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Minimising carbon emissions and energy expended for electricity generation in New Zealand through to 2050

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HIGHLIGHTS

- NZ electricity demand is estimated to reach 75 TW h/year (2050) from 43 TW/h (2011).
- New NZ generation for 2050 is best derived from geothermal, wind and hydro.
- The EROI for NZ's electricity sector will decrease from 34 (2011) to 18 (2050).
- Renewable generation is favourable over fossil fuel with CCS for CO_2 reductions.

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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 reaching and maintaining a renewables electricity target above 90% through to 2050, while also increasing electricity generation at an annual rate of 1.5% while allowing for a 50% switch to plug in electric vehicle transportation for personal use vehicles. Under this scenario NZ's electricity demand is anticipated to reach a maximum of between 70 and 75 TW h by 2050. If NZ is carbon emissions constrained to 1990 levels, to minimise energy expended, electricity growth will predominantly come from wind (18 TW h) and geothermal (13 TW h), and hydro (5.6 TW h) to a lesser extent. Renewables resources will produce nearly 95% of electricity generation. The analysis demonstrates that NZ is in a very good position to sustainably meet their future electricity needs while maintaining very low carbon emissions levels and economically desirable EROI levels.

1. Introduction

New Zealand (NZ) is a remote island country in the South Pacific with a population of 4.4 million, expected to peak at 6 million between 2040 and 2060 [1]. NZ is well endowed with energy resources. Both renewable and non-renewable energy resources 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 thermal electricity generation. Liquid fuels for transport and off grid power generation, however, have limited availability domestically and imported crude oil supplies the nations' needs.

There is strong political will within NZ for 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 [2]. To help achieve this goal a 10 year moratorium against new fossil fuel based generation beginning in 2008 was legislated. The moratorium was repealed in 2008 after a change of Government; although a high renewables target has remained a key strategy for reducing NZ greenhouse gas (GHG) emissions and for creating a more 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) [3]. However, almost all of the attractive 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 [4].

It is generally accepted that a high renewables target for electricity generation is a realistic and achievable aspiration for NZ. However, as the best renewable energy sites are utilised first the energy expended to generate the next usable quantity of energy gets progressively higher, and the Energy Return on Energy

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Invested (EROI) will conversely decline. More analysis of the actual effect of a 90% renewables target stretching beyond 2025–2050 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 [5].

In addition to economic considerations, environmental impacts of electricity generation through carbon, water [6], and land footprints [7] also play an important role when deciding how best to increase generation. Carbon Emissions Pinch Analysis (CEPA) developed by Tan and Foo [8] is a useful graphical technique to express the impact of electricity generation in terms of carbon footprint for individual plants/resources and for the sector as a whole. Geothermal generation while considered renewable can have a significant carbon footprint depending on the geology and associated geothermal systems of the area. New hydro power can also have a carbon footprint if the hydro lake formed removes large amounts of vegetation from the landscape [9]. These site specific carbon emission or environmental factors need to be accounted for in energy planning analysis. Economic factors that can also affect energy planning include security of supply, amortised total cost, type of electricity market and need for local employment opportunities.

It is anticipated that the declining EROI of fossil fuels will have a significant impact on the economic vitality of national economies [7]. Likewise switching to renewable energy sources with lower EROI values may have a negative impact on economies because of the strong link between EROI and quality of life. Although EROI and CEPA approaches have been separately used for emissions targeting and energy planning, the trade-off between the energy cost and the associated emissions cannot easily be determined. The minimisation of energy costs and environmental targets are usually contradictory objectives which means improving in one objective results in sacrificing the other [9]. A number of approaches have been developed to account for this trade off, including a cost based criterion for carbon emissions/energy production optimisation [10], plus a general modelling approach for optimal planning of energy systems subject to carbon and land footprint constraints [11].

The aim of this paper is to apply CEPA and EROI analysis to planning how NZ can best meet future electricity demand for a population that is anticipated to peak in 2050, while also meeting the goal of 90% renewable generation and lower environmental impacts in terms of carbon footprint. Energy generation methods are analysed through spreadsheet optimisation to determine the 2050 generation mix that meets 1990 or 2011 emissions levels, while minimising energy expended.

The work combines for the first time CEPA and EROI analysis, to a national case study, with and without carbon capture and storage (CCS) as an energy penalty. EROI analysis is extended to include thermal energy required to capture and store carbon emissions so that renewable and non-renewable electricity generation resources/technologies may be compared on a carbon neutral basis. The novel approach enables more realistic economic constraints to be applied to the CEPA planning method. Carbon emissions per capita for NZ are also compared to Australia and the USA. Predicting future electricity demand in NZ includes a growth rate of 1.5%, closure of a NZ aluminium smelter (which is 15% of current electricity consumption in NZ) and the 50% uptake of plug-in electric vehicles in the private transport sector.

2. Theory and methods

2.1. 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 [8,10,11]. Emissions targeting was originally confined to total site analysis, which focused on optimisation and emissions reduction of industrial sites [12]. CEPA extends the pinch analysis technique from industrial sites to broader macro-scale applications and can be readily applied to the electricity generation sector [13], although it can also be applied to primary energy usage. Sectorial and regional studies can also be conducted for power systems emissions constraint planning with CCS [14] including retrofitting [15] and for multi-period scenarios [16] and variable CO_2 sources and CO_2 sinks [17].

A major aspect of CEPA involves the construction of supply composite curves that plot cumulatively the quantity of electricity generated for the several fuel sources against total equivalent carbon emissions (CO_2-e) from those sources. The fuel source with the lowest Emissions Factor (EF) (the amount of emissions produced per unit of electricity e.g. kt CO_2-e/GW h) 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 Grid Emissions Factor (GEF) 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 Fig. 1. Fig. 1A presents the current supply and demand for electricity and the associated emissions of 1000 kt CO_2-e. If the new emissions target reduces to 400 kt CO_2-e (Fig. 1B), the demand profile now meets the supply profile causing a pinch. From the pinch point two options for achieving the emissions target based on Fuel A with renewables and Fuel B with renewables are shown. There are many other combinations of fuels and renewables that can achieve the target, but options A and B are important limits bounding the various combinations. Option A uses renewable energy to lower emissions by 600 kt CO_2-e whereas option B lowers emissions by switching fuels from B to A and adding renewables. Since option B maximises the use of fuel A, which has the second to lowest emissions factor, this option represents the minimum quantity of renewables needed to be sourced to achieve the emissions target. For further information about CEPA, the reader is referred to Tan and Foo [8] and Atkins et al. [18] for a detailed outline of the method.

2.2. Energy returned on energy invested analysis

EROI as a concept is essentially the ratio of the amount of useful energy produced to the amount of energy expended in order to generate the unit of useful energy. The concept was first proposed by American systems ecologist Hall et al. [19]. The useful energy 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 [20]. The EROI method traditionally uses a first law of thermodynamic analysis approach

Table 1
Example electricity and emissions scenario.

	Quantity (GW h)	Emissions (kt CO_2-e)	Emissions Factor (kt CO_2-e/GW h)
Demand			
Industrial	350	350	1.0
Residential & commercial	650	650	1.0
Total demand	1000	1000	1.0
Supply			
Renewables	300	0	0
Fuel A	400	200	0.5
Fuel B	300	800	2.67
Total supply	1000	1000	1.0

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