Carbon Emissions Reduction and Net Energy Generation Analysis in the New Zealand Electricity Sector through to 2050

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ABSTRACT

Carbon Emissions Pinch Analysis (CEPA) and Energy Return On Energy Investment (ERoEI) analysis are combined to investigate the feasibility of New Zealand reaching and maintaining a renewables electricity target of above 80% by 2025 and 2050, while also increasing electricity generation at an annual rate of 1.5%, and with an increase of electricity generation in the distant future to accommodate a 50% switch to electric vehicle transportation. To meet New Zealand's growing electricity demand up to 2025 the largest growth in renewable generation is expected to come from geothermal generation (four-fold increase) followed by wind and hydro. To meet expected demand up to 2050 and beyond, including electric vehicle transportation, geothermal generation will expand to 17% of total generation, wind to 16%, and other renewables, such as marine and biomass, will make up about 4%. Including hydro, the total renewable generation in 2050 is expected to reach 82%.

INTRODUCTION

New Zealand (NZ) is a remote island country in the South Pacific with a population of 4.4 million, expected to reach 5 million by 2026. NZ is well endowed with energy resources. Both renewable and non-renewable energy sources are available for electricity generation with hydro, geothermal, wind and biomass accounting for a little less than 80% of generation in 2011. Coal, natural gas and biomass are available for process heat and traditional Vapour Cycle and Gas Turbine Combine Cycle thermal electricity generation. Liquid fuels for transport and off grid power generation, however, are not available domestically and imported crude oil supplies the nations' needs. How NZ will meet its' growing energy needs into the future is a matter of considerable interest. It is anticipated that to meet its energy demand for electricity through to 2050, significant on-going renewable and non-renewable resource development and plant investment will be require.

There is a strong political will within NZ to see continued growth in the renewable electricity generation sector. In 2007 the NZ Government set a 90% renewable energy target for the electricity sector to be met by 2025 [1]. To help achieve this goal the Government legislated against any new fossil fuel based generation for a 10 year period from 2008. The moratorium was later repealed after a change of Government in 2008; although a high renewables target has remained a key strategy for reducing NZ greenhouse gas (GHG) emissions and for creating a sustainable energy future for NZ.

NZ already has a high proportion of renewable generation mainly due to the large amount of hydro generation (77% in 2011) [2]. However, almost all of the "easy" hydro generation capacity has been fully utilised and hydro storage capacity is limited to about two months, which leads to supply concerns during dry years. In 1992 and 2008 there was a severe nationwide drought causing very low hydro lake levels, which then required increased generation from thermal plants. A large pump storage project that triples hydro lake storage capacity to six months has been proposed and detailed hydrological modelling suggests the impacts of the drought in 1992 on the electricity sector could have been averted [3]. The pump storage plan for improving security of electricity supply also needs to complement water storage plans for irrigating farms in the Canterbury plains area and this is a topic of on-going investigation.

NZ has large lignite and bituminous coal reserves and the future use of these fuels for electricity and potentially liquid fuels production continues to be debated. For now cheap imported coal from Indonesia and easy to access domestic coal is used in some thermal power stations. Harder to mine deposits are being left for a time when the energy extraction and environmental cost are competitive with the alternatives.

A high renewables target for electricity generation is considered to be a realistic aspiration for NZ. However, as the ‘easy’ renewable energy sites get used up the energy needed to be expended to get the next usable quantity of energy gets progressively higher, and the Energy Return on Energy Invested (ERoEI) will conversely decline. More analysis of the actual effect of such a renewables target stretching beyond 2025 to 2050 on the generation mix, emissions levels, economic costs to the country, and security of supply is needed. Analysis as to possible electricity generation scenarios needs to consider both carbon emissions and the declining ERoEI for each renewable and non-renewable resource.

Geothermal generation while considered renewable can have a significant ‘carbon footprint’ depending on the geology and associated geothermal systems of the area. Hydro power can also have a significant ‘carbon footprint’ if the hydro lake formed removes large amounts of vegetation from the landscape [4]. These site specific carbon emission or environmental factors need to be accounted for in any analysis. This paper will use a method known as Carbon Emissions Pinch Analysis (CEPA) and Energy Return on Energy Invested (ERoEI) to examine the implications of a high renewables target and a growing energy demand on the generation mix and emissions levels in 2025 and 2050 in NZ. Some per capita CEPA comparisons will also be made with Australia and the USA.

CARBON EMISSIONS PINCH ANALYSIS

Carbon Emissions Pinch Analysis (CEPA) was first developed by Tan & Foo and co-workers and is based on the application of traditional Pinch Analysis techniques used in heat and mass integration to minimise energy and water usage [5-7]. Emissions targeting was originally confined to total site analysis, which focused on optimisation and emissions reduction of industrial sites [8]. CEPA extends the pinch analysis technique from industrial sites to broader macro-scale applications and can be readily applied to the electricity generation sector [9], although it can also be applied to primary energy usage. Sectorial and regional studies can also be conducted for emissions planning and reduction.

A brief explanation of the technique is presented here; however for a detailed explanation of the methodology for constructing composite curves see Tan & Foo [5] and Foo *et al.* [7]. The basis of the technique is constructing what are called composite curves of both the electricity demand and supply. These composite curves are then manipulated and modified depending on the desired objectives. Example demand and supply composite curves are illustrated on the left in Fig. 1 for the data given in Table 1. The supply composite curve is constructed (shown as the solid black line in Fig. 1) by plotting cumulatively the quantity of electricity generated for the several fuel sources against total emissions from those sources. The fuel source with the lowest Emissions Factor (EF) (the amount of emissions produced per unit of electricity e.g. $ktCO_2$-e/GWh) is plotted first, followed by the next highest and so on. The slope of the line is equal to the emissions factor. All emissions factors are expressed as carbon dioxide equivalent and include all relevant greenhouse gases.

The demand composite curve (dashed line) is also constructed using the same method as the supply composite curve however as a first approximation it can be assumed that the emissions from the various demand sectors is proportionate to the electricity usage and therefore will produce a straight line from the origin to the end of the supply composite curve. The demand curve could consider demand by sector, as in this case, or also by region. The ends of the total supply and demand composite curves should coincide. The slope of the demand line then is known as the Grid Emissions Factor (GEF), which is simply the average total emissions factor or specific emissions for the entire system. In this example the GEF is equal to 1 $ktCO_2$-e/GWh.

Table 1. Example electricity and emissions scenario

	Quantity (GWh)	**Emissions ($ktCO_2$-e)**	**Emissions Factor ($ktCO_2$-e/GWh)**
Demand			
Industrial	350	350	1
Residential & Commercial	650	650	1
Total Demand	**1000**	**650**	
Supply			
Renewables	300	0	0
Fuel A	400	200	0.5
Fuel B	300	800	2.67
Total Supply	**1000**	**1000**	

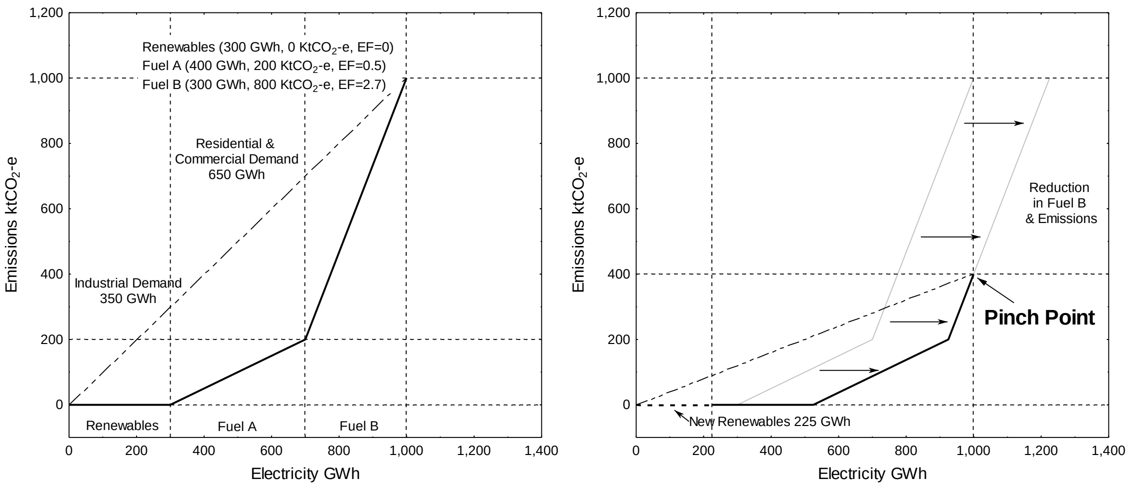

Fig. 1. Example demand and supply composite curves

Once the composite curves are constructed for the base case, a new demand curve is drawn that ends at the target demand and emissions levels. The graph on the right in Fig. 1 illustrates a new demand curve with no increase in demand but a 600 $ktCO_2$-e decrease in the emissions levels. The supply composite curve is shifted to the right until the supply and demand curves intersect and the point at which they cross is known as the “Pinch Point”. The amount that the supply has been shifted then becomes the amount of renewables (zero emissions) that need to be added in order for the target to be met. The overhang of the supply curve to the right of the pinch point represents the amount and type of generation that needs to be substituted with renewables. The amount of renewables needed to meet the target would need to be increased if fuel types below the pinch point were substituted instead of those above. Likewise if non-zero emission generation sources are substituted instead the generation profile would also be different for the target to be met. In this example the amount of generation from Fuel A could be increased in addition to adding renewables in order to reach the targets, however it is clear that this amount is constrained by the pinch point. CEPA may be also applied to compare the unique electricity generation and carbon emission profiles between countries using a per capita basis.

ENERGY RETURNED ON ENERGY INVESTED ANALYSIS

Another important measure that needs to be factored in to energy generation planning is the Energy Returned on Energy Invested (ERoEI) [10]. Equation 1 defines how ERoEI is calculated for a given energy project.

$$ERoEI = \frac{\dot{E}_{gen}}{\dot{E}_{\exp}} = \frac{\dot{E}_{gen}}{\sum (E_{con} + E_{dec})/t_{life} + \dot{E}_{ex} + \dot{E}_{par}} \quad (1)$$

Where $\dot{E}_{gen}$ is the gross useful energy generation per year, t_{life} is the expected lifetime of the plant and $\dot{E}_{\exp}$ is the energy expended for extracting ($\dot{E}_{ex}$) and processing ($\dot{E}_{par}$) the natural resource including construction (E_{con}) and decommissioning (E_{dec}) of the heat or power plant. Fig. 2 illustrates how energy is both expended and generated through-out the lifetime of a project. Projects with high ERoEI are desirable and are typically the first to be implemented. Where the ERoEI is less than unity, it means that a project has a net energy consumption rather than generation.

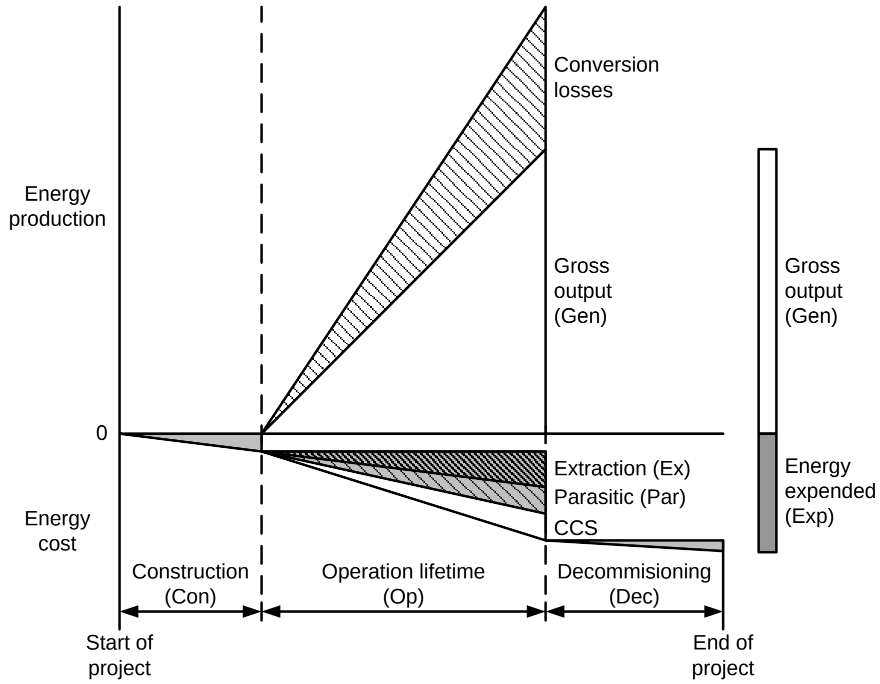

Fig. 2: Analysis of energy generation and expended across the lifetime of a typical energy generation project.

In the early stages of new technology development, the ERoEI can often be low, even less than one (Fig. 3). However, as the new technology matures and more efficient extraction and energy generation techniques become available, the ERoEI for a natural resource can vastly improve. Often it is during the technology development phase that Governments provide funding to develop the expertise and technology relevant to their country's natural resource profile. As focus shifts from small-scale operation to large-scale operation, a significant reduction in the energy overhead may occur resulting in an increase in ERoEI. Once the technology is economically competitive with the existing energy generation techniques, large scale implementation occurs. For small countries, such as NZ, the risk and cost associated with the technology development phase can often be too great for significant forward investment and, as a result, technology is imported.

The first energy generation projects should target projects where the ERoEI is greatest. As more of a country's available renewable and non-renewable resources are exhausted due to growth in energy demand, projects with lower ERoEI are implemented until each resource is completely depleted or fully utilised, as is the case for renewable energy. Typically the quality and the ease of extraction of a resource degrade as more of the resource is accessed. However, new exploration that locates high quality resources is always a possibility to again lift the ERoEI. Fig. 3b plots the energy generation against the energy expended over the life time for a given natural resource. The resulting slope of the curve is the inverse of ERoEI, where shallower slopes indicate high ERoEI and steeper slopes represent poor ERoEI.

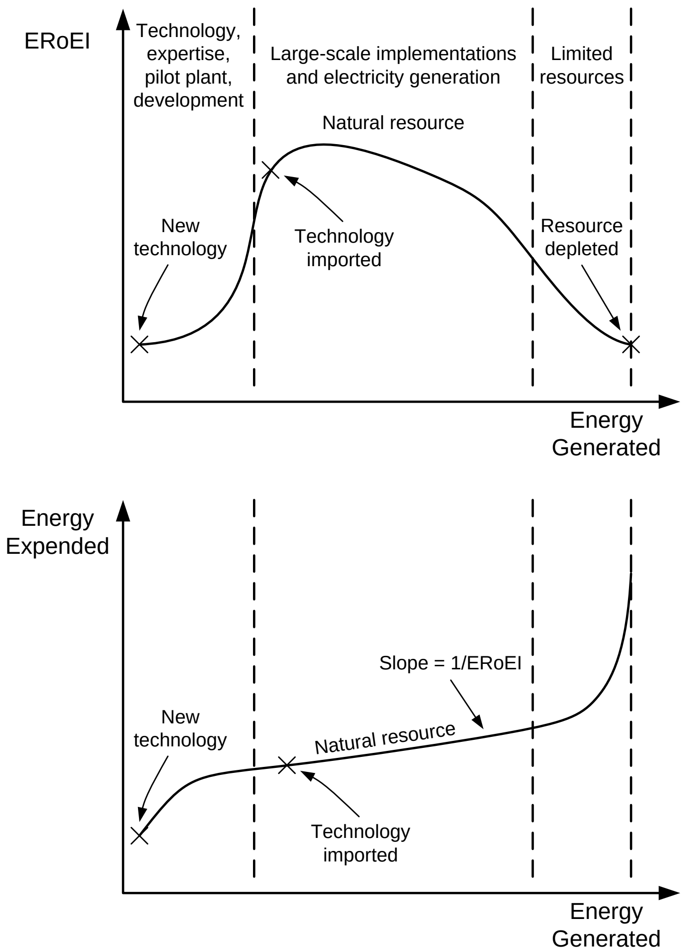

Fig. 3. The influence of technology development and availability of natural resource on ERoEI (a) and the energy expended to utilise the resource (b)

The ERoEI varies greatly depending on the type and quality of the natural resource and the technology available to extract and the conversion efficiency to generate useful energy (Fig. 4). Hydro is a renewable resource with one of the highest ERoEI; however, its value is highly dependent on the geography. At present, coal in NZ has a reduced ERoEI due to environmental and political regulation that discourage coal mining even though good quality coal is available.

As a result NZ power plants import coal rather than burn their own because the economics and the ERoEI are favourable to do so. In the 1930's oil had an estimated ERoEI of 100, which has declined as the extraction and new exploration of oil has become more difficult resulting in more modest ERoEI values.

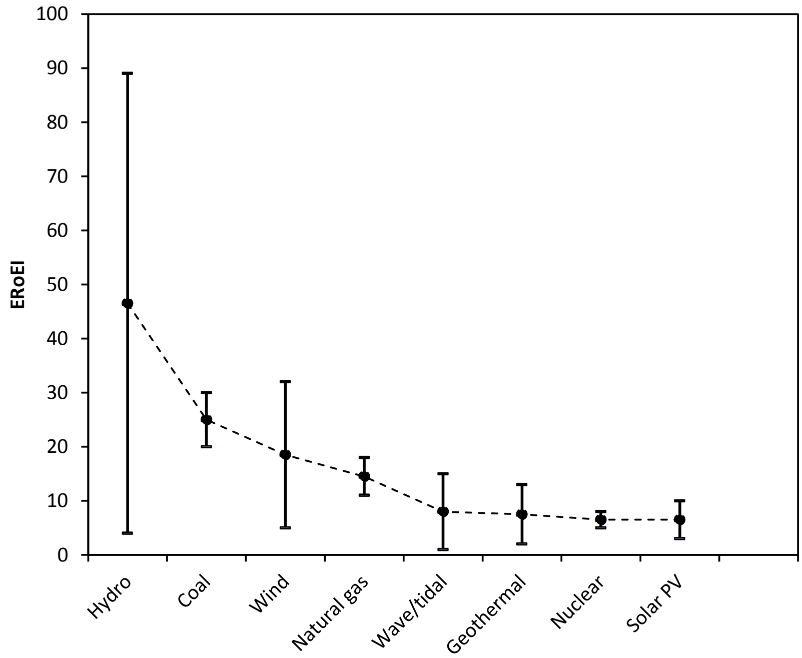

Fig. 4: Typical ERoEI values for various resources to produce electricity. Data taken from the review of Gupta and Hall [10]

Traditionally, ERoEI has been calculated without respect to carbon emissions and its associated energy cost (Equation 1). To account for the varying carbon emissions from the energy generation sources, an energy penalty for carbon emissions may be included to calculate an equivalent carbon reduced or carbon neutral ERoEI defined as ERoEI* for electricity (Equation 2).

$$ERoEI^* = \frac{\dot{E}_{gen}}{\sum\left(E_{con} + E_{dec}\right)/t_{life} + \dot{E}_{ex} + \dot{E}_{par} + \dot{E}_{ccs}} \quad (2)$$

Where E_{CCS} is the energy required for Carbon Capture and Storage (CCS). E_{CCS} may be calculated using

$$\dot{E}_{CCS} = \dot{E}_{gen}\left(\varepsilon - \varepsilon_{acc}\right)P \quad (3)$$

Where ε is the equivalent carbon emissions factor in ktCO$_2$-e/GWh$_{ele}$, ε_{acc} is the acceptable carbon emissions factor and P is the energy penalty associated with CCS in GWh/kt CO$_2$-e. When ε_{acc} is set at zero (as is done in this study), it compares the ERoEI* for each technology/resource as if they were carbon neutral. The value of P is subject to the specific CCS technology. In this study P is assumed to be 0.15 and 0.30. Substituting Equation 3 into 2 gives

$$ERoEI^* = \frac{\dot{E}_{gen}}{\sum\left(E_{con} + E_{dec}\right)/t_{life} + \dot{E}_{ex} + \dot{E}_{par} + \dot{E}_{gen}\left(\varepsilon - \varepsilon_{acc}\right)P} \quad (4)$$

Equation 4 may be rearranged to show the relationship to the traditional definition of ERoEI.

$$ERoEI^* = \frac{1}{\frac{1}{ERoEI} + \left(\varepsilon - \varepsilon_{acc}\right)P} \quad (5)$$

The idea of composite curve similar to CEPA may be applied to concepts of ERoEI and ERoEI*. The composite curve of the various energy generation resources may be created by plotting total energy expended on the y-axis and total energy generated on the x-axis so that the a slope of curve is equal to the inverse of ERoEI (or ERoEI*).

NEW ZEALAND ELECTRICITY SECTOR

The electricity generation-carbon emission profile of NZ is compared against Australia (Aus) and the United States (USA) on a per capita basis for 2011 (Fig. 5). The generation demand levels in the USA and Australia are met by consumption of fossil fuels by gas and coal, compared to NZ where renewables make up a much higher proportion of the generation mix, yielding much lower per capita emissions. The USA has a lower emissions per capita compared to Australia due to a significant nuclear generation that has very low emissions. The generation mix in each country is clearly unique and a reflection of the range of exploitable energy resources – renewable and non-renewable – available in the country. This is clearly demonstrated by the high utilisation of hydro and geothermal generation in NZ which has been endowed with large reserves of easily recoverable hydro and geothermal resources for its population base. Where easy to exploit renewable energy resources are limited, countries are forced to either constrain energy use, burn more fossil, or install nuclear plants to cover the shortfall. As a result, in these countries the emissions per capita is controlled by the proportion of fossil fuel to nuclear electricity generation. For example, France has the lowest per capita carbon emissions in the developed world due to 75% of its electricity generation coming from nuclear power [11].

The electricity generation mix in NZ for the years 1990, 2006, 2007, and 2011 are illustrated in Fig. 6. The total electricity demand and emissions for NZ in 2011 were 43,138 GWh and 5,580 ktCO_2-e respectively (GEF = 0.129 ktCO_2-e/GWh) and the generation mix was 57.6% hydro, 18.4% gas, 4.7% coal, 13.4% geothermal, 4.5% wind and 1.5% other renewables. The total amount generated from renewables (including geothermal) was 77%, with the remainder from fossil-fuel based thermal generation. Emissions factors were calculated based on data from the Ministry of Economic Development (MED) Energy Data Set [3].

It is important to note that although geothermal generation is often referred to as renewable generation it does have an emissions factor and for the current scenario the aggregate emissions factors for all geothermal generation is 0.128 ktCO_2-e/GWh. This emissions factor is site specific and can vary by almost two orders of magnitude depending on the geology and fluid circulation within the geothermal field. In this work the average emissions factor is used. Individual geothermal fields and the effect on the emissions factor for NZ have previously been reported [12]. Similarly if a lifecycle approach is taken, all of the renewable generation sources have emissions factors due to construction, materials, maintenance, and the like. Lifecycle emission factors reported in the literature vary considerably depending of the technology and location [13]. For example, estimates for wind generation range from around 0.013 ktCO_2-e/GWh for heavy foundations in Japan (load factor of 25%) to 0.0025 ktCO_2-e/GWh for offshore wind in the UK (load factor of 30%) [14]. Similar variation is found for other renewable technologies such as hydro, biomass, and for nuclear. Obviously there is great uncertainty in the estimates of life cycle emissions due to differences in the assessment methodology, conversion efficiency, and the like. Despite the variation, the life cycle estimates for wind and hydro are typically at least one to two orders of magnitude lower than geothermal and fossil-fuel based thermal generation and therefore the life cycle emissions have been ignored in this analysis.

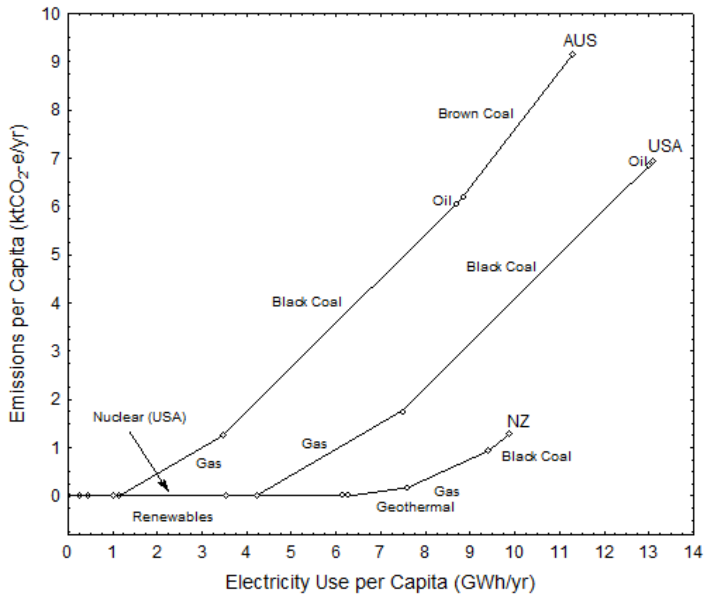

Fig. 5. Comparison of generation mix profiles between countries on a per capita basis in 2011

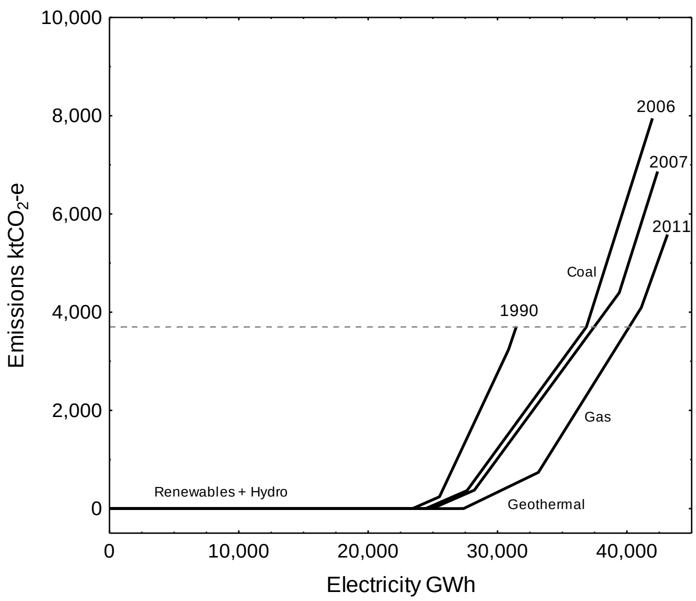

Fig. 6. A comparison of carbon emissions and electricity generation in New Zealand for 1990, 2006, 2007, and 2011

The generation mix from 1990 to 2011 has changed significantly with the bulk of the increased generation coming from geothermal (which has doubled from 1990 to 2006 and then roughly doubled again from 2006 to 2011) and the remainder from a large increase in natural gas and coal (Table 2). Only a minor increase in generation from hydro or wind has occurred since 1990. It should also be pointed out that the emissions factors for coal and natural gas have improved slightly since 1990 as a result of efficiency increases due to the increased use of combine cycle gas turbines for example.

Emissions from the electricity sector have almost doubled from 3,700 $ktCO_2$-e in 1990 to just less than 5,600 $ktCO_2$-e in 2011. Emissions peaked in 2005 and 2006 when emissions were around 8,000 $ktCO_2$-e. There was a 14% reduction in emissions from 2006 to 2007 due to the replacement of coal with natural gas. Emissions continued to decrease from 2007 to 2011, with a further reduction in coal fired generation and a doubling of geothermal generation. The average emissions factor from geothermal generation increased 15% from 0.115 to 0.128 $ktCO_2$-e/GWh due to the geology and location of the new geothermal generation.

A plot of the estimated energy expended per annum against annual electricity generation in NZ for each resource is presented in Fig. 7. The energy expended values are estimated using the mid-point ERoEI values of Fig. 4. For New Zealand the average ERoEI across the electricity sector is about 20, which is mainly the result of a high percentage of renewable hydro generation. A notable difference between Figs. 6 and 7 is the order and ranking of the resources. In particular, from an energy return point of view, coal is extremely favourable and advantageous, but it comes at the possible environmental cost of increased CO_2 emissions. As a result, for some resources there is a conflict between achieving a high ERoEI while minimising emissions.

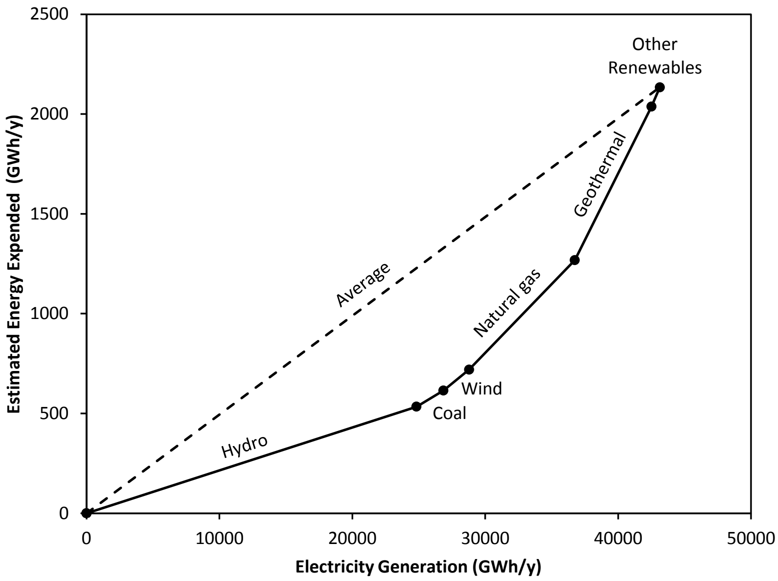

Fig. 7. The estimated annual cumulative energy expended for New Zealand electricity generation in 2011

To compare resources it would be fairer to compare on a common carbon basis, e.g. a similar carbon level or a carbon neutral level. This is done in Fig. 8 using Equation 4 where the energy expended $\dot{E}_{\exp}$ including the energy to remove carbon emissions $\dot{E}_{ccs}$ is plotted against electricity generation $\dot{E}_{gen}$ for three levels of CCS energy penalties P of 0, 0.15 and 0.3. The slopes of the lines in Fig. 8 are the inverse of ERoEI*. By including the energy penalty for carbon emissions, energy return favourability shifts in the NZ case towards low emissions renewable resources such as wind and biomass. However, it should be noted that there is significant limitations on the generation capacity of renewable resources. As a result, it is impossible to presently plan to replace all fossil fuel consumption with renewable generation while meeting a growing energy demand. Rather a balanced approach between renewable and non-renewable generation is needed until new technologies are developed to enable expanded economic renewable generation.

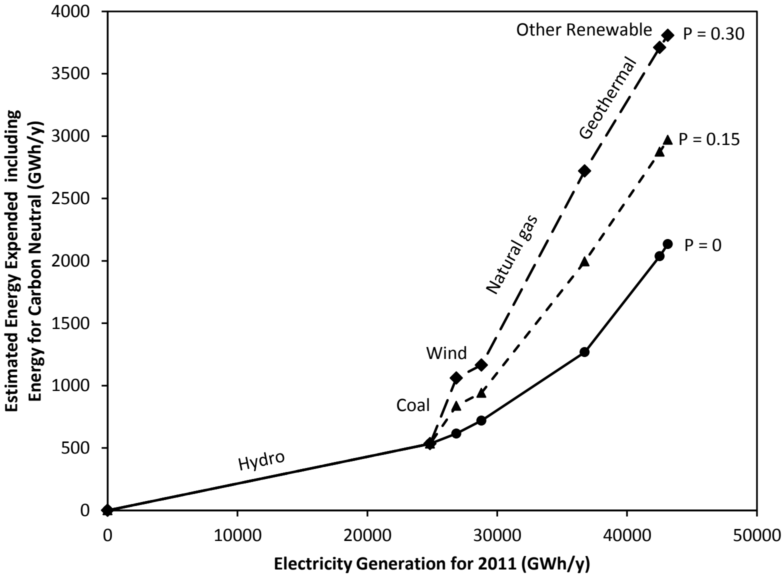

Fig. 8. The estimated annual cumulative energy expended including an energy penalty for carbon emissions for New Zealand electricity generation in 2011

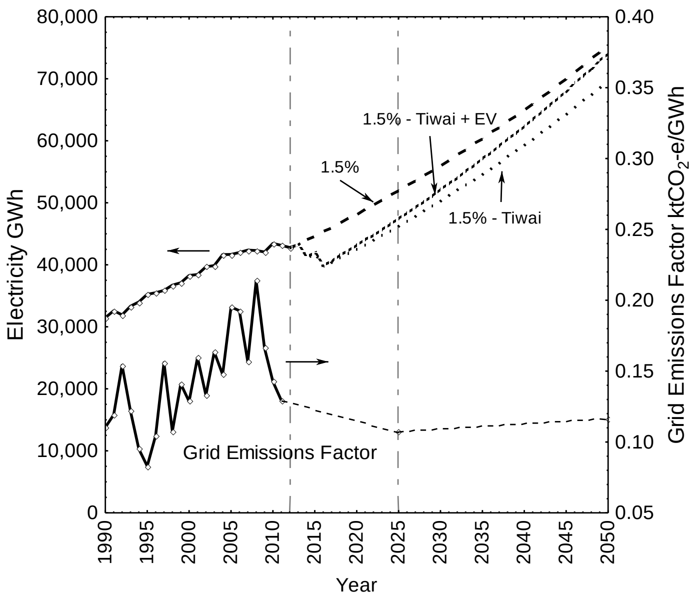

Fig. 9: Projected electricity demand growth in NZ to 2025 and 2050

NEW ZEALAND ELECTRICITY SECTOR PROJECTED TO 2025 AND 2050

The electricity sector in NZ has experienced consistent growth in the demand since 1990 and a corresponding increase in net emissions (Fig. 9). Superimposed over the natural increase in demand and generation capacity has been far reaching and significant restructuring of the electricity industry, which has had a profound effect on investment behaviour of both generators and distributors [15]. The increase in demand from 1990 to 2008 averaged 1.77%

per year and there has been an increasing trend to higher Gross Emissions factor (GEF) over the same period, which demonstrates that the increase in demand has been satisfied predominantly by fossil-fuel based generation. The GEF is sensitive to the generation mix and also the level of the hydro storage lakes, which is illustrated by the sharp jump in the GEF in 1992 due to a “dry year' and low hydro lake levels. As a result of the Global Financial Crisis in 2008, the growth in electricity demand has reduced somewhat, however growth rates are expected to return to traditional levels from 2012 due to the relative strength of the NZ economy. Three scenarios for future demand are shown: (A) a 1.5% per year increase in demand, (B) a 1.5% per year increase and the gradual closure of Tiwai Point Aluminium smelter, and (C) a 1.5% per year increase and the gradual closure of Tiwai Point Aluminium smelter plus a gradual uptake of electric cars (390,000 by 2025, and 1,300,000 by 2050).

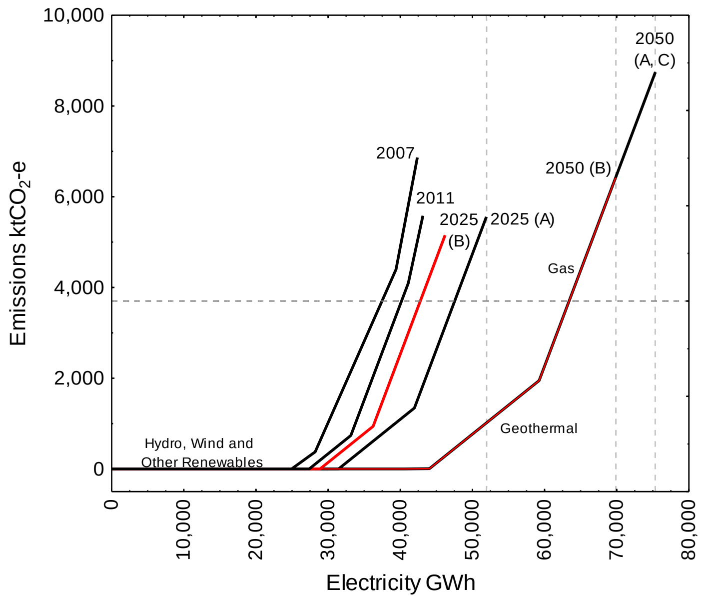

Fig. 10. Projected electricity generation growth in NZ for 2025 and 2050

Table 2. Existing electricity capacity and generation in 2011 and new capacity and generation needed to meet demand in NZ for 2025 and 2050

	2011		2025 A		2025 B		2050 A, C		2050 B	
	Capacity MW	Gen. GWh	Capacity MW	Gen. GWh	Capacity MW	Gen. GWh	Capacity MW	Gen. GWh	Capacity MW	Gen. GWh
Wind	750	1931	800	2102	200	526	3000	7884	3000	7884
Hydro	5670	24831	300	1314	150	657	600	2628	600	2628
Geothermal	730	5770	600	4730	200	1577	600	4730	600	4730
Other renewables	300	627	130	654	60	319	750	2046	750	2046
Gas	1300	7955	-	-	-	-	1000	6132	100	613
Coal	350	2026	-	-	-	-	-	-	-	-
Total	9100	43138	1830	8801	610	3079	5950	23421	5050	17902

The Aluminium smelter at Tiwai Point in the South Island uses approximately 13% of the electricity generated in NZ. The Manapouri hydro-dam supplies this smelter. The smelter is predicted to close over the next few years and it has been assumed that the demand form the smelter will be halved in 2014 and the smelter will completely close in 2016. This is illustrated in Fig. 9 as Scenario B and C.

The expansion of generation to meet the increased demand from 2011 to 2050 for case B while maintaining a high renewables object would require wind to increase to 16% of total generation, hydro is 45%, geothermal is 17% and other renewables like biomass, marine or solar to increase to 4%. Growth in solar thermal is unlikely due to NZ's frequent cloudy weather which limits generation. Some biomass growth is likely but overall growth will be constrained by competing use for land and for use of biomass in sustainable materials production. Marine energy has the greatest potentially for large scale adoption in the future. NZ being an island country has a vast marine energy resource. As marine energy technology moves beyond the technology development and early adopter stage to the large-scale commercial installation stage the ERoEI will improve and by 2050 some marine energy is predicted in this analysis to be present in the generation mix of NZ. If scenario B arises electricity generation in NZ will be above 80% renewable and the overall GEF will be a modest 0.097 ktCO_2-e/GWh, 70% above 1990 levels.

CONCLUSION

Carbon Emissions Pinch Analysis and carbon equivalent Energy Return on Energy Investment analysis are useful techniques for electricity sector emissions planning and targeting. Applying the methods to the NZ electricity sector demonstrate that renewable generation resources like wind and hydro are favourable from both an emissions and energy return on investment point of view, but geothermal is similar to gas. For NZ to meet a 40% increase in electricity demand by 2050 while achieving renewable generation above 80%, an extensive reduction in fossil-fuel based thermal generation will be required, and a significant increase in wind, geothermal, hydro and even marine will be required. High quality renewable energy resources are available to achieve these increases.

NOMENCLATURE

Energy used for Carbon Capture and Storage	$\dot{E}_{CCS}$
Energy used in construction	E_{con}
Energy used in decommissioning	E_{dec}
Energy used in extraction	$\dot{E}_{ex}$
Electricity generation	$\dot{E}_{gen}$
Equivalent total electricity expended	$\dot{E}_{\exp}$
Parasitic load	$\dot{E}_{par}$
Energy returned on energy invested	$ERoEI$
Energy penalty for CCS	P
Life of a project	t_{life}
Emissions factor	ε
Acceptable emissions factor	ε_{acc}

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