reduction in fuel use is obtained when comparing a normal vehicle to a hybrid vehicle for the same distance travelled based on data from the NZ Ministry of Transport [23] and the Ministry of Business, Innovation and Employment [3]. By 2050 it is expected with rising fuel prices, the vast majority of the LPVs, LCVs and Buses will contain some form of efficient hybrid engine.

Increased Integration of Electricity in Transport Vehicles

Integration of electricity into the transport sector has traditionally focused on the electrification of rail. However, there is growing popularity around the future adoption of electric vehicles. Some organisations [26] and politicians [27] have campaigned on the misleading notion that electric vehicles have zero emissions. In this section we show the actual emissions from an electric vehicle over its life are dependent on the weight of the car and battery, and the overall GEF for electricity production in a given country. Where it means that additional coal will be burned to supply electricity to an electric vehicle, the overall emissions will be greater than the typical petrol engine car.

It is important when considering alternate LPVs that the lifecycle GHG emissions are included, especially for electric vehicles where increased emissions occurs with the manufacture and replacement of the batteries. As the range of the vehicle in electric mode increases the mass of the battery must become greater. There is a large variation in the reported GHG emissions of battery manufacture from 6 kg CO_2-e/kg_{bat} [28] to 22 kg CO_2-e/kg_{bat} [29]. The variation is due in part to the different assumptions and system boundaries used in the LCA studies. A value of 15 kg CO_2-e/kg_{bat} has been used in this study. The GHG emissions associated with the production of the car is assumed to be 5 kg CO_2-e/kg_{bat} and is within the range of 4 to 6.5 kg CO_2-e/kg_{bat} reported in the literature [30]. The extra battery emissions will normally be attributed to the country that makes the batteries, but in this analysis these emissions have been included as an operating and battery emissions factor (Table 3).

Table 3. Estimated emission factors for three light passenger vehicles.

	Embedded Car Emissions[a] [kt CO_2-e]	**Embedded Battery Emissions[b] [kt CO_2-e]**	**Fuel Consumption**	**Operating Emissions Factor[c] [kt CO_2-e/ 100 km]**	**Life Cycle Emissions Factor [kt CO_2-e/ 100 km]**	**Operating & Battery Emissions Factor [kt CO_2-e/ 100 km]**
ICE (Internal combustion engine)	7500	-	0.072 L/km	17.57	21.32	17.57
P-HV (Plug-in Hybrid Vehicle)	7500	1800	0.0214 L/km 0.20 kWh/km	5.74	10.39	6.64
EV (Electric vehicle)	7800	8100	0.24 kWh/km	1.16	9.11	5.36

[a] Based on 5 kg CO_2-e/kg_{car}

[b] Based on 15 kg CO_2-e /kg_{bat}

[c] Based on NZ 2050 GEF 0.049 kg CO_2-e/kWh, 50% EV mode for P-HV, Petrol EF 2.44 kg CO_2-e/L

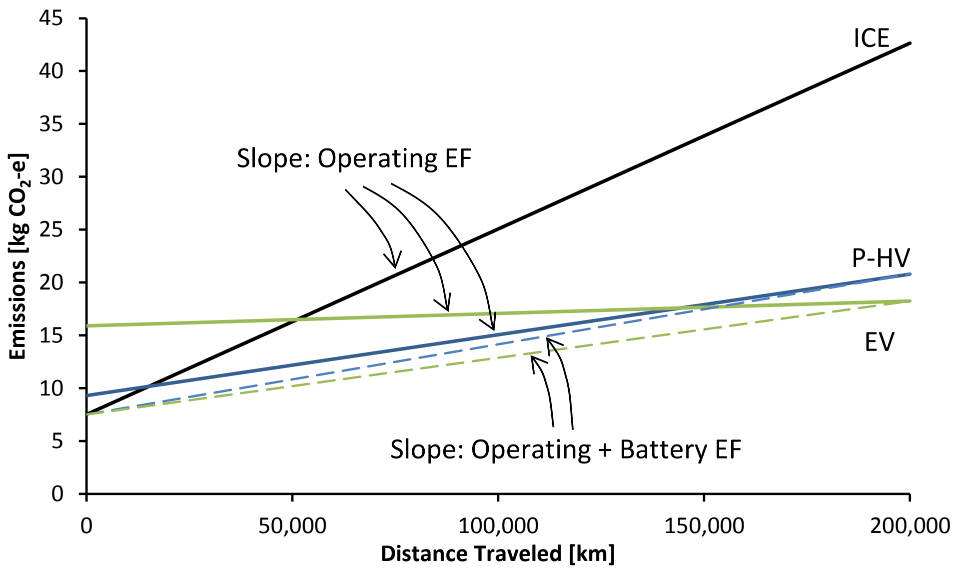


Figure 10. Emissions for LPVs based on the 2050 estimated electricity GEF for NZ (0.049 kg CO_2-e/kWh).

The emissions as a function of distance for Internal Combustion Engine vehicles (ICE), plug-in hybrids, and Electric Vehicles (EV) is shown in Figure 10 based on the 2050 GEF of 0.049 kt CO_2-e/GWh_e [15]. The various EFs used to construct Figure 10 are given in Table 3. The slopes of the solid lines represent the operating emissions factors (EF) for each vehicle type. The dashed lines in the figure represent the operating and amortised battery emissions for P-HV and EV, and is used to determine the actual GHG reductions possible by switching from ICE to P-HV and EV. The total reduction in GHG emissions over the total life of the vehicle is

49% and 43% for P-HV and EV respectively. The EV has greater final overall emissions than the P-HV due to the significant increase in the emissions associated with the manufacture and replacement of the batteries. The overall lifecycle contribution of the fuel decreases as vehicles become more electrified. The fuel contribution for the ICE is 82 %, while the P-HV and EV have fuel contributions of 55 % and 13 % respectively.

The slope of the EV line in Figure 10 is derived from the GEF for electricity production. As the GEF increases, the slope of the EV (and P-HV) line also increases. For countries where the GEF is greater than 0.566 kt CO_2-e/GWh_e, the adoption of EVs is counter-productive in terms of reducing overall emissions. At present New Zealand has a GEF for electricity of 0.129 kt CO_2-e/GWh_e, Australia has a GEF of 0.811 kt CO_2-e/GWh_e, and the USA has a GEF of 0.530 kt CO_2-e/GWh_e [15]. Converting significant proportions of the electricity grids in Australia and the USA to renewables and low carbon emitting fuels are needed before EVs present themselves as a viable solution to reducing carbon emissions.

Government Policy and Intervention

Governments play a critical role in setting policies that encourage the use of more efficient transport methods. For example, many highways in the USA and other countries have car-pool lanes dedicated to high occupancy vehicles (usually two or more people in a vehicle), which aims to increase the fill rate of on-road LPVs. Dedicated bus lanes in inner cities and/or adjacent to highways are also common in major cities as a way to improve the travel time on public buses, which also leads to increased fill rates. In Hasselt, Belgium the city council decided to abolish bus fares in 1997 [31]. This resulted in the number of travellers on buses increasing from 350,000 in 1997 to 4,600,000 in 2007. In 2013, the city revisited the policy and under the weight of an on-going financial recession reverted to charging adults (19+ years) €0.60 per trip. Establishing safe cycle ways is another approach targeted towards reducing the number of single passenger cars on the road. California introduced an effective financial incentive programme to encourage the uptake of P-HVs.

New Zealand can do more to promote the use of more efficient transport methods. Recently NZ’s largest city Auckland finally introduced the concept of an integrated ticket that allowed passengers to freely transit between buses and rail. In the Auckland CBD, there are several peak hour bus lanes, but the peak-hour congested highways lack dedicated high occupancy lanes. Several rail related projects are currently underway to improve the connectivity between residential Auckland and key business centres.

3.5. Transport Planning for New Zealand through to 2050 with Reduced Emissions

Table 4 and Figure 11 illustrate three scenarios for achieving transport emissions reduction to 1990 levels by 2050 using the CEPA graphical method. A variety of transport fuel options are possible for reaching the demand and emissions target.

Scenario (A) requires adoption of hybrid vehicles by LPV, LCV and buses for fuel savings of 77 PJ, P-HVs and EVs in the LPV class enable replacement of 46 PJ of liquid fuels with 3.6 TWh electricity from the national grid (4.8% of ~75 TWh total). Freight and city rail is electrified replacing a thermal fuel need of 2.9 PJ with 0.3 TWh of electricity. The remainder of the transport demand is met using liquid fuels from biomass of 46 PJ and oil derived fuels of 155 PJ. This quantum of biofuel is the minimum requirement in 2050 to achieve the 1990 emissions level for transport. Scenario (B) is similar to (A) with the exception that oil is assumed to have such a low EROI in 2050 that it is better for Fischer-Tropsch (FT) liquid fuels from coal to be used. In this case, 169 PJ of biofuel and 32 PJ of FT fuels from coal is required to meet the emissions target. In the first instance, preference is given to producing liquid fuels from oil or coal as opposed to renewable sources due to the higher EROI resulting in a lower energy expend requirement (Figure 3). Scenario (C) assumes business-as-usual fleet efficiencies (no significant hybrid vehicle uptake) with only low EROI oil available. Rail in this case is still electrified. As a result 291 PJ of biofuels and 32 PJ of FT coal is needed to keep within the emissions target. This represents the maximum biofuels requirement for NZ in 2050.

Table 4. Options for NZ to meet 1990 emissions level in 2050.

	P-HV & EV fuel savings [PJ]	**Electrification [TWh]**	**Biofuels [PJ]**	**Oil & Gas fuels [PJ]**	**FT Coal [PJ]**
Scenario A	77	3.9	46	155	-
Scenario B	77	3.9	169	-	32
Scenario C	0	0.3	291	-	32

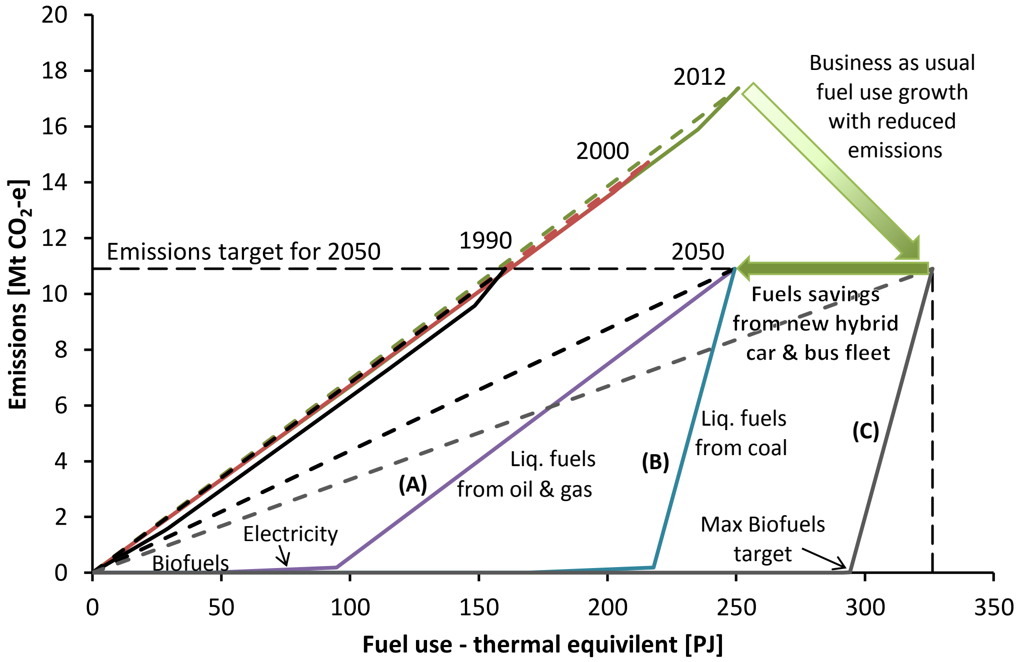


Figure 11. Emissions – fuel use composite curves to meet 2050 over all transport demand for (a) 1990 and (b) 2011 emissions cap.

These scenarios assume that existing transport modes continue to be used in a similar manner and similar amount per capita as in 2012. Further emissions reduction can be achieved with further transport mode substitution, for example more freight by rail and marine rather than truck and LCV and more public transport by light rail and bus, and even more cycling. As public transport infrastructure improves in Auckland and between and in high population urban centres within the Auckland-Hamilton-Tauranga growth triangle, more cost competitive low emission alternate transport options to road like rail, bus and cycling will increase in use overtime. Government initiatives, emission reduction priorities and the falling EROI of oil based transport fuels reflected in higher prices will play an important role in this change.

The challenge of meeting the 1990 emissions level in 2050 critically depends on the local production of biofuels, most likely from waste biomass from forestry. This needs to be done with the minimum amount of extra energy being expended by the economy to ensure that the transition to a new fuel source does not reduce NZ's economic competitiveness. How that will be achieved is a research priority for NZ which requires the careful consideration of all the

natural energy resources of NZ and for opportunities for industrial symbiosis for improved EROI of the biofuel.
The anticipated transport supply and demand profiles for freight and passenger transport from Scenario (A) in 2050 is compared to the profiles for 2012. Where a transport mode requires a liquid fuel, emissions is determined using a weighted emissions factor (53.5 kt CO_2-e/PJ) for renewable biofuel (zero emissions) and liquid fuel from oil (69.3 kt CO_2-e/PJ). LPVs benefit significantly from increased overall efficiency from the uptake of hybrid systems and from the integration of electricity as a main power source.

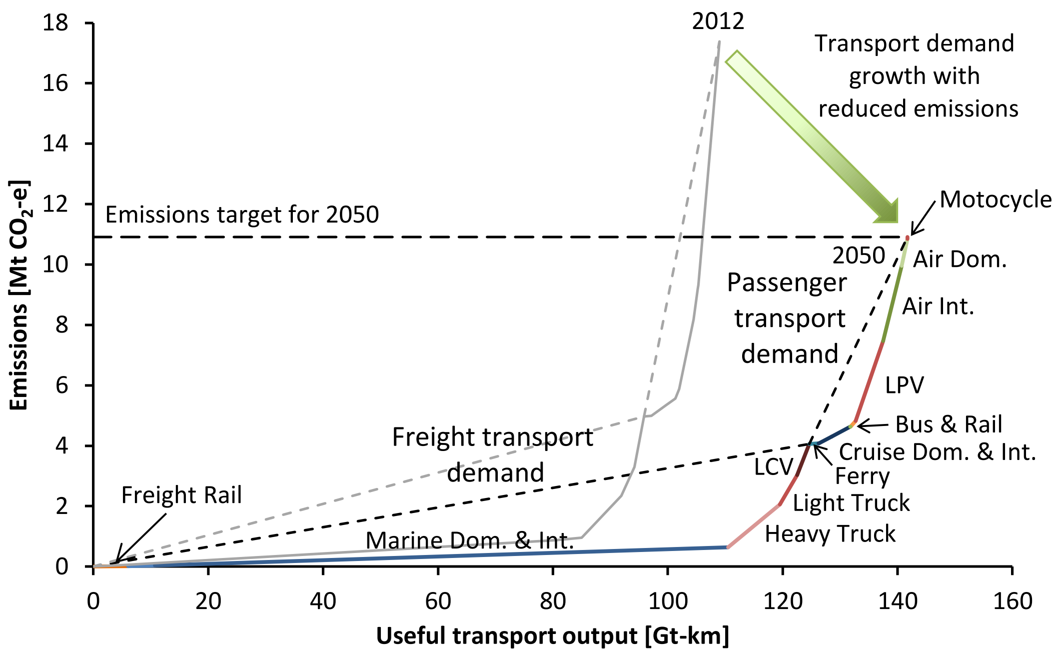


Figure 12. Combined emissions composite curve for freight and passenger transport supply and demand in New Zealand for 2050 Scenario A compared to 2012 profiles as a benchmark.

This study shows that even with energy production and consumption becoming a significant global challenge in the future, NZ with a growing population is still well placed to reduce transport emissions to 1990 levels by 2050 while maintaining economically sustainable levels of energy expenditure. The key to NZ meeting low transport emissions and low energy expenditure in the future is the large scale up-take of hybrid and electric vehicles by LPV and LCV fleets and the production of 46 PJ of biofuels (Scenario A). EROI values for oil will continue to decline. When values reach near six alternate liquid fuel options like Coal Fischer Tropsch (FT) will become economically viable. However, Coal FT will require the production of much higher levels of biofuel (169 PJ) to maintain the 1990 emissions target (Scenario B). Producing 169 PJ of biofuels is a significant investment and resource availability challenge for NZ. Land and water resources are currently used for food, agriculture and forestry production and supply large quantities of biomass for liquid fuel energy production will add further strain to NZ’s finite natural resources.
The switch to P-HV and EV over the next 30 years is therefore critical for NZ, since it does not require using more natural resources or the building of significant new infrastructure. Slightly lower emissions will result if battery emissions are not counted in the country using them (as done here), but by the country where the battery was made. Some government policy help is also likely to be needed.
Future work will look closer at how the EROI of various fuel sources, including electricity and hydrogenated biomass from renewable hydrogen, affect the amount of energy the NZ economy

has to expend to meet future energy demands. Emissions reductions in the process heat sector will also be examined.

4. CONCLUSION

In conclusion NZ transport has the potential to reduce emissions to 1990 levels by 2050 while accounting for the increases in freight and passenger transport demand due to a rising population. Essential strategies to lower emissions include the widespread uptake of hybrid and electric vehicle technology allowing for efficient liquid fuel use and electric power, the electrification of freight and passenger rail, and the production of at least 46 PJ of renewable biofuels. With the expected increases in vehicle energy efficiency the energy requirement in PJ for transport can be fairly stagnant between now and 2050 while still meeting the required transport demand. As oil EROI decreases in the future coal FT will become economical, but to maintain 1990 emissions in 2050 biofuel production will need to increase almost three fold to 169 PJ which will require considerable local biomass resources and considerable energy investment in new biofuel plants.

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