Energy Return on Energy and Carbon Emissions Investments for New Zealand Wind Energy Farms

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ABSTRACT

This paper analyses the Energy Return on Energy Invested (EROI) and Energy Return on Carbon Emissions (EROC) of current wind farms in New Zealand. The weighted average EROI for a New Zealand wind energy farm over a 20 year life span is 35, with some sites above 50, while others are as low as 6.5. These values are higher than many other electricity generation methods reported in the literature with hydropower being the main exception. The average EROC value for NZ wind energy farms is 0.477 GJ/kg CO_2-e, which is 56 times the EROC of a combined cycle natural gas power station. The substantial range of EROI values are driven by two factors: (1) average wind speeds for a given site and (2) the blade diameter of the turbine, where larger is better. Future work will include an economic analysis of the wind farms.

KEYWORDS

Wind energy, energy ratio analysis, Energy Return on Investment, Life Cycle Analysis, energy planning, carbon footprint.

INTRODUCTION

An overarching goal of the current New Zealand (NZ) Energy Strategy is to increase the share of renewable electricity generation to greater than 90 % by 2025. Available renewable generation sources in NZ include hydro, wind, geothermal, solar and biomass. In 2015 about 80 % of the grid, up from 65 % in 2008, was from renewable hydro, geothermal and wind. A more recent Government set target is part of the 2015 Paris Accord, which is to reduce carbon emissions to 30 % below 2005 levels by 2030. NZ electricity generation accounts for 19 % of emissions in NZ and so the electricity sector has a role to play in achieving this target.

Consistently high average wind speeds are critical to making wind an economically viable generation option. NZ has a great wind resource, with the Cook Strait and Manawatu gorge channelling strong winds to create excellent wind energy resource. Most NZ farms operate at an average capacity factor of at least 30 %, with some individual turbines achieving over 50 %. Denmark, a world leader in wind energy uptake, experiences slightly lower capacity factors of 25 – 30 % [1]. The average capacity factor for wind energy farms in Europe is 21 %, with the highest being 57.9 % [2].

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NZ's potential for wind energy is considerable and is an important resource for NZ to increase its renewable electricity generation. Up to 6600 MW is projected to be available across the nation [3]. Wind currently contributes 5 % of NZ electricity, which amounts to a total capacity of 621 MW. There are 23 proposals consented, under investigation or in the planning stage that total a capacity of another 3000 MW. Hydro accounts for 58 % of our total electricity generation, however the most attractive sites have already been utilised, and the damming of rivers has significant opposition and environmental impact [3]. Geothermal has increased over fourfold since 1990 to 17.2 % in 2015 and there is an estimated further 850 MW capacity of untapped economic geothermal potential [5].

The concept of an energy ratio is valuable for analysing the fundamental viability of a resource. It overcomes the uncertainty that often surrounds economic analyses around determination of various factors such as market prices, capital cost competition, and government policy. One important energy ratio that uses a Life Cycle Analysis approach, is Energy Return on Energy Invested (EROI). This ratio was originally proposed by Hall et al. [6] and continues to find relevance in very recent literature [7]. EROI for electricity production is defined as the ratio of the electrical output compared to the summation of the energy, direct, indirect and embedded, inputs. Estimates of EROI values for NZ electricity range from 25 (coal power stations) up to 41 (hydro power) [4]. A second increasingly important ratio is carbon footprint, which may be inversed to give an electricity production per unit of emission. The inverse of the carbon footprint is called the Energy Return on Carbon Emissions (EROC).

EROI can vary greatly depending on the type and quality of the natural resource, whether it be renewable or non-renewable, and the technologies used for extraction, processing and conversion [8]. Hydro is a renewable resource often with the highest but also wide range of EROI values. EROI is chiefly dependent on the water flow, hydraulic head, and geography including the volume and quality of fill needed for the dam, and much less dependent on turbine conversion technology. Other renewables like wind, wave, geothermal and solar are consistently lower than hydro. With these resources, besides geography and climate, the development of new technology significantly contributes to the EROI values. Fossil fuel derived electricity EROI values have less spread due their ongoing abundance, which is expected to taper off in the coming decades, especially if clean coal technology like Carbon Capture and Sequestration (CCS) needs to be employed. To date, there has been little work on EROI in the context of the New Zealand electricity industry and this is an area of needed work [9]. Life Cycle Analyses of embodied energy [10] and emissions [11] are reported in literature for NZ wind energy farms. However, application of EROI and EROC concepts were not part of these studies nor were consented future wind sites included. This, therefore, represents the gap in literature that is targeted in this study.

Achieving the energy and emissions targets will require intelligent use of resources to expand the electricity sector. A method is needed for comparison between prospective wind energy sites in NZ. Ideally it should compare energy cost, economic cost, greenhouse gas emissions levels, environmental impact, security of supply and local employment opportunities [4]. This investigation focuses around two of these key factors in EROI and EROC of existing and consented future NZ wind farms.

ENERGY RETURN ON ENERGY AND EMISSIONS INVESTMENTS

The production of electricity requires the investment of energy as an input and emissions as a by-product. Two useful energy ratios for describing the return on investment of electricity generation are: energy return on energy invested (EROI) and energy return on carbon equivalent emissions (EROC).

$$\mathrm{EROI} = \frac{E_{gen}}{E_{input}} \quad (1a)$$

$$\mathrm{EROC} = \frac{E_{gen}}{C_{plant}} \quad (1b)$$

The electrical output, E_{gen}, is the electricity delivered to the grid over the plant's lifetime. Energy input, E_{input}, includes the energy required to manufacture and transport all of the necessary materials and parts, construction energy, lifetime operating energy costs and maintenance, and decommissioning, over the life of the plant. Carbon equivalent emissions associated with the project, C_{plant}, is the summation of all the emissions resulting from constructing, operating, fuelling, and decommissioning the plant, over the life time of the plant. The inverse of EROC is often called the emissions footprint. The determination of EROI and EROC requires a lifecycle assessment of the energy project.

METHODOLOGY

This investigation uses consistent life cycle analysis to determine EROI and EROC for the majority of current and consented future wind energy sites in NZ. Correlations for dominant wind farm variables, such as turbine dimensions and average wind speed, are formulated using data from current sites. These correlations are applied to estimate the energy ratios for future wind projects.

Life Cycle Analysis

Life Cycle Analysis (LCA) sums all of the relevant energy and material inputs and outputs over the lifetime of a product, process, or service. LCA was used to sum all of the material and energy flows and average these over the expected 20 year lifetime of a wind farm. Two embodied energy [10] and emissions [11] analyses have been done for NZ renewables and these were used as guides for this analysis. The methods for calculating power output, roading, cabling, earth works, turbine materials, transport, and operation, are outlined in the following sections.

Actual and estimate lifetime power output

Existing NZ wind farms have public information available about the annual output of the site. To predict the output of future sites, a model was formed which determines the average power output based on the realisable wind potential of the wind at the site. NZ's National Institute of Water and Atmospheric Research (NIWA) maintain a wind energy map of NZ as presented in Figure 1. The wind data includes the power density, P, of the site in W/m^2 of footprint, based on the Vestas V67 model, assuming 12.3 $turbine/km^2$.

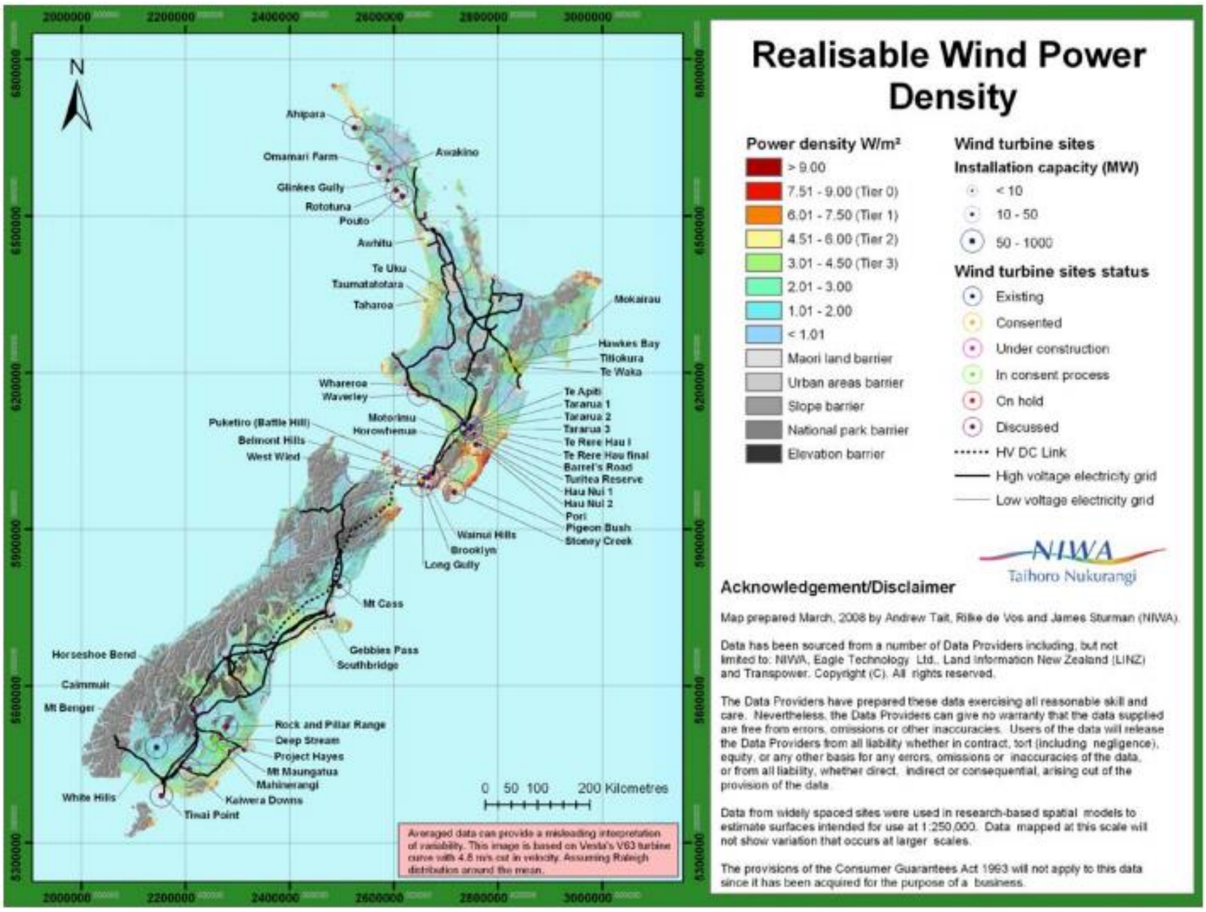

Figure 1. Wind Energy map of New Zealand from NIWA (www.niwa.co.nz)

The accuracy of the NIWA map was checked by comparing it with the output electricity data from existing farms, as plotted in Figure 2. Although the correlation is weak ($R^2 = 0.4$), the NIWA data is the only available dataset for the basis of a prediction. To account for the poor correlation, a sensitivity analysis is carried out for future wind site.

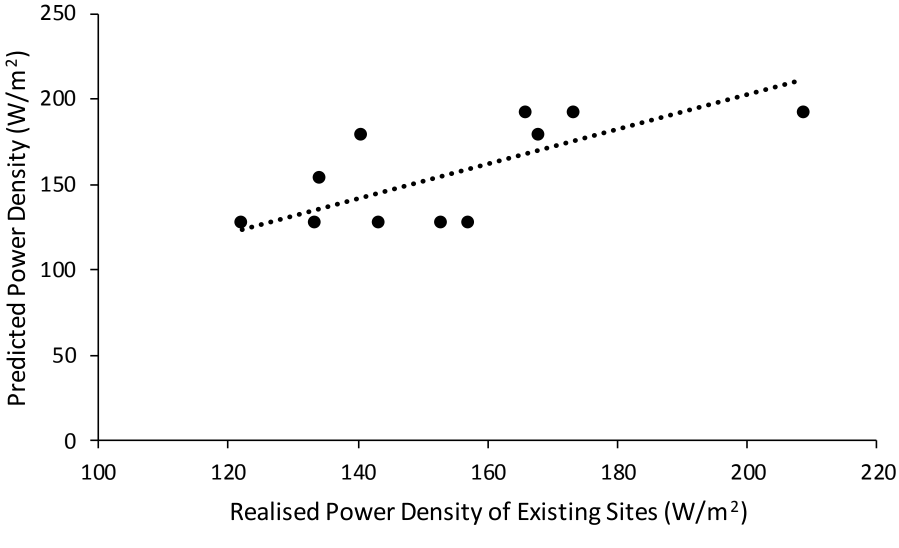

Figure 2. Comparison of NIWA map with realised power density of existing sites

Using these datasets, the correlation for predicting specific power output per turbine is

$$E_{gen}(GJ/turbine) = 12.7\, P \cdot D^2 \quad (2)$$

Wind turbines require electrical power for: (1) yaw mechanisms that keep the blades turned into the wind, (2) blade-pitch controls that meter the spinning rotor, (3) aircraft lights and data-collection electronics, (4) oil heaters, pumps, and coolers for the multi-ton gearbox, and (5) hydraulic brakes for locking blades down during excessively high wind speeds. In still conditions, the generator is used in reverse, i.e. a motor, to keep the blades moving slowly and prevent damage to the bearings. Fernando [10] estimates the operation power cost from the grid to be equivalent to 5 % of the turbines operating and maintenance cost.

Roading

The lengths of access roads, L_{main}, for new and existing sites were estimated using satellite images from Google Earth by measuring length of required roading between the wind farm and the nearest pre-existing road. The embodied energy of the road was taken as 1.86 GJ/m and the emissions as 22.6 kg/m [12].

Roading is also needed between individual turbines at a site. A detailed analysis of NZ wind farms at West Wind, Te Uku, and Tararua was performed to determine an average distance between turbines. The average distance between turbines, L_{sub}, for these three farms is 573m. This average distance is applied for future and other existing wind farm sites to estimate total roading requirements.

$$E_{road}(GJ/turbine) = 1.86\left(\frac{L_{main}}{n} + L_{sub}\right) \quad (3a)$$

$$C_{road}(kg/turbine) = 22.6\left(\frac{L_{main}}{n} + L_{sub}\right) \quad (3b)$$

Cabling

The length of underground cabling required was estimated as 1.5 times the distance between turbines [10]. The embodied energy of the cabling is 0.271 GJ/m and the emissions factor is 21.3 kg/m [11].

$$E_{cable}(GJ/turbine) = 0.407\, L_{sub} \quad (4a)$$

$$C_{cable}(kg/turbine) = 32.0\, L_{sub} \quad (4b)$$

Earth Works

There is energy associated with earth works at the site, such as digging and flattening. Specific values per turbine are taken from Rule et al. [11].

$$E_{earth} = 1.1\, GJ/turbine \quad (5a)$$

$$C_{earth} = 5{,}600\, kg/turbine \quad (5b)$$

Turbine Materials

The mass and materials of the turbine foundation, tower, blades, nacelle and hub were taken from the manufacturer's product information [13]. Figure 3 correlates the tower height with the tower mass based on product specifications given by Vestas.

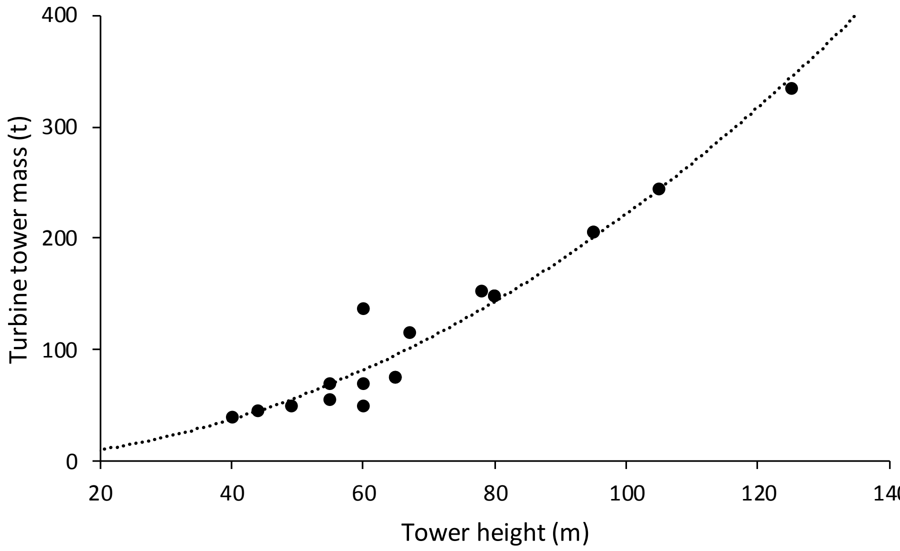

Figure 3: Relationship for estimating turbine tower mass

The nacelle (generator housing) and hub (blade mount) are structural steel with a combine mass of 87 t. The mass of the structural steel may be estimated using

$$m_{steel,1}(kg/turbine) = 0.0214\,H^2 + 0.0845\,H + 87 \qquad (6a)$$

Simple scaling laws dictate a cubic rise in blade mass with increasing turbine size. Three bladed turbines are the recommended solution. When compared to three blade designs, a 3 % loss is incurred for two bladed designs and a 7 % – 13 % loss for one bladed design. A four bladed design offers marginal efficiency increases which do not justify the manufacturing cost of an extra blade [14].

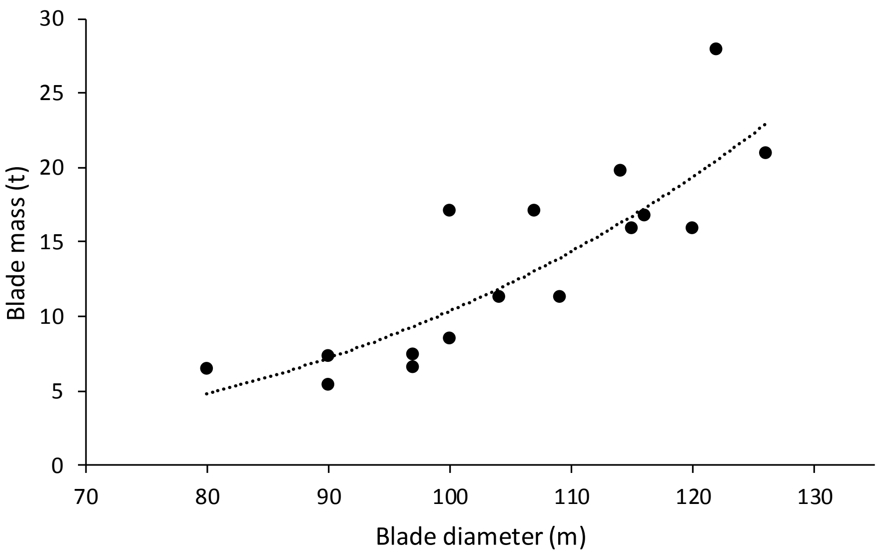

Figure 4: Power law correlation for estimating turbine blade mass

$$m_{\text{fibre glass}}(\text{kg}/\text{turbine}) = 1.37 \text{ x } 10^{-6}\ D_{\text{blade}}^{3.44} \qquad (6b)$$

The applied embodied energy per tonne of material for a gear box and generator are presented in
Table 1. The mass of concrete and reinforcing steel used in the foundation was estimated to be proportional to the tower height and the blade length [11].

$$m_{\text{concrete}}(\text{kg}/\text{turbine}) = 0.163\, H \cdot D \qquad (6c)$$

$$m_{\text{steel},2}(\text{kg}/\text{turbine}) = 0.00634\, H \cdot D \qquad (6d)$$

Table 1. Embodied Energy Factors of Wind Farm Materials and Components [11]

Component	Embodied Energy			Emissions		
Steel (Structural)	$EF_{S,S}$	31.4	GJ/t	$CF_{S,S}$	1240	kg CO_2-e/t
Concrete	EF_C	1.19	GJ/t	CF_C	150	kg CO_2-e/t
Steel (Reinforcing)	$EF_{S,R}$	8.60	GJ/t	$CF_{S,R}$	350	kg CO_2-e/t
Fibreglass	EF_F	29.3	GJ/t	CF_F	690	kg CO_2-e/t
Gearbox	E_{GB}	799	GJ/turbine	C_{GB}	54,460	kg CO_2-e/turbine
Generator	E_{GN}	789	GJ/turbine	C_{GN}	54,550	kg CO_2-e/turbine

Combining Equations 6a, b, c, and d with the information in
Table 1 gives

$$E_{\text{materials}}(\text{GJ}/\text{turbine}) = 0.672\, H^2 + 2.65\, H + 0.248\, H \cdot D + 40.1 \text{ x } 10^{-6}\ D_{\text{blade}}^{3.44} + 4{,}320 \qquad (7a)$$

$$C_{\text{materials}}(\text{kg}/\text{turbine}) = 26.5\, H^2 + 105\, H + 26.7\, H \cdot D + 0.945 \text{ x } 10^{-3}\ D_{\text{blade}}^{3.44} + 217{,}000 \qquad (7b)$$

Transport

The shipping distance, S, and the overland distance, L_{trans}, were found between each wind site and the manufacturer of the turbines. The predominant supplier is the Danish Vestas, who require 22,000 km to ship the tower and blades from Denmark to NZ. Rule et al. [11] estimated the embodied energy and carbon emissions factors for transport as shown in Table 2.

Table 2. Energy and Emissions Factors for transport

Transport mode	Embodied Energy (MJ/t.km)	Emissions (kg/t.km)
Shipping	0.25	0.014
Land Transport	1.25	0.068

$$E_{trans} = \left(0.00025\, S + 0.00125\, L_{trans}\right)\left(m_{steel,1} + m_{fibre\ glass}\right) \quad (8a)$$

$$C_{trans} = \left(0.000014\, S + 0.000068\, L_{trans}\right)\left(m_{steel,1} + m_{fibre\ glass}\right) \quad (8b)$$

Operation

Turbines are designed to have a service lifetime of 20 y. It is expected that during the turbine lifetime one reconditioning and/or renewal of half of the gears and the generators will be undertaken, which, at a minimum, comprises a replacement of the sealed bearings [12]. Additional materials for servicing of the turbines are included in the form of oil changes and gear lubrication and so on. Fernando [10] estimates service and maintenance to be 1,170 GJ per turbine over its lifetime. This corresponds to carbon emissions of 79.7 t per turbine. This includes enough materials to renew half of the gearboxes once in the lifetime of a wind energy farm. This estimate is conservative as several of the gears and the generators will be repaired rather than renewed.

$$E_{op} = 1{,}170\ \mathrm{GJ / turbine} \quad (9a)$$

$$C_{op} = 79{,}700\ \mathrm{kg / turbine} \quad (9b)$$

RESULTS AND DISCUSSION

To find the EROI and EROC of each of the twelve NZ wind farms, which have a combined total of 442 turbines, the equations presented in the methodology section were substituted into

$$EROI = \frac{E_{gen}}{E_{road} + E_{cable} + E_{earth} + E_{materials} + E_{trans} + E_{op}} \quad (10a)$$

$$EROC = \frac{E_{gen}}{C_{road} + C_{cable} + C_{earth} + C_{materials} + C_{trans} + C_{op}} \quad (10b)$$

Results expectedly show a strong correlation between the energy input and the emissions of a particular site (Figure 5). The average EROI for NZ wind is 34.7, but ranges from as high as

58.4 and as low as 6.6. This wide range of EROI values is mainly accounted for by differences in wind speed and blade diameter for the sites.

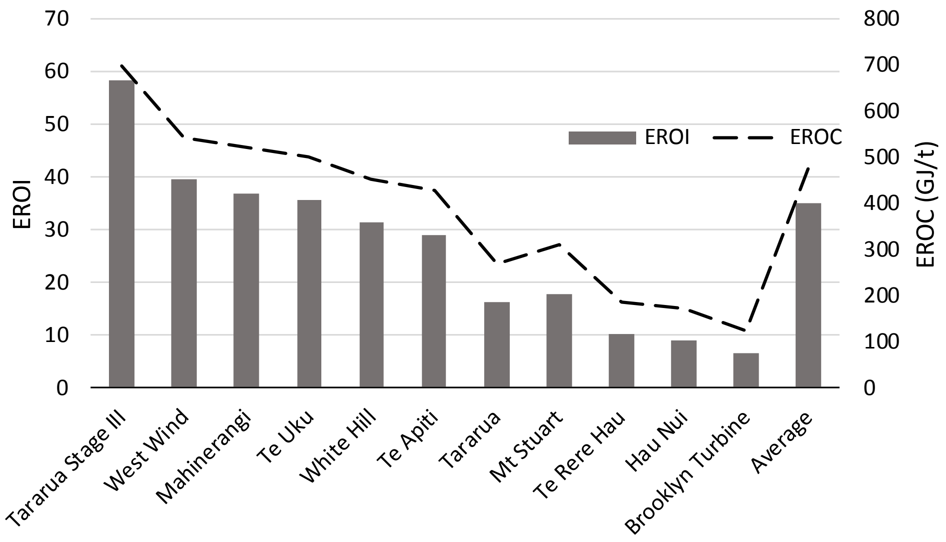

Figure 5. Energy Return on Investment and Energy Return on Carbon Emissions of NZ wind energy farms

The sensitivity analysis in Figure 6 shows how various parameters affect EROI. From Figure 6, the main variables affecting EROI, and also EROC, are the wind speed and the blade diameter. Figure 7 presents the breakdown of lifetime energy inputs for the Tararua Stage III site, which has an EROI of 58.4 and EROC of 0.697 GJ/kg CO_2-e.

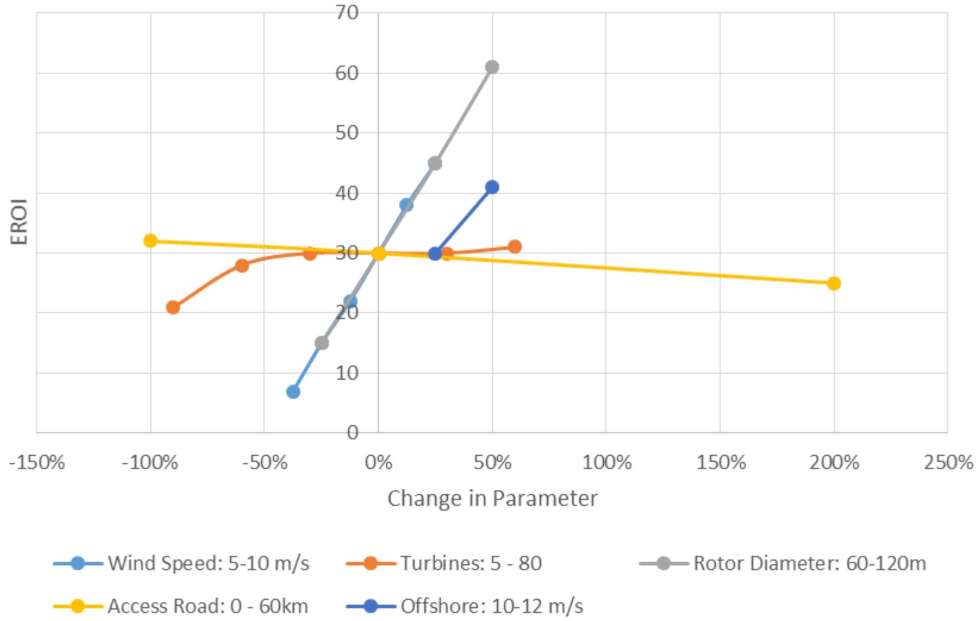

Figure 6. Sensitivity analysis of EROI

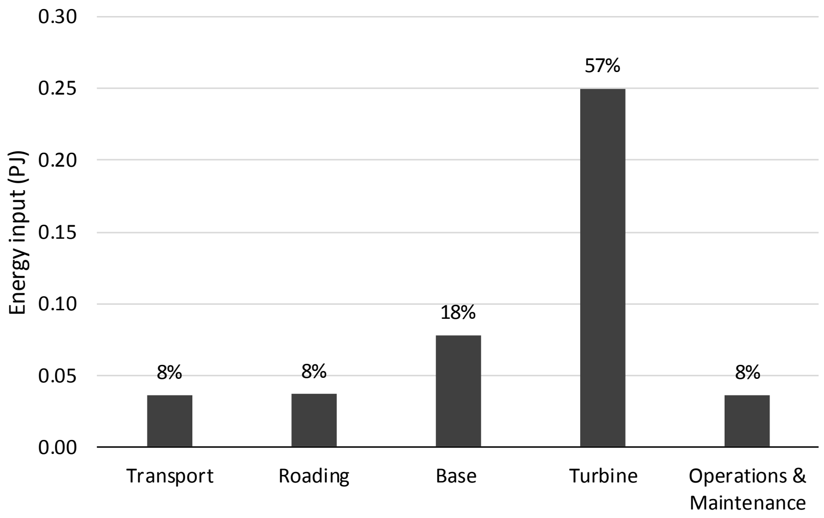

Figure 7. Breakdown of wind farm energy inputs for Tararua Stage III

The weighted average of EROC across all wind farms is 0.477 GJ/kg CO_2-e, Tararua Stage III achieving the highest EROC value of the sites. In terms of emission footprint (the inverse of EROC), the average footprint for NZ wind energy farms is 2.1 kg CO_2-e/GJ. Compared to geothermal at 35.5 kg CO_2-e/GJ, gas combined cycle at 117 kg CO_2-e/GJ and coal fired power stations at 204 kg CO_2-e/GJ [4], wind energy has a negligible emission footprint as well as being a renewable source of electricity.

Figure 1 shows many areas with high wind speeds remain prospective, such as around Gisborne City (North Island, east coast) and Marlborough region (South Island, north east). Most sites in NZ have turbines with 80 – 90 m blade diameters. Vestas now produce wind turbines with 120 m diameter blades, indicating that future wind sites may achieve EROI values greater than 60 due to the technological advance. Along with greater diameters, newer turbines also have lower maintenance requirements than older models. Older turbines have average annual maintenance costs of around 3 % of the original cost of the turbine whereas new turbines need only 1.5 – 2 % [15].

High wind speeds are critical to making wind an economical electricity generation option. However the high average wind speeds, which makes the NZ wind resource productive, are often accompanied by turbulent winds. These intermittencies in wind speed create variable mechanical loads on the wind turbine structure, causing fatigue and ultimately leading to failure [17]. Turbine operators avoid damage by locking the blades in highly turbulent conditions, in an effort to avoid material fatigue and failure, while sacrificing the opportunity to generate power. As the technology improves, so does the turbines ability to operate in turbulent conditions.

The main drawback of wind generation is its variability, which is impossible to accurately predict. This creates a barrier for companies wanting to sell their electricity to the grid market. A good base load of reliable electricity is required to offset changes in wind energy. Hydro power has the ability to pair well with wind as a regulator if the proximity is sufficiently close, making wind power more viable here than elsewhere, due to our large proportion of hydro power (58 %). However, there is only around 4,000 GWh (14.4 PJ) of storage capacity in the NZ hydro network, making it difficult to store wind power [18]. Without baseload renewable electricity with adequate turn-down, wind energy will likely need to rely on fossil fuel power plants to maintain a reliable electricity supply. Future work will understand the potential for effective demand side storage, such as using residential and industrial hot water systems and electric car batteries, since wind energy is an expanding generation source that needs storage.

Wind farms have been met with mixed public support. The beauty of NZ scenery is central to our tourist industry and some people feel that wind turbines are unsightly, whereas others find them aesthetic and complementary to the landscape [16]. Noise is also another deterrent for public support. Under new rules, a strict acoustic noise standard has to be met by all prospective wind farms. This is often met by locating the wind farms away from built up areas. A recent survey showed that 75 % of New Zealanders support the development of wind farms [16].

CONCLUSION

Wind is a competitive electricity generation resource in New Zealand in terms of both EROI and EROC. New Zealand has the key advantage of high average wind speeds that also result in high capacity factors. New turbine blade technologies has enabled larger blade diameters that is leading to significantly increased EROI and EROC values. Wind needs to be paired with hydro or another baseload electricity supply, however, to overcome the drawback of variability.

NOMENCLATURE

C	Carbon equivalent emissions (kg CO_2-e/unit)
D	Blade diameter (m)
E	Energy (GJ/unit)
EROC	Energy return on carbon emissions equivalent (GJ/kg CO_2-e)
EROI	Energy return on energy investment
H	Height (m)
L	Roading length (m)
m	Mass (t)
n	Number of turbines at a site
P	Power density (W/m^2)

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