White Paper

Forest-to-Furnace

An analysis of the woody bioenergy value chain; with an emphasis on fossil fuel energy inputs, fossil carbon emissions, EROEI and ROI.

Comparing 'Arboreal Energy ltd biocoal' with woodchip and white pellets.

(inspired by Well-to-Wheel analyses)

unlike money

energy is neither created nor destroyed
but
exergy is different

Arboreal Energy
May 2024

Version 1.12

Some basic knowledge is required.

The wood we are focusing on is pinus radiata. In New Zealand this is an exotic conifer frequently grown in plantations as a commercial crop. Approximately 35Mt of logs are harvested annually in New Zealand (2022), 90% of which is radiata pine. Harvest maturity is at 25-30 years. A good harvest ready tree has the mass of approximately 3 tonnes. The harvest yields approximately 650-850 tonnes of logs to the hectare. Freshly harvested pine logs have a density of approximately 1 tonne to 1 cubic metre hence often the mass and volume are used indiscriminately to describe a quantity of logs. The mass of unsold (residue) wood per hectare varies considerably, in many cases this can be assumed to be equivalent to 25% of the mass of the harvested log yield.

However with log value continually dropping in real terms and global energy cost increasing in real terms most trees are now worth more as energy than as logs.

Trees are Energy

A freshly harvested log (by mass) is 56% water, thus only 44% of the fresh log is wood

Dry wood (0% water) has an energy content of 20.2 GJ/t.

Simplistically if a log is only 44% wood then the energy content is 44% of 20.2 GJ/t thus freshly harvested pine logs contain 8.89 GJ/t. However the presence of water in the fuel 'consumes' a proportion of this useful energy as this water has to be heated and vapourised during combustion.

Fuels with a moisture content thus have a gross and nett energy (Sometimes referred to as **H**igher **H**eat **V**alue and **L**ower **H**eat **V**alue).

1 kg of water requires the addition of 2,584,841 Joules to heat it to boiling point and vapourise it, thus the 560kg of water in a tonne of fresh pine would consume 1.447GJ. Giving a nett useful energy content of 7.44GJ/t for fresh wood.

The typical 'barrel' of crude oil contains 6GJ of energy, hence a tonne of fresh pine has more nett energy than a barrel of oil.

Trees are Energy!!

A discerning energy buyer is interested in the **nett** energy they are buying, the value or quality of that nett energy is defined by many factors such as; $/GJ, moisture content, energy density (GJ/m^3 and GJ/t), availability, reliability of supply, transportability, storability, usability and combustion temperature. These factors all contribute to the exergy efficiency. Exergy being the useful/useable energy.

Within the energy economy is the concept of **E**nergy **R**eturn **o**n **E**nergy **I**nvested (ERoEI) and the concept of **S**urplus **E**nergy. It is this surplus energy of the energy industry that enables our complicated societies and our elevated quality of life. Without industry, supported by surplus energy, our societies would revert back to 'hunter gatherer' and the simplest versions of 'subsistence farming'. Fossil fuels, coal and then oil and gas, are the source of surplus energy that lifted our societies via the industrial revolution to where we are now.

Increasing margins of returned energy enable progressive enhancements to society.

It is important that 'Energy Transition' is 'Energy Progression' and not 'Energy Regression'.

Hypothetically the instantaneous withdrawal of fossil fuel from our society would result in rapid population decline.

Most equipment used in harvesting and transporting wood is diesel powered. The wood processing may use other sources of energy such as electricity and geothermal steam.

The production of diesel requires energy. For every 1MJ of diesel delivered to the equipment's tank an extra 0.2163MJ has been invested in it.

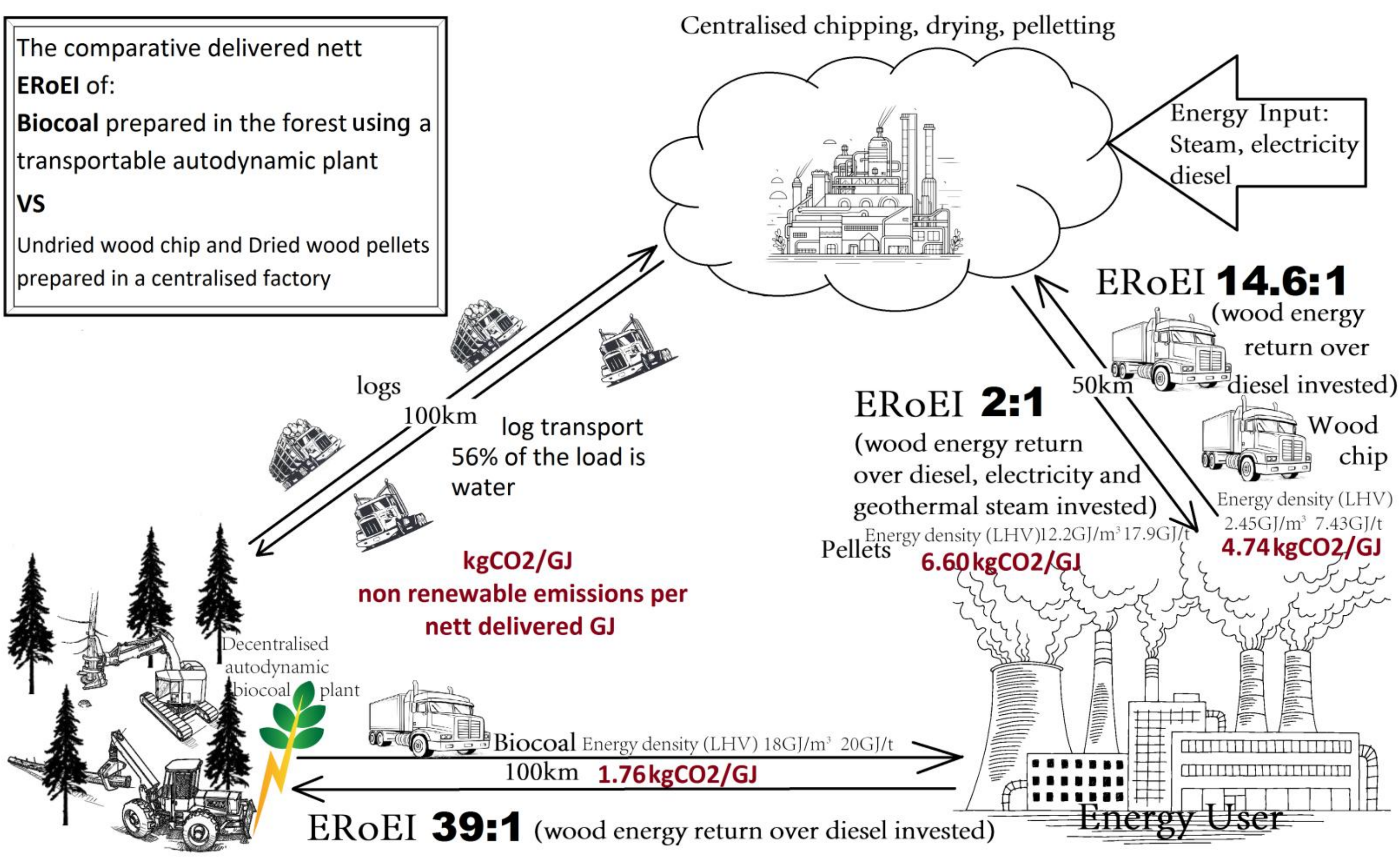
This is the 'well-to-tank' value chain energy expenditure.

Not all energy is equal (in what it can do) thus there are things you can do with a GJ of electricity or diesel that you cannot do with a GJ of wood.

Valuable forms of energy like electricity and diesel should be used wisely.

In this study we have not delved into the embodied energy of equipment and infrastructure. For example the harvesting and transport equipment directly associated with one large harvest crew may exceed 300 tonnes (Harvester, forwarder, skidder, processor, stacker, log trucks, bulk trucks and workers' utes). If this equipment had an embodied energy, during manufacture, of 66MJ/kg and was amortized over 10 years, or 1 million tonnes of harvested logs, this would represent another 20MJ energy invested per m^3 harvested.

The ERoEI and non renewable emissions comparison of four types of woody bioenergy



Biocoal is a term to describe Torrefied Wood Briquettes
Torrefaction is an ideal preprocessing method for woody biomass which lends itself to distributed processing due to the fact that the process can be "autodynamic", by virtue of the volatile byproducts containing enough energy to run the process.

Arboreal ENERGY has designed an integrated biocoal production plant that can be situated in the forest and function as a **R**esidue **M**anagement **S**ystem . Powered by approximately 15% of the (renewable) energy in the residue the integrated biocoal preprocessing machine, comminutes, dries, torrefies and briquettes the raw material producing an energy dense fuel that is a 'drop-in' replacement for coal.
This integrated method eliminates much of the cost and effort normally associated with residue utilisation.

This white paper builds on the basic understanding of wood as energy and the concept of ERoEI to show that the Arboreal ENERGY method is best, leading to more profit and less emissions.
The traditional 'business as usual' model would be to build a centralized monolithic bioenergy processing hub. This hub would be connected to the existing energy infrastructure, for example; the electric grid, the natural gas pipeline, possibly also connected to geothermal steam and maybe even use coal or oil delivered by train. Raw woody biomass would be delivered to the processing hub by a fleet of trucks. The residue might be chipped in the forest using diesel powered chippers or chipped at the hub using electricity. Either way the wood is transported from the forest to the hub wet. This transportation of 56% water biomass could be described "for every truck load of dry wood there is also a truck load of water".
The 'business as usual' options

1. At the hub the chipped wet wood could be on sold as 'hog fuel' and once again for every truck load of dry wood there is a truck load of water being delivered to the energy user. Undried chip or hog fuel is sold as the cheapest fuel when sold by the tonne or by the cubic metre. However due to the low nett energy density this fuel displays a poor exergy efficiency, the extra truck loads needed to transport the water content increases the fossil CO2 emissions. This fuel has a low maximum combustion temperature and a low LHV energy density of **2.45GJ/m3** or **7.43GJ/t** Non renewable emissions per nett delivered GJ of 4.74KgCO2/GJ

2. At the hub some of the chipped wood is used as fuel for heating the dryer that dries the wood chip. The dried chip is then pelleted using electrical power, the pellets are delivered to the energy user. This fuel has a moderate maximum combustion temperature and a moderate LHV energy density of **12.2GJ/m3** or **17.9GJ/t** Non renewable emissions per nett delivered GJ **7.22KgCO2/GJ**

3. At the hub the chipped wood is dried using geothermal steam. Geothermal steam contains some non renewable C02. Using geothermal steam to dry the chip instead of the harvested, transported and chipped wood, leads to slightly less emissions for the same product. The dried chip is then pelleted using electrical power, the pellets are delivered to the energy user. This fuel has a moderate maximum combustion temperature and a moderate LHV energy density of **12.2GJ/m3** or **17.9GJ/t** Non renewable emissions per nett delivered GJ of **6.6KgCO2/GJ**

The ArborealENERGY option

- At the harvest landing site, the residue is (or harvested [pulp] trees are) loaded into the biocoal production machine. The current design of the machine is scaled to utilize 200 tonnes of raw wood per day which is the maximum daily quantity of residue from a larger harvest crew. This loading of the machine is integrated into the harvest method and thus incurs minimal extra handling expense. The machine operates in a continuous manner and produces biocoal at an approximate rate of 2.5tonnes per hour. The daily production is equivalent to 2 bulk truck-trailer unit loads. The product is 'dropshipped' straight from forest to consumer or, if for export, to the port. This fuel has a high maximum combustion temperature and a high LHV energy density of **18GJ/m3** or **20GJ/t** Non renewable emissions per nett delivered GJ of **1.67KgCO2/GJ**

If the 4 renewable energies are; hydro, solar, wind and biomass (geothermal is a grey area) then 'efficiency' is the 5th. Historically in western culture 'sloth' was one of the seven 'mortal sins', 'convenience' is the equivalent in our modern society. Exergy efficiency is often sacrificed for the sake of convenience or a quick fix. Business-as-usual is often perpetuated due to avoiding change and is not progressive. A centralised biomass processing hub is a relic of the Victorian industrial mindset which does not suit the distributed nature of woody biomass supply.
The most obvious advantage of the distributed autodynamic processing and dropshipping business model utilized by ArborealENERGY is the reduction in road freight. The central processing hub in this theoretical scenario only adds 50km to the distribution chain (in reality it would probably be a greater proportion), however those 50km are transporting the bulky and wet raw material. A study in New Zealand of logging trucks showed round trip (one leg empty and one leg loaded) transport gave a 1.64MJ/tkm for the load movement. The ArborealENERGY method only transports the high value finished, dried and densified product.

> The study has ignored the overheads associated with a 'bricks and mortar' centralized hub. The cost and emissions associated with such would be considerable, especially if the embedded emissions associated with its construction were taken into account. It should be noted that the SolidEnergy wood pellet plants which were originally established as a government project and branded "Nature's Flame" have struggled to meet their growth forecasts (the Taupo plant was aiming for 300kt output by 2015) the Rolleston plant closed in 2012 and the Rotorua plant though opened in 2005 disappeared without a trace. The inefficiencies associated with this centralisation takes its toll.
>
> Publication date: 20 November 2009
>
> Nature's Flame, a subsidiary of Solid Energy, is the biggest pellet manufacturer in New Zealand. Renewable energy general manager Andy Matheson says output at the company's new Taupo plant wi reach 300,000 tonnes a year by 2015. Even though the plant will need only three staff and will use low- cost geothermal steam for drying, he concedes it will struggle to make money at current oil prices. Its viability depends on strong carbon pricing, or another surge in world oil prices. The domestic market fc wood pellets, which is largely driven by the demand for a low particulate emission fuel in cities with strict air quality plans, is already catered for by the company's existing 50,000 tonne pellet plants in Rolleston and Rotorua.

The study used a harvesting energy consumption of 9.65MJ/t.
Chipping energy consumption of 77.2MJ/t was used for the biomass hub products. In the case of the ArborealENERGY biocoal plant a more efficient method of comminuting the feedstock is used powered by the torrefaction byproduct energy, thus has minimal non renewable CO2 emissions associated with it (just a small fraction of the harvesting energy).
Most drying plants are under 30% efficient, this efficiency factor was used to derive how much wood chip needs to be combusted to dry the wood chip for pelleting. However the geothermal drying requirements were calculated from the geothermal energy supplied to Nature's Flame divided by their potential pellet output.
Information on pelletising energy is hard to find in New Zealand and does not have a simple theoretical basis. Forcing biomass through a pellet die is intrinsically inefficient and the dies wear rapidly. ArborealENERGY will use a briquetting method that has better financial, emissions and energy efficiency. However that being said the ArborealENERGY briquetting method is also powered using torrefaction byproduct energy, thus has minimal non renewable CO2 emissions associated with it (just a small fraction of the harvesting energy).
Screen shots of the scratch pad spreadsheet used for all the calculations are included in the figures.

Conclusion

In forest autodynamic preprocessing of woody biomass into torrefied wood briquettes (biocoal) and drop shipping direct to industrial users or export **gives the best ERoEI** with regards to the **non renewable** energy invested.

Arboreal ENERGY biocoal **ERoEI 39:1** **Emissions 1.76kgCO_2/GJ**

geothermal dried wood pellets **ERoEI 2:1** **Emissions 6.6kgCO_2/GJ**

In forest autodynamic preprocessing of woody biomass into torrefied wood briquettes (biocoal) and drop shipping direct to industrial users or export gives **the least non renewable CO_2 emissions** per nett delivered GJ of energy.

The energy and economic margins on woody biomass fuel are tight, generally chemically unaltered biomass fuel is only economic if it is utilising timber/pulp processing waste where the harvesting and raw material transport costs have covered by upstream industry, even then it is often subsidized by these industries as a method of waste disposal. Though rising carbon tax prices do improve the competitive possibilities of renewable fuel this will also increase the costs of energy inputs into the woody biomass fuel value chain.

The purpose of carbon tax is to skew the economy away from fossil fuels and towards renewable fuels, this study broadly suggests that these are the various carbon tax levels that lead to profitability for the studied woody biomass fuels using woody biomass sourced from the forest.

Necessary NZU value to cross threshold of profitability
with current fossil fuel values (April 2024)

Fuel type	Carbon tax level (NZU)
Arboreal ENERGY biocoal	$20
Woodchip/hogged fuel	$50
Geothermal dried pellets	$100
Biomass dried pellets	$125

Having explained the economic, energetic and emissions advantages of distributed autodynamic biocoal production with machines designed and built by Arboreal ENERGY it is important to emphasise that the Arboreal ENERGY solution is also very **scalable**.

Each transportable machine can produce approximately 15,000 tonnes of biocoal per annum. Currently there is harvest residue opportunities for 200 Arboreal ENERGY transportable machines throughout the country, producing a total of 3,000,000 tonnes of biocoal per annum. If the economic trend continues where the best forestry return is to direct low value logs into energy products then more machines could be accommodated in the new 'trees as energy' economy.

One of the main thrusts of energy transition is 'electrification' or using electricity to replace fossil fuel. However even the idea that electricity can replace fossil fuel is a partial misconception as electricity is a method of transference rather than a source of energy. Two main 'electrification' examples are the replacement of coal fired boilers with electrode boilers in milk factories (which use approximately 1,000,000 tonnes of coal a year) and the use of EVs for transport (transport being the biggest use of energy in the country). These two arms of energy transition place great demand on the grid and ultimately places the country at risk of electrical energy insecurity. Simultaneously there is pressure to 'do something about' the use of fossil fuel for electricity generation at Huntly, New Zealand's only coal fired power station. Huntly with its stockpile of solid carbon feedstock is New Zealand's reserve battery, especially important during 'dry years' when water levels are low in the hydro electric supply. Huntly has tested torrefied wood in its coal fired system and it performed well, they are looking for a domestic supply. A 300,000 ton stockpile of Arboreal ENERGY biocoal at Huntly would largely solve the 'dry year problem' of dispatchability. Biocoal storage is cheap and simple compared to white wood pellets.

> The supply of electrical power via the national grid is a very dynamic process. The supply response time has to be as quick as micro seconds and as enduring as seasons.
> The behavior of free market forces have to be channeled into certain behaviours to keep the voltage, frequency and price within constraints.
> The high speed response is in the rotational inertia of heavy equipment and the electronics of batteries. Gas peaker generation covers surges of diurnal demand. Unfilled seasonal demand can be filled by utilising stored coal or biocoal
> Wind, solar and hydroelectric are not fully dispatchable elastic supplies, their availability is not under the control of mankind. If these renewable sources form too higher proportion of the grid it can become unstable.

At present the global demand for energy has no limit, in the developing world the appetite for energy is growing dramatically thus if domestic demand is filled there is an untapped global export market for Arboreal ENERGY biocoal.
Each new machine will create several jobs, many of them in rural areas.

Addendum

Some comparisons between a windturbine and an ArborealENERGY biocoal machine

They are very different mechanisms for harvesting indirect solar energy.

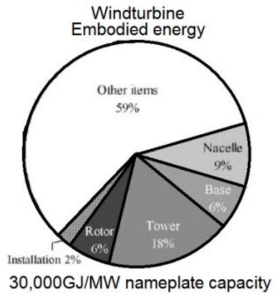
Wind is kinetic energy from atmospheric movements cause by changes in density due temperature and water vapour content due to the sun's warming. Woody biomass is an accumulation of solar energy in the form of chemical energy.

In some ways they are both harvesting "free energy", the wind is there for free and just needs harnessed, likewise forest harvest residue is abandoned and is available for collection.

There is concern that energy transition is a 'super wicked problem' which does not produce the surplus energy necessary to support our complex, energy intense societies of the 21st century.

Here we shall take a further look at embedded energy and energy return on this invested energy as well as the energy return on the invested dollars (NZD 2024)

> Currently Microsoft and Amazon data centers use as much energy as Iceland and Greece respectively



Windturbines of various generating capacities are built, surprisingly there is not much economy of scale, thus to discuss them on a per MW capacity stance is valid.

Steel and concrete are used in windturbine construction as well as more special materials.

Though windturbines have a particular nominal or nameplate capacity their actual output over a year is often about 30% of the nominal capacity, this reduction is the 'capacity factor'. Solar panels also have a capacity factor. Windturbines have a capacity factor of about 30% and solar panels about 15%.

One study has suggested that windturbines have 30TJ invested in them per MW capacity.

https://www.researchgate.net/publication/223338285_Life_cycle_energy_and_greenhouse_emissions_analysis_of_wind_turbines_and_the_effect_of_size_on_energy_yield

Generally it is accepted that a wind turbine returns its embodied energy in its first year, also they are seen to have an average life expectancy of 20 years thus giving an **ERoEI of 20:1**

The cost of a windturbine in NZ is ≈$2,000,000NZD per MW.

An ArborealENERGY biocoal machine also has a cost of $2,000,000NZD

Some simplified calculations demonstrating the ERoEI

> Virgin steel has embodied energy of 32.0GJ/t
> Concrete has embodied energy of 1.6GJ/t
> Recycled steel has embodied energy of 10.1GJ/t

Wind turbines weigh approx 150t/MW, the concrete base is 240t/MW with 20t/MW of steel reinforcing.

(Nuclear power plants use ~1000t of concrete per MW, but have a capacity factor >90%)

Depreciation cost $/GJ

Assuming a 20 year life for both windturbine and biocoal machine which both cost $2,000,000.

A 1MW wind turbine's life time energy output (20yearsx365daysx24hoursx60minutesx60seconds x300,000Watts) is 189,220GJ, giving a depreciation rate of **$10.57/GJ**

A biocoal machine's life time energy output (20yearsx250daysx60tonnesx20GJ) is 6,000,000GJ, giving a depreciation rate of **33¢/GJ**

Thus embodied energy in a 1MW windturbine is (150 x 32GJ + 240 x 1.6GJ + 20 x 10.1GJ) 5386GJ

Giving a **35:1 Energy Return on Embodied energy Input**

The ArborealENERGY biocoal machine weighs 40tonnes and is largely made of steel thus has an embodied energy of 1,280GJ

For a 20 year life this gives an **ERoEI of 4,688:1**

For a 10 year life this gives an **ERoEI of 2,343:1**

Basically the biocoal machine's energy payback on embodied energy is just one day of operation.

As mentioned earlier not all energy is equal, a GJ of electricity from a windturbine is worth ≈$55/GJ whereas the biocoal energy is worth ≈$20/GJ.

The lifetime revenue return on the capex invested

Windturbine **$5.20 revenue : $1 capex**

ArborealENERGY Biocoal machine **$60 revenue : $1 capex**

Comparison of energy return on $ investment

Wind vs biocoal (demonstrating the relevance of energy density)

A wind turbine in NZ costs approximately $2million per MW nameplate capacity, actual output is approximately 30% of nameplate, i.e. only a minority % of the time at full capacity.

Hence a 1MW turbine's annual (365daysx24hoursx60minutesx60secondsx300,000Watts) output is 9,461GJ

The ArborealENERGY transportable autodynamic biocoal machine costs approximately $2million. This machine is designed to produce 60 tonnes of biocoal per day, each tonne contains 20GJ, thus the daily output is 1200GJ.

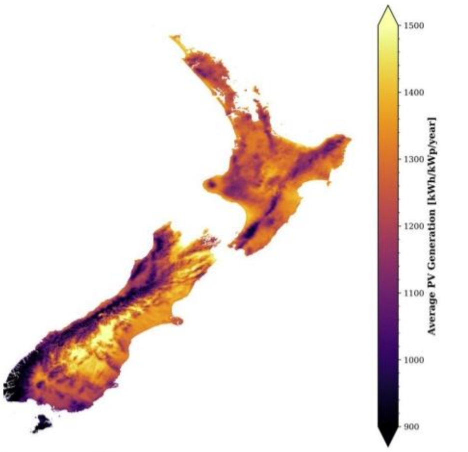
One $2m biocoal machine in just over a week (8 days) will deliver the same quantity of energy as a $2m wind turbine does in a year. Even if you factor in a 33% conversion factor to turn the biocoal into electricity at a thermal power plant like Huntly then the ArborealENERGY machine enables more electrical power to be generated in 24 days than an equivalent value windturbine does in a year.

Why the massive contrast in ROI? The important factor is the energy density and intensity of the source and product. Harvestable pine trees represent a 25 year accumulation of solar energy (trees being a solar panel battery combo) this is why a 25 year harvest interval is more feasible than frequent harvesting of a biomass crop, for example; coppicing, straws and grasses.

The wind being harvested is only a day or so accumulation of solar energy.

> Harapaki Wind Farm completed July 2024 has 41 Siemens Gamesa SWT-DD-120 turbines @ 4MW giving a total nameplate capacity of 164MW. The capex was $448 million which is $2.7mNZD per MW

The roi comparison of ArborealENERGY biocoal with solar farms in New Zealand
Using public domain information from Far North Solar Farms.



mbie.govt.nz/assets/utility-scale-solar-forecast-in-aotearoa-new-zealand-v3.pdf

Figure 5: Annual solar generation from a 1kWp fixed axis optimally tilted and oriented PV system with 13.5% soiling, self-shading, module mismatch, DC-AC and wiring losses at each LCDB km x km cell considered in the model. Dividing the legend values by 8,760 hours per year gives the annual capacity factor. This is a measure of a solar system's ability to convert its capacity, and the substantial investment in it, into soleable energy. The capacity factors in this figure vary substantially from 0.118 to 0.197 (with module tracking and array over-sizing included).

fnsf.co.nz

Far North Solar Farms https://fnsf.co.nz/

$2,000,000,000 expected cost

Where	MW	ha	Homes powered	Status
Pukenui	22	17	2,000	Under Construction
Greytown	175	235	40,000	Resource consent in dispute?
Ohau A	278	340	60,000	In design
Waiotahe	55	101	16,000	Consented
Waitara	68	95	14,000	Consent application
Marton	41	37	7,800	Consented
Tasman	106	109	20,000	Consent application
The Point	420	670	100,000	Consent application
Edgecumbe	38	30	6,800	Early works underway
Foxton	42	40	7,000	Consented
Canterbury	135	200	28,000	Consent application
Totals	1380	1874	301,600	Only 1 under construction

https://businessdesk.co.nz/article/energy/2b-solar-farm-project-aims-to-generate-15-of-daytime-electricity

Using the information provided, these solar farms have a peak output of 1.4GW, using the 15% capacity factor this gives a true output of 210MW for $2bn, which is **$9.5m per MW of 24/7 output.**

Comparison of Arboreal Energy biocoal machines compared to FNSF solar power

Energy Source	Capex $/MW	Power density W/m^2
Biocoal machine	$145k per MW	$153kW/m^2$
PV Solar farm	$9.5m per MW	$11W/m^2$
How many times better is a ArborealENERGY biocoal machine.	Biocoal is 65.5 times better	Biocoal is 14,000 times better

Local councils are keen to benefit from the revenue generated by solar farms, what rates will be levied by councils is yet to be seen. Any fixed infrastructure is liable for taxation, as can be seen by the decay urban central business districts, council taxes are often raised to the point that there is no profit left for the business owner.
In comparison transportable ArborealENERGY biocoal machines will not be liable for taxation by local and regional government.

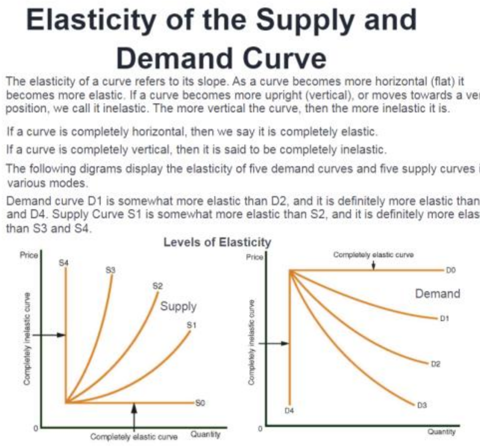
Decommissioning costs. The installed life of PV arrays is unlikely to exceed 20 years. It is possible and likely that regional councils will expect a bond to be paid to ensure end-of-life removal and disposal of solar farm infrastructure. Soon used PV arrays maybe seen as toxic waste. https://hbr.org/2021/06/the-dark-side-of-solar-power

It is possible that the decommissioning cost of a solar farm maybe as high as $100 per panel when all the inground fixings are taken into account. There are approximately 1500 panels per MW, thus the $2b solar farm investment of FNSF which has approximately 2,000,000 panels might cost $200m to decommission.

Whereas in comparison, the ArborealENERGY biocoal plants, which are built mainly of steel, would have a scrap value exceeding the decommissioning cost.

Solar power does have a place in New Zealand's energy mix, it is a very young technology and the complete lifecycle of a solar farm in New Zealand is yet to be observed. So the true LCOE is uncertain.

Confluence of trends leading to a future electrical energy shortfall in NZ
and
related price increases.



As a primer to understanding the [electrical] energy markets it is prudent to learn about Enron and the 2000-2001 California electricity crisis https://en.wikipedia.org/wiki/2000%E2%80%932001_California_electricity_crisis

Some excerpts that catch the eye:

California had a shortage of electricity supply caused by market manipulations and capped retail electricity prices.
caused an 800% increase in wholesale prices
A demand-supply gap was created by energy companies, mainly Enron, to create artificial shortages.
Traders were thus able to sell power at premium prices, sometimes up to a factor of twenty times its normal value.
Deregulation did not encourage new producers to create more power and drive down prices.
Instead, with increasing demand for electricity, the producers of energy charged more for electricity.
The crisis cost between US$40 and $45 billion.

Enron was gaming the market, by making the electrical energy supply inelastic.

Here in New Zealand (2024) there is minimal (base load) reserve electrical generation capacity. The installed base load generating capacity of New Zealand is about 9GW. If demand goes over 10GW the wholesale prices rises geometrically and there is likelihood of load shedding. Recent daily peak output in the 1st week of July reached 273,552 MWh giving an average whole price of $350 per MWh during that day and an average power generation of 11,400MW. https://app.em6.co.nz/

Some of the known (expected quantities), unknown (expected but less quantifiable) and unknown unknowns (out of the blue or so called black swan, not a good metaphor for NZ) trends worth watching:

1. Knowns: Total extra base load capacity 4400MW
   - Electrification of (fossil fuel) process heat is expected to replace 20-30PJ of fossil fuel, which equates to 400MW continuous generation through the year
   - Electrification of light vehicles, 1MW per 1000 cars, 2m EVs by 2029, = 2000MW continuous generation
   - Domestic heat pumps, 1m heat pumps @ 2kW = 2000MW
2. Unknowns: Total extra base load capacity 1800MW
   - Immigration, this last year there was nearly 0.2 million immigrants, it is reasonable to expect that before 2029 there will be 1million extra immigrants. 1MW per 1000 homes, 1m immigrants need 300k homes = 300MW
   - Information Computing Technology, data centres, AI and crypto activity (currently 81 data centres in NZ using 500MW ?) will increase by 20% per year? Currently the rise of the computational energy requirements of AI is almost a "black swan event" Thus this category will need an extra 1,250MW of continuous generation capacity.
   - Electrification of Heavy transport is not likely to happen in a pure sense, due to the low energy density of batteries, however in the long term heavy transport is expected to be part of the "hydrogen economy".
     Note every heavy truck charger would require at least a 1MW connection.
     Thus by 2029 only 100MW extra generation capacity will be required for electrification of heavy transport.
   - Improvement of standard of living, energy use per capita is linked to wealth and standard of living, obviously this overlaps many of the other items listed. Thus only add 1% per year to domestic electricity consumption. 50MW
   - The hydrogen economy. If fully implemented is expected to require 125TWh per annum of additional electricity, which is three times the current electricity demand!
     Though the hydrogen economy can't be ignored and policy has been pushing its development up a very steep hill against very strong financial headwinds, it is very unlikely to have a major impact before 2029 thus only 100MW extra generation will be required by 2029
3. Unknown unknowns
   - Global war restricting the availability of fossil fuel sourced energy
   - Massive refugee immigration at an order of magnitude greater than current immigration
   - Totally unforeseen needs for energy. For example data centres effectively are an energy export method if the data work done is for overseas consumption.
   - New tech both for using electricity and for generating electrical energy
   - ☺ pandemics?
   - Who knows?

Leading up to 2029 at the very minimum

New Zealand needs to install 1GW of extra **base load generation** per year to fill demand.

This will cost $5 per Watt.

Who is going to invest $5,000,000,000 per annum into base load generation?

References

1. **New Zealand forestry data** https://www.nzfoa.org.nz/images/Facts_and_Figures_2022-2023_-_WEB.pdf
2. **Type of product:** woodchip not dried (similar to hog fuel), wood pellets(drying energy supplied from burning woodchip), wood pellets(drying energy supplied from geothermal steam), biocoal ("autodynamic" integrated process using torgas from the torrefaction process).
3. **Moisture content of harvested wood % : 56%** The water content of green, fresh radiata pine is around 56% on average. https://www.mbie.govt.nz/dmsdocument/125-industrial-bioenergy-
4. **Energy content of harvested wood bone dry GJ/t: 20.2 GJ/t** The average gross calorific value of oven dried Pinus radiata with a moisture content of 0% is assumed to be 20.2 GJ/t. https://www.mbie.govt.nz/dmsdocument/125-industrial-bioenergy-
5. **Moisture content of product %water:** Widely available information, for this analysis the pellets are 10% moisture, the woodchips are the same a fresh logs at 56%, and biocoal briquettes at 2%
6. **Energy to vapourise water GJ/t: 2.6GJ** Specific heat capacity of water is 4.184MJ/degree C per tonne, specific latent heat of vapourisation of water at atmospheric pressure is 2.257GJ/t. Using a start temperature of 15ºC total heat energy needed per tonne of water is 0.35564GJ+2.257GJ = 2.6GJ to evaporate 1 tonne of water
7. **Transport energy cost MJ/tkm: 1.64MJ/tkm**(using round trip value of 0.0425 l/tkm derived from https://fgr.nz/documents/download/4750 and 1litre diesel containing 38.6MJ.)
8. **Harvesting energy: 96.5MJ/t** 2.5ldiesel per tonne. Harvesting used the equivalent of more than 52 million litres of diesel (or 1998 terajoules of energy) in 2008 (Statistics NZ, 2009). Distributed over 20.38 million cubic metres of logs produced in NZ that year (NZFOA, 2010), this results in an average fuel consumption of 2.55 l/m3 (98 MJ/m3). A survey of New Zealand forest managers and harvest planners resulted in reported fuel consumption between 2.0 and 2.5 litres of diesel per cubic metre of logs harvested and loaded on truck. https://fgr.nz/documents/download/3969
9. **Chipping energy MJ/t: 77.2MJ/t** Most diesel powered chippers, regardless of type, use 0.5l of diesel to produce 1m3 of chip (Determining long-term chipper usage, productivity and fuel consumption (Raffaele Spinelli July 2014). Bulk loose wood chips are about **one quarter** to one third the density of the logs they are derived from.
10. **Drying energy geothermal GJ/t of product: 6.7GJ** Natures Flame wood pellet plant has an 18MW geothermal steam connection (24 hours a day, 7 days a week, 365 days a year) to produce 85,000 tonnes pellets per annum. This equates to 6.7GJ drying energy per tonne pellets produced.
11. **Multiplier, energy invested on diesel 1.2163:** Energy input 0.2163 MJ/MJ WELL-TO-WHEELS Analysis of heavy truck fuel https://www.diva-portal.org/smash/get/diva2:1324115/FULLTEXT01.pdf
12. **Emissions per GJ geothermal: 3.5kg CO2/GJ** using geothermal energy ….at 3.5kgCO2e/GJ https://www.geothermal-energy.org/pdf/IGAstandard/NZGW/2020/044.pdf
13. **Emissions per GJ electricity generated GJ: 25kgC02/GJ (**90kg/MWh) https://app.em6.co.nz/
14. **Emissions per GJ wood: 91.75kgC02/GJ** 1 Kg of carbon on complete combustion will produce 3.67 Kg. of CO2. default carbon fraction (0.50 g C g-1dm) https://nzjforestryscience.springeropen.com/articles/10.1186/s40490-018-0119-5
15. **Emissions per GJ diesel: 69kgCO2/GJ** https://www.engineeringtoolbox.com/co2-emission-fuels-d_1085.html
16. **Natures Flame/Solid Energy monolithic wood pellet plants** https://www.beehive.govt.nz/speech/opening-natures-flame-pellet-mill-rotorua https://www.scoop.co.nz/stories/print.html?path=BU0506/S00441/natures-flame-to-open-mill-in-rotorua.htm https://www.scoop.co.nz/stories/print.html?path=BU1003/S00158/solid-energy-opens-large-wood-pellet-plant.htm
17. **The energy trilemma** https://www.genesisenergy.co.nz/about/sustainability/future-of-huntly
18. **Huntly and biomass** https://www.genesisenergy.co.nz/about/news/genesis-biomass-trial-successful
19. **Dispatch** https://en.wikipedia.org/wiki/Dispatchable_generation

Figures

Figure 1

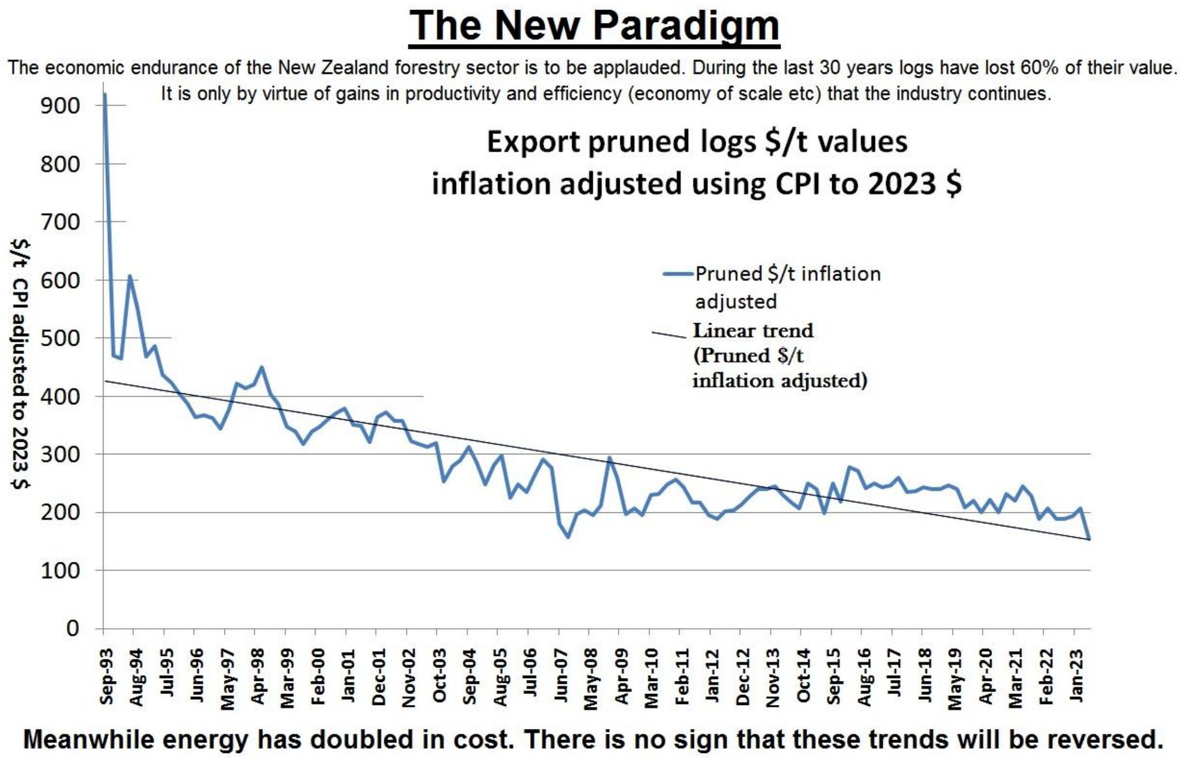


Figure 2

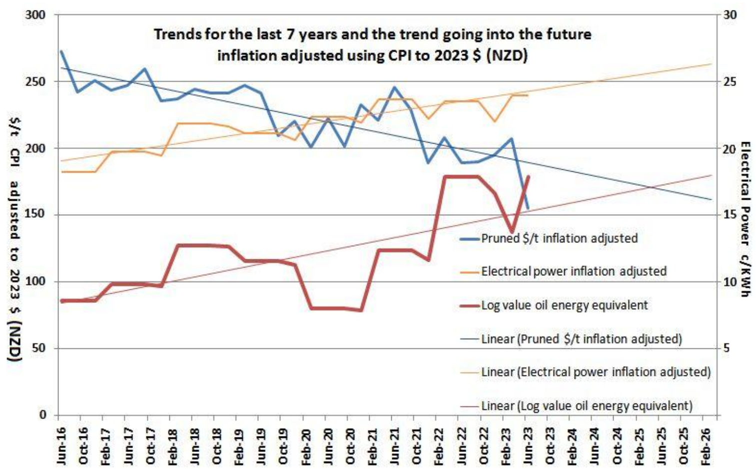


Figure 3

Indicative Average Current Log Prices – April 2024

Log Grade	$/tonne at mill	$/JAS m3 at wharf
Pruned (P40)	175-200	170
Structural (S30)	120-145	N/A
Structural (S20)	93-100	N/A
Export A	N/A	108
Export K	N/A	99
Export KI	N/A	90
Export KIS	N/A	81
Pulp	46	N/A

In April 2024 Brent crude was worth $141 NZD per barrel thus all but the top grade of logs had a gross energy value exceeding their log value. (logs @ 8.89GJ/t oil @ 6GJ/bbl) If carbon tax is added to the oil cost (≈$20NZD per barrel) the energy value of highest grade logs exceeds their market log value

Figure 4

The definition of ERoEI

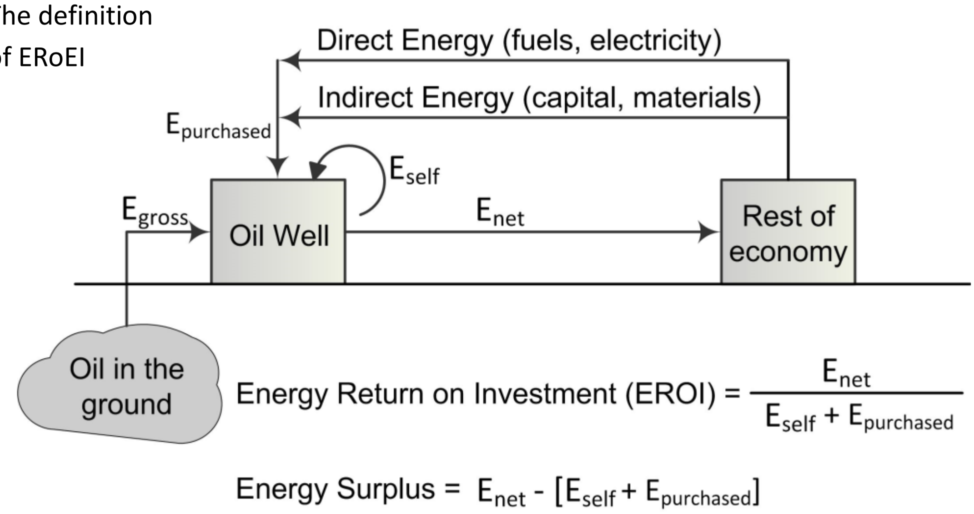


Figure 5

The implications of ERoEI

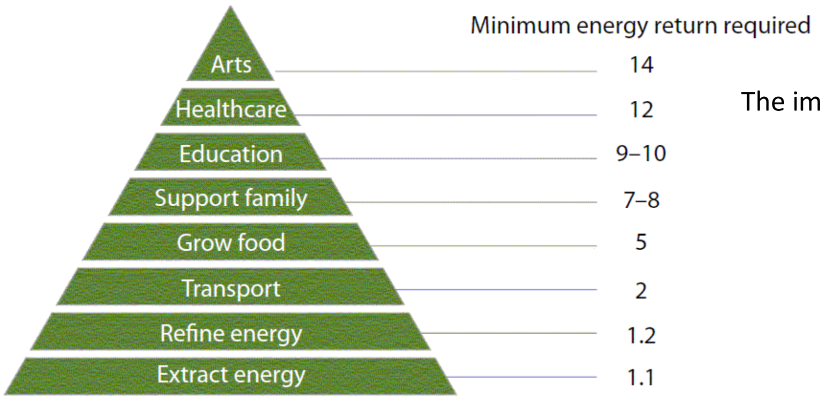


Figure 14: Energy returns required for human welfare

Source: Pedro A Prieto and Charles A S Hall, *Spain's Photovoltaic Revolution: The Energy Return on Investment*, Springer 2013

Figure 6

ERoEi diagram for woody biomass

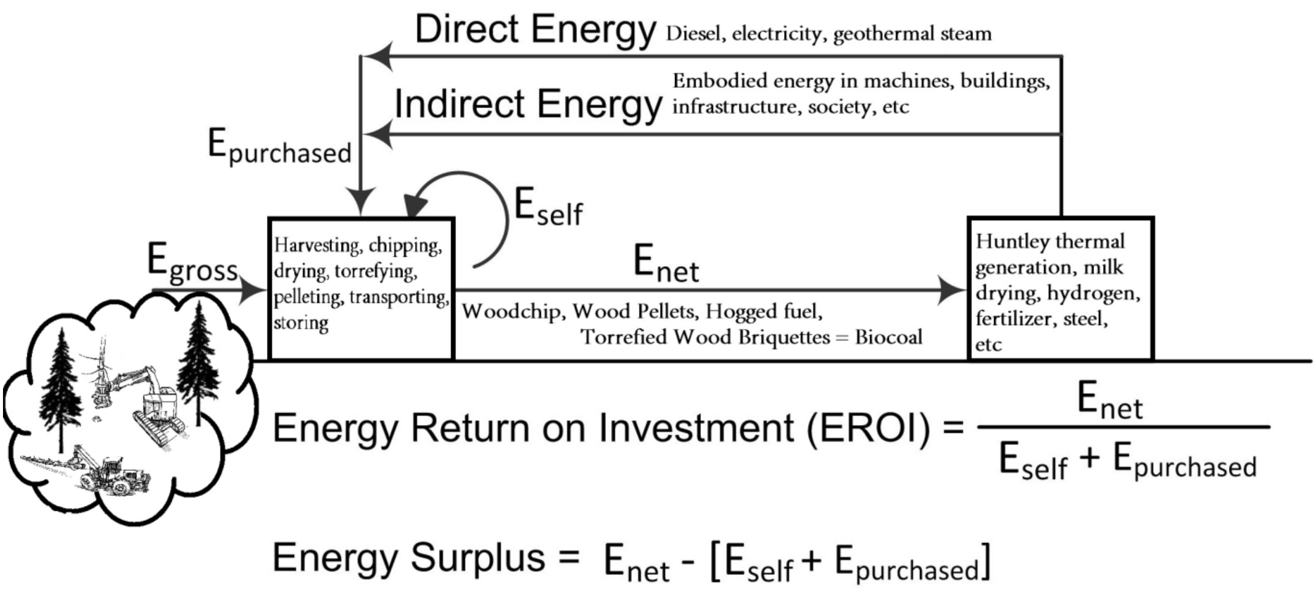
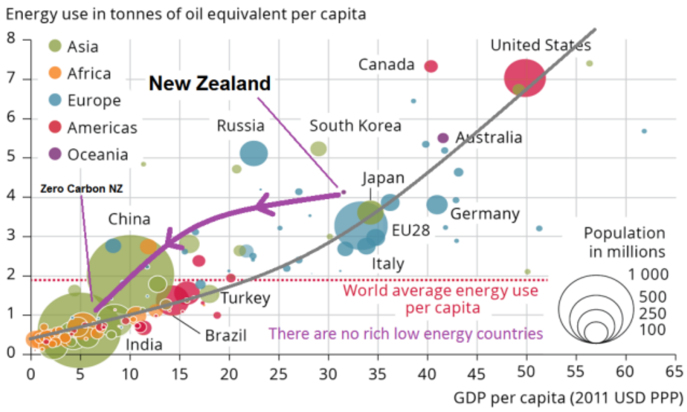


Figure 7

Low energy intensity life style



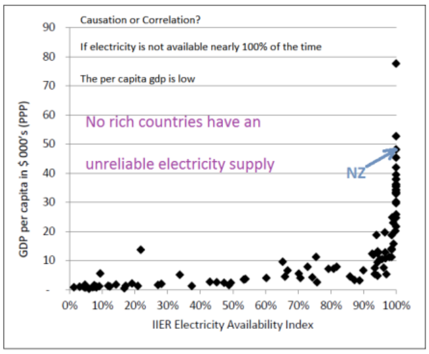
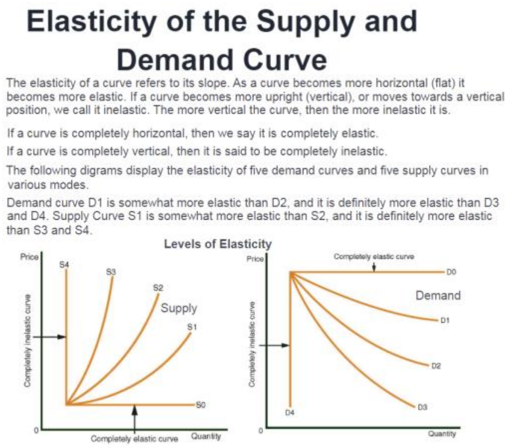


Figure 29 IIER Electricity Availability Index vs GDP/Capita (PPP) for 99 Countries

(Source: World Bank, WRI, EBRD 2010)

Figure 8



Elasticity of the Supply and Demand Curve

The elasticity of a curve refers to its slope. As a curve becomes more horizontal (flat) it becomes more elastic. If a curve becomes more upright (vertical), or moves towards a vertical position, we call it inelastic. The more vertical the curve, then the more inelastic it is.

If a curve is completely horizontal, then we say it is completely elastic.

If a curve is completely vertical, then it is said to be completely inelastic.

The following digrams display the elasticity of five demand curves and five supply curves in various modes.

Demand curve D1 is somewhat more elastic than D2, and it is definitely more elastic than D3 and D4. Supply Curve S1 is somewhat more elastic than S2, and it is definitely more elastic than S3 and S4.

Figure 9

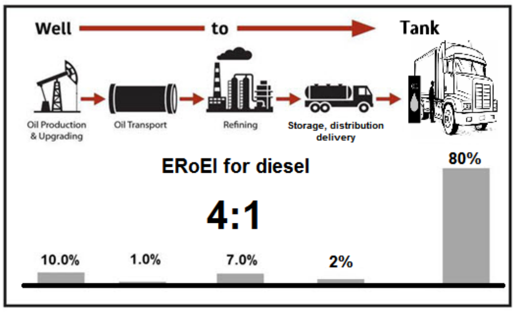
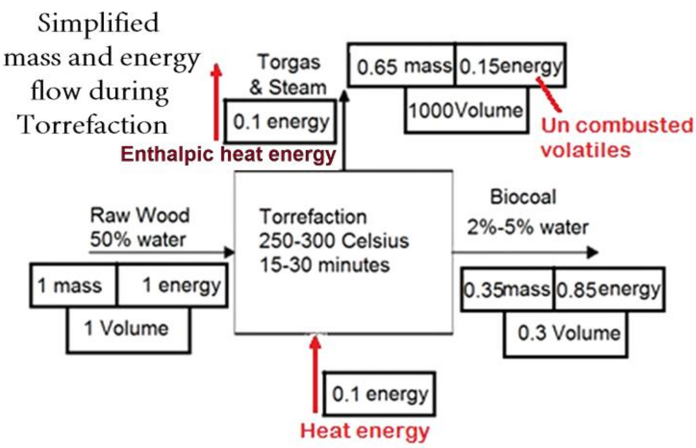
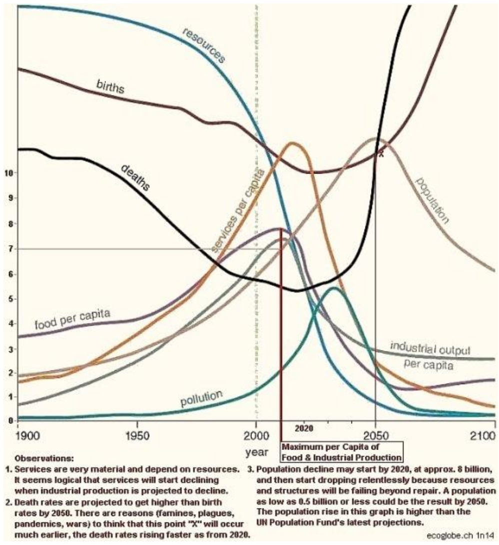


Figure 10





	A	B	C	D	E
1	Line description (Highlighted lines are most important, green numbers are user entered variables or constants)	woodchip	wood pellets dried using chip fuel	wood pellets dried using geothermal	Autodynamic biocoal production
2	nett GJ to be delivered	20	20	20	20
3	moisture content of harvested wood as a decimal fraction	0.56	0.56	0.56	0.56
4	energy content of harvested wood bone dry GJ/t	20.2	20.2	20.2	20.2
5	Actual gross energy content of harvested wood GJ/t	8.888	8.888	8.888	8.888
6	Nett LHV energy of harvested wood GJ/t	7.432	7.432	7.432	7.432
7	moisture content of product as decimal fraction	0.56	0.1	0.1	0.02
8	Energy to vapourise water GJ/t 0.35564GJ+2.257GJ	2.6	2.6	2.6	2.6
9	Actual drying efficiency as a decimal fraction	0.3	0.3	0.3	1
10	gross energy density of fuel GJ/t (torrefaction modifies the chemistry)	8.888	18.18	18.18	20.052
11	nett energy LHV of product GJ/t	7.432	17.92	17.92	20
12	tonnage product to be delivered t	2.691065662	1.116071429	1.116071429	1
13	tonnage to be harvested for product t	2.691065662	2.282873377	2.282873377	2.654206597
14	tonnage of water to be evapourated t	0	1.166801948	1.166801948	0
15	GJ required for drying wood, evapouration	0	3.033685065	0	0
16	multiplied by, dryer inefficiency factor	1	10.11228355		
17	extra tonnage harvested for processing fuel t	0	1.360640951	0	0
18	total to be harvested t	2.691065662	3.643514328	2.282873377	2.654206597
19	Harvesting Energy Gj/t	0.0965	0.0965	0.0965	0.0965
20	Actual harvesting energy GJ	0.259687836	0.351599133	0.220297281	0.256130937
21	transport out of forest to central plant km half the round trip	100	100	100	0
22	Round trip transport energy cost GJ/tkm	0.00164	0.00164	0.00164	0.00164
23	Transport energy to plant GJ	0.441334769	0.59753635	0.374391234	0
24	chipping energy GJ/t	0.0772	0.0772	0.0772	0
25	Actual chipping energy GJ	0.207750269	0.281279306	0.176237825	0
26	drying energy geothermal GJ/t of product	0	0	6.7	0
27	If geothermal energy was used, how much would be used GJ	0	0	7.477678571	0
28	pelletizing energy GJ/t	1.2	1.2	1.2	0
29	Actual Pelletizing energy GJ	0	1.339285714	1.339285714	0
30	geothermal CO2 emissions tCO2/GJ	0	0	0.0035	0
31	electricity supply CO2 emissions tCO2/GJ	0.025	0.025	0.025	0
32	Actual electricity CO2 t	0	0.033482143	0.033482143	0
33	Actual geothermal (if used) CO2 t	0	0	0.026171875	0
34	total wood invested energy GJ	0	12.09337677	0	3.538588235
35	Renewable emissions from wood fuel tCO2/GJ	0.09175	0.09175	0.09175	0.09175
36	Renewable emissions from invested wood fuel CO2 t	0	0.927802016	0	0.324665471
37	transport to furnace km, half the round trip	50	50	50	100
38	Furnace transport delivery energy GJ	0.220667384	0.091517857	0.091517857	0.164
39	total diesel used GJ	1.129440258	1.321932646	0.862444196	0.420130937
40	Multiplier eroei on diesel, Energy invested Well-to-Tank	1.2163	1.2163	1.2163	1.2163
41	Total diesel invested GJ	1.373738186	1.607866677	1.048990876	0.511005258
42	diesel emissions factor CO2t/GJ	0.069	0.069	0.069	0.069
43	total diesel emissions tonnes t	0.094787935	0.110942801	0.07238037	0.035259363
44	Product production description	Just fresh raw wood chip delivered to furnace, chipped at central plant	Central plant to chip wood and then dry final product using wood chips as fuel, pelleted using electricity	Central plant to chip wood and then dry final product using geothermal steam, pelleted using electricity	Autodynamic biocoal plant in forest
45	total non renewable emissions invested for this product t CO2	0.094787935	0.144424944	0.132034388	0.035259363
46	total renewable emissions invested for this product t CO2	0	0.927802016	0	0.324665471
47	total invested emissions renewable + non renewable	0.094787935	1.072226959	0.132034388	0.359924833
48	Emissions renewable from combusting product t CO2	2.19449408	1.861623884	1.861623884	1.839771
49	Total emission t CO2 invested and inherent	2.289282015	2.933850843	1.993658272	2.199695833
50	Total emissions CO2 t/GJ	0.114464101	0.146692542	0.099682914	0.109984792
51	EROEI (Energy return on non wood energy invested)	14.56	6.79	2.20	39.14
52	EROEI (Energy return on total energy invested, including wood fuel)	14.56	1.53	2.03	4.94
53	Cost of diesel $/GJ	$50.00	$50.00	$50.00	$50.00
54	Cost of electricity $/GJ	$50.00	$50.00	$50.00	$50.00
55	Cost of geothermal steam $/GJ	$8.00	$8.00	$8.00	$8.00
56	Cost of pipeline gas $/GJ	$11.00	$11.00	$11.00	$11.00
57	Cost of coal $/GJ	$6.00	$6.00	$6.00	$6.00
58	Cost of NZU $/t Carbon tax	$60.00	$60.00	$60.00	$60.00
59	Cost of coal including carbon tax $/GJ	$11.66	$11.66	$11.66	$11.66
60	Emissions cost $	$5.69	$8.67	$7.92	$2.12
61	Emissions cost $/GJ	$0.28	$0.43	$0.40	$0.11
62	Cost of non wood energy invested $	[redacted]	[redacted]	[redacted]	[redacted]
63	Cost of non wood energy invested $/GJ	[redacted]	[redacted]	[redacted]	[redacted]
64	Energy and NZU costs input (non wood) $/GJ	[redacted]	[redacted]	[redacted]	[redacted]
65	Cost of raw wood $/t (this is harvesting cost)	[redacted]	[redacted]	[redacted]	[redacted]
66	Raw material wood and energy input cost $/delivered GJ of product	[redacted]	[redacted]	[redacted]	[redacted]
67	Tonnes delivered for 20GJ	2.69	1.12	1.12	1.00
68	Cubic metres to be delivered for 20GJ (divided by density)	8.15	1.64	1.64	1.11
69	Raw material wood and energy input cost $ per delivered tonne	[redacted]	[redacted]	[redacted]	[redacted]
70	Raw material wood and energy input cost $ per delivered cubic metre	[redacted]	[redacted]	[redacted]	[redacted]
71	Energy density nett GJ/m3 (LHV)	2.45	12.19	12.19	18.00
72	Energy density nett GJ/tonne (LHV)	7.43	17.92	17.92	20.00
73	Kg CO2 (non renewable) per nett GJ delivered	4.74	7.22	6.60	1.76

	A	B	C	D	E
1	Line description (Highlighted lines are most important, green numbers are user entered variables or constants)	woodchip	wood pellets dried using chip fuel	wood pellets dried using geothermal	Autodynamic biocoal production
2	nett GJ to be delivered	20	20	20	20
3	moisture content of harvested wood as a decimal fraction	0.56	0.56	0.56	0.56
4	energy content of harvested wood bone dry GJ/t	20.2	20.2	20.2	20.2
5	Actual gross energy content of harvested wood GJ/t	=B4*(1-B3)	=C4*(1-C3)	=D4*(1-D3)	=E4*(1-E3)
6	Nett LHV energy of harvested wood GJ/t	=B5-((1*B3)*B8)	=C5-((1*C3)*C8)	=D5-((1*D3)*D8)	=E5-((1*E3)*E8)
7	moisture content of product as decimal fraction	0.56	0.1	0.1	0.02
8	Energy to vapourise water GJ/t 0.35564GJ+2.257GJ	2.6	2.6	2.6	2.6
9	Actual drying efficiency as a decimal fraction	0.3	0.3	0.3	1
10	gross energy density of fuel GJ/t (torrefaction modifies the chemistry)	=B4*(1-B7)	=C4*(1-C7)	=D4*(1-D7)	=20.052
11	nett energy LHV of product GJ/t	=B10-(B7*B8)	=C10-(C7*C8)	=D10-(D7*D8)	=E10-(E7*E8)
12	tonnage product to be delivered t	=B2/B11	=C2/C11	=D2/D11	=E2/E11
13	tonnage to be harvested for product t	=(B12*(1-B7))/(1-B3)	=(C12*(1-C7))/(1-C3)	=(D12*(1-D7))/(1-D3)	=((E10/E5)/85)*100
14	tonnage of water to be evapourated t	=B13-B12	=C13-C12	=D13-D12	0
15	GJ required for drying wood, evapouration	=B14*B8	=C14*C8	0	0
16	multiplied by, dryer inefficiency factor	1	=C15/C9		
17	extra tonnage harvested for processing fuel t	0	=(C16/C6)	0	0
18	total to be harvested t	=B13+B17	=C13+C17	=D13+D17	=E13+E17
19	Harvesting Energy Gj/t	0.0965	0.0965	0.0965	0.0965
20	Actual harvesting energy GJ	=(B13+B17)*B19	=(C13+C17)*C19	=(D13+D17)*D19	=(E13+E17)*E19
21	transport out of forest to central plant km half the round trip	100	100	100	0
22	Round trip transport energy cost GJ/tkm	0.00164	0.00164	0.00164	0.00164
23	Transport energy to plant GJ	=(B13+B17)*B21*B22	=(C13+C17)*C21*C22	=(D13+D17)*D21*D22	=(E13+E17)*E21*E22
24	chipping energy GJ/t	0.0772	0.0772	0.0772	0
25	Actual chipping energy GJ	=(B13+B17)*B24	=(C13+C17)*C24	=(D13+D17)*D24	0
26	drying energy geothermal GJ/t of product	0	0	6.7	0
27	If geothermal energy was used, how much would be used GJ	0	0	=D26*D12	0
28	pelletizing energy GJ/t	1.2	1.2	1.2	0
29	Actual Pelletizing energy GJ	0	=C28*C12	=D28*D12	0
30	geothermal CO2 emissions tCO2/GJ	0	0	0.0035	0
31	electricity supply CO2 emissions tCO2/GJ	0.025	0.025	0.025	0
32	Actual electricity CO2 t	0	=C29*C31	=D29*D31	0
33	Actual geothermal (if used) CO2 t	0	=C27*C30	=D27*D30	0
34	total wood invested energy GJ	0	=C17*C5	0	=((E5*E13)/100)*15
35	Renewable emissions from wood fuel tCO2/GJ	0.09175	0.09175	0.09175	0.09175
36	Renewable emissions from invested wood fuel CO2 t	=B15*B35	=C16*C35	0	=E34*E35
37	transport to furnace km, half the round trip	50	50	50	100
38	Furnace transport delivery energy GJ	=B12*B22*B37	=C12*C22*C37	=D12*D22*D37	=E12*E22*E37
39	total diesel used GJ	=B38+B25+B23+B20	=C38+C25+C23+C20	=D38+D25+D23+D20	=E38+E25+E23+E20
40	Multiplier eroei on diesel, Energy invested Well-to-Tank	1.2163	1.2163	1.2163	1.2163
41	Total diesel invested GJ	=B39*B40	=C39*C40	=D39*D40	=E39*E40
42	diesel emissions factor CO2t/GJ	0.069	0.069	0.069	0.069
43	total diesel emissions tonnes t	=B41*B42	=C41*C42	=D41*D42	=E41*E42
44	Product production description	Just fresh raw wood chip delivered to furnace, chipped at central plant	Central plant to chip wood and then dry final product using wood chips as fuel, pelleted using electricity	Central plant to chip wood and then dry final product using geothermal steam, pelleted using electricity	Autodynamic biocoal plant in forest
45	total non renewable emissions invested for this product t CO2	=B43	=C43+C32	=D43+D33+D32	=E43
46	total renewable emissions invested for this product t CO2	0	=C36	=D36	=E36
47	total invested emissions renewable + non renewable	=B45+B46	=C46+C45	=D46+D45	=E46+E45
48	Emissions renewable from combusting product t CO2	=B10*B12*B35	=C10*C12*C35	=D10*D12*D35	=E10*E12*E35
49	Total emission t CO2 invested and inherent	=B48+B47	=C48+C47	=D48+D47	=E48+E47
50	Total emissions CO2 t/GJ	=B49/B2	=C49/C2	=D49/D2	=E49/E2
51	EROEI (Energy return on non wood energy invested)	=B2/B41	=C2/(C41+C29)	=D2/(D41+D29+D26)	=E2/E41
52	EROEI (Energy return on total energy invested, including wood fuel)	=B2/B41	=C2/(C41+C29+C16)	=D2/(D41+D29+D27)	=E2/(E41+(((E13/100)*15)*E5))
53	Cost of diesel $/GJ	50	50	50	50
54	Cost of electricity $/GJ	50	50	50	50
55	Cost of geothermal steam $/GJ	8	8	8	8
56	Cost of pipeline gas $/GJ	11	11	11	11
57	Cost of coal $/GJ	6	6	6	6
58	Cost of NZU $/t Carbon tax	60	60	60	60
59	Cost of coal including carbon tax $/GJ	=B57+(B58*0.0944)	=C57+(C58*0.0944)	=D57+(D58*0.0944)	=E57+(E58*0.0944)
60	Emissions cost $	=B45*B58	=C45*C58	=D45*D58	=E45*E58
61	Emissions cost $/GJ	=B60/B2	=C60/C2	=D60/D2	=E60/E2
62	Cost of non wood energy invested $	[redacted]	[redacted]	[redacted]	[redacted]
63	Cost of non wood energy invested $/GJ	[redacted]	[redacted]	[redacted]	[redacted]
64	Energy and NZU costs input (non wood) $/GJ	[redacted]	[redacted]	[redacted]	[redacted]
65	Cost of raw wood $/t (this is harvesting cost)	[redacted]	[redacted]	[redacted]	[redacted]
66	Raw material wood and energy input cost $/delivered GJ of product	[redacted]	[redacted]	[redacted]	[redacted]
67	Tonnes delivered for 20GJ	=B12	=C12	=D12	=E12
68	Cubic metres to be delivered for 20GJ (divided by density)	=B67/0.33	=C67/0.68	=D67/0.68	=E67/0.9
69	Raw material wood and energy input cost $ per delivered tonne	[redacted]	[redacted]	[redacted]	[redacted]
70	Raw material wood and energy input cost $ per delivered cubic metre	[redacted]	[redacted]	[redacted]	[redacted]
71	Energy density nett GJ/m3 (LHV)	=B2/B68	=C2/C68	=D2/D68	=E2/E68
72	Energy density nett GJ/tonne (LHV)	=B2/B67	=C2/C67	=D2/D67	=E2/E67
73	Kg CO2 (non renewable) per nett GJ delivered	=(B45/B2) *1000	=(C45/C2) *1000	=(D45/D2) *1000	=(E45/E2) *1000

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