ENERGY RETURN ON INVESTMENT (EROI) FOR DISTRIBUTED POWER GENERATION FROM LOW-TEMPERATURE HEAT SOURCES USING THE ORGANIC RANKINE CYCLE

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ABSTRACT

Energy Return on (Energy) Investment, EROI, is a measure of the future energy benefit from energy expenditure. EROI can be used in addition to price signals to determine how an energy technology should inform energy policy. Organic Rankine Cycle (ORC) technologies are employed in a wide variety of plant sizes, designs and locations. The relationship between the capital cost of an energy generation technology and its EROI is non-linear, which suggests ORC technology has a wide range of possible EROI values depending on its design and size. This paper investigates the EROI of two ORC electricity generation plants and evaluates this against other technologies.

The first part of the paper investigates two ORC power plants as case studies. This investigation is to produce an estimate of the energy input required to build the plants and the resulting EROI. The second part of the paper briefly evaluates the calculated EROI compared to other technologies, and how this comparative energy cost might inform energy policy.

1. EROI ANALYSIS

The Energy Return on Investment (EROI) is the ratio of the energy delivered to society over the energy required to produce that energy delivery.

$$\mathrm{EROI} = \frac{\text{Energy Delivered by a process}}{\text{Energy Supplied to a process}} = \frac{D_{TOTAL}}{S_{TOTAL}} \qquad (1)$$

EROI is used to compare the quality of different energy technologies, as it shows the magnitude of the yield from an investment in terms of energy. EROI has been demonstrated as a measure of an energy source's capacity to facilitate net growth (Cleveland, Costanza, Hall, & Kaufmann, 1984).

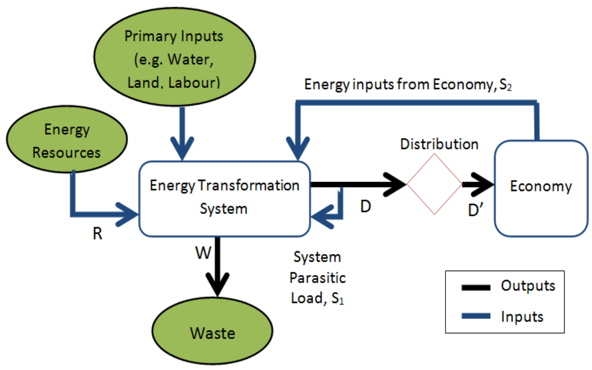

Figure 1) The energy - economy system as defined in this paper. Adapted from (Dale, 2010).

The EROI figure is can be used to compare the value of a technology outside of economic influences such as subsidies, government provisions and discount factors. EROI analysis is intended to highlight the change in level of investment necessary to extract energy over time. (C. W. King & Hall, 2011)

Through its relation to economies, it is expected that smaller, distributed systems of power generation will have a smaller EROI. These systems usually come at a greater cost than large, centralised systems. The extra expense of smaller systems can sometimes be mitigated through the reuse of existing materials.

1.1 General Methodology

Recent studies on EROI have been found to use a range of methodologies. The methodology a specific analysis uses is often chosen to best compare relevant aspects of a certain technology.

An attempt has been made by (Mulder & Hagens, 2008) to define a standard methodology for EROI analysis. Included in this methodology are various categories of EROI based on the chosen system boundary.

This methodology was further refined by (Murphy et al., 2011), who presented a more detailed definition of system boundaries. A simplified description of these system boundaries is detailed in Figure (2) below.

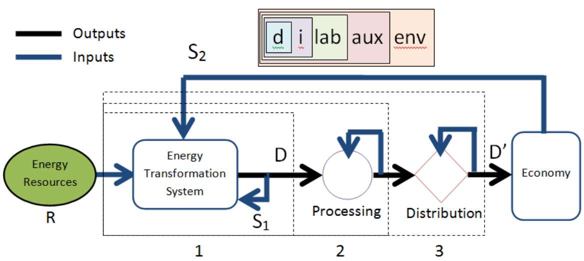

Figure 2) Model of energy - economy system showing system boundaries for EROI analysis. Adapted from (Murphy, Hall, Dale, & Cleveland, 2011)

The designations "d,i,lab,aux and env" represent direct, indirect, labour, auxiliary and environmental input from the economy. The simplest EROI calculations only investigate direct and indirect inputs. The system boundaries "1,2,3" represent the boundary levels extraction, processing and distribution respectively.

(Murphy & Hall, 2010) stated that larger system boundaries lead to lower calculated EROI values. Murphy introduced $EROI_{stnd}$ as a common benchmark to be used across all studies, on top of any other EROI values that are calculated.

$$\mathrm{EROI_{stnd}} = \mathrm{EROI_{1,i}} = \frac{\mathrm{D}}{\mathrm{S_{2d}+S_{2i}}} \quad (2)$$

This equation includes the direct and indirect energy material inputs for the extraction of the energy resource.

A further analysis, $EROI_{3,i}$ includes consideration for the processing and distribution costs such as transformers and power lines to connect an electrical plant to the grid.

$$\mathrm{EROI_{3,i}} = \frac{\mathrm{D'}}{\mathrm{S_{2d}+S_{2i}}} \quad (3)$$

Figure (1) depicts this as the net energy distributed by the system (which accounts for S_1), divided by the direct ($\mathrm{S_{2d}}$) and indirect ($\mathrm{S_{2i}}$) costs drawn from the economy in order to produce and distribute this energy.

A study into the EROI of the Nesjavellir geothermal steam power plant in Iceland has recently been published (Atlason & Unnthorsson, 2013). The Nesjavellir power plant produces 120 MW gross electricity and 300 MW of hot water as a co-product, delivered as district heating. The power plant was constructed by Icelandic engineering firms and commissioned in 1990. Nesjavellir provides an interesting opportunity for comparison, as it is a large power plant using a proven technology that also required a large amount of infrastructure to be built in order to supply the electricity and hot water to its customers.

1.2 Study Procedure

In order to be compared with Nesjavellir, the two case studies in this analysis are performed using a similar framework to the study by (Atlason & Unnthorsson, 2013). The $EROI_{stnd}$ and $EROI_{3,i}$ are calculated in this study. Decommissioning energy costs are not included in the study, in line with the Nesjavellir study.

A limitation of high level energy analysis is the availability of energy data. As pricing information is usually more available than energy data, it was often necessary to estimate the energy embodied in a part or service by using an energy intensity conversion. This conversion relates that average amount of MJ required per dollar spent within various industries.

$$S_2[MJ] = \$_{investment}[\$] \cdot e_{investment}[\tfrac{MJ}{\$}] \quad (4)$$

Equation (4) shows a significant limitation of this analysis, as it assumes that every dollar spent has the same energy intensity. The most suitable figure for a conversion rate found was in a paper by (Murphy et al., 2011), who quoted 14 MJ/$ in the U.S heavy and energy industry in 2005. The energy intensity figure was adjusted for inflation where necessary by using the U.S. consumer price index (B. o. L. Statistics, 2013) as recommended in (Murphy et al., 2011). Prices quoted in NZD were converted to USD by using the exchange rate at the time of quotation. The PureCycle turbines investigated are manufactured in the U.S. by United Technologies (UTC Pratt & Whitney, 2009).

A key aspect of EROI analysis is whether the energy produced by the cycle that is used in the process (system pumps etc.), is to be included in the numerator or denominator (S_1 in Figure 1). This study uses the "investors' view" as given in (Weißbach et al., 2013), where parasitic energy used at the plant is taken from the numerator, $\mathrm{E_S}$. This differs from the Nesjavellir study, and so the results are adjusted for comparison in Section 5.

1.3 Binary power generation system

The power cycle investigated in the study is the binary (ORC) geothermal cycle. The study investigates small scale units to estimate the reduction in EROI resulting from inefficiencies in small scale electricity production. ORCs were chosen as they are more commonly used then steam for small scale, distributed production (DiPippo, 2011).

Both the case studies investigate UTC PureCycle turbines as they are intended to utilize the potential advantages of smaller scale production. United Technologies advertise the PureCycle turbine as being relatively affordable, as 92% of its hardware is adopted from the existing mass-produced Carrier refrigeration line (UTC Pratt & Whitney, 2009).

2. CASE STUDY 1 - WAIKITE

The Waikite site was chosen for a comparative analysis as it is uniquely situated near electricity infrastructure and an existing hot water use. This means that connection of the plant requires negligible power line and hot water piping development, which accounted for about a third of the total embodied energy in the Nesjavellir study.

The Waikite site uses a hot (97°C) water spring, and so no geothermal well drilling will be necessary for the project. The Waikite plant is intended to use low-ODP R245fa refrigerant.

While no power plant at the Waikite site has actually been constructed, a feasibility analysis was performed by East Harbour Energy (White, 2009), with funding from EECA. Prices quoted in the study were in NZD, converted from USD at an exchange rate of 0.62 USD/NZD where applicable.

Table 1) Capital budget for the proposed Waikite plant. Costs are in 2009 NZD and USD. Adapted From(White, 2009).

Plant Capital Cost	NZD	USD
Planning	***$135,000***	***$83,700***
Generation Plant	**$1,048,000**	**$649,760**
UTC Genset, cooling tower, spares	$781,000	$484,220
Building incl. foundations	$95,000	$58,900
Pumps, Pipework and balance of plant	$48,000	$29,760
Consultancy and project management	*$44,500*	*$27,590*
Contingency	$80,000	$49,600
Electrical Connection and controls	**$120,000**	**$74,400**
Transformers	$50,000	$31,000
Wiring/Switchgear	$25,000	$15,500
Consulting Fees	*$10,000*	*$6,200*
Controls and Instrumentation	$10,000	$6,200
Contingency	$25,000	$15,500
Total Energy Capital Budget	$1,114,000	$690,680
Total Capital Budget	**$1,303,500**	**$808,170**

The figures shown in italics in Table (1) were deemed not to be associated with the U.S. energy industry or energy intensive, and so were not converted to an energy cost using the energy intensity equation (4).

2.1 Power generation at Waikite

The gross power output of the proposed geothermal power plant is 272 kW. A capacity factor of 92% is used in the feasibility study. This gives the Waikite plant an annual production of 7897 GJ.

After being used for power generation, the Waikite geothermal water is then cooled to 40°C and used for the nearby Waikite hot pools.

2.2 Energy component calculation

2.2.1 Power usage at site

From the feasibility study, the single largest parasitic energy use is from the system working fluid pump, using 27 kW of the 272 kW produced. Some pump work is also required to pressurize the supply water and return the exiting water to the cooling baffles for the hot pools. The energy load of the fans in the condenser and ancillary pumps to move the hot water was estimated at 26 kW.

The power usage at the site reduces the energy delivered, D and D' to 219 kW.

2.2.2 Maintenance

A maintenance budget was provided with the feasibility study. The budgeted "Total Energy Operating Cost" (Table 2), was found to be 5.80% of the "Total Energy Capital Budget" per year.

Table 2) Expected annual operating costs for Waikite 272kW Binary power plant. Items in italics are not included in the energy cost conversion.

Operating Costs	NZD	USD
Balance of plant - parts, labour	$24,000	$14880
Ancillary systems servicing	$5,000	$3100
Routine Service, breakdown attendance and operational support	$35,610	$22078
Daily fixed charge - electrical connection	*$7,000*	*$4340*
Rates	*$3,000*	*$1860*
Site Rental	*$10,000*	*$6200*
Total Energy Operating Cost/Year	**$64,610**	**$40,058**
Total Operating Cost / Year	***$84,610***	***$52,458***

As no other data was available on the maintenance of the plant, the cost-based estimate in Table (2) was used. The total energy operating cost ($) was converted to an energy value (GJ) by using the estimated energy intensity for the US energy industry as outlined in section 1.2. An adjusted value of 12.96 MJ/USD$ in 2009 (when the price was quoted), gives a maintenance energy cost estimate of 519 GJ/yr.

2.2.3 Transportation

The power system in the feasibility study was a United Technologies (UTC) Turboden PureCycle 280 modular ORC unit. This unit is produced in the US with a shipping weight of 12,519 kg and an operating weight of 15,104 kg (UTC Pratt & Whitney, 2009).

The energy required to ship the materials from Los Angeles to the port of Tauranga was considered. The sea route between these destinations is around 10461 km. The Hapag Lloyd ship 'Coral Bay' was chosen for the analysis as it frequently travels between these two destinations. This ship will perform the journey in 296 hours.

A typical bunker oil usage for a ship such as this is about 0.00315 kg / km / tonne carried. By using an average energy value for oil of 41.87 GJ/tonne (APS, 2013), the total energy required for the transport was calculated. Approximately 17.3 GJ was needed to transport the materials via ship from Los Angeles to Tauranga. As the energy required for transportation was found to be relatively small, a more detailed analysis was not conducted.

2.2.4. Groundwork and station house

As the expected site for the plant rests at the end of a car park, minimal groundwork is necessary for the plant. The Waikite plant study reserved a capital budget for 'Building incl. foundations' of $58,900 USD. By using the average energy intensity for the U.S. energy industry adjusted to 2009 dollars, a total energy cost of 763 GJ was estimated for groundwork.

2.2.5. Energy transfer system to user

As the delivery system for the surface water to the hot pools is already in place, there is negligible expected energy cost for building a hot water transfer system from the plant.

There are some expected costs associated with the transfer of electricity from the plant to the nearby 11kV power lines. This includes a transformer, wiring and switchgear with an expected budget of $31,000 USD for transformers and $15,500 USD for wiring and switchgear. By using the energy intensity conversion from part 1.2, this equates to an energy cost of 602 GJ.

2.2.6. Pumping, fans and pipework

Like the transport, groundwork and energy transfer system, this cost is relatively minimal in the Waikite plant scenario.

It was determined in the feasibility study that the water supply is not sufficient to satisfy the cooling load. Cooling towers would be necessary in order to recirculate the cooling water. A low-noise water-cooled cooling tower was used in the study requiring about 4 liters/s of make-up water from a borehole down the valley.

The cost of pumps, pipework, working fluid storage and transfer is quoted as $29,760 USD. The additional cost of the cooling tower and fans was included with the turbine genset number in the bill, and so an estimation of this cost component must be made. At the cooling requirements expected, this cost of a similar unit is about $97,960 USD, but this is only an approximation (Cooling Tower Systems, 2013).

Using the energy intensity conversion from part 1.2., this equates to a total energy cost of 1655 GJ.

2.2.7. Power generation equipment

The price of the genset minus cooling tower, spare parts, controls and contingency costs was estimated to be $457,560 USD. Using the energy intensity conversion from part 1.2, the energy cost can be estimated as 5929 GJ.

2.2.8 Sum of embodied energy.

The total embodied energy for the plant was calculated as 8966 GJ. With operation and maintenance, this gives an energy payback time (EROI = 1) of 1.5 years.

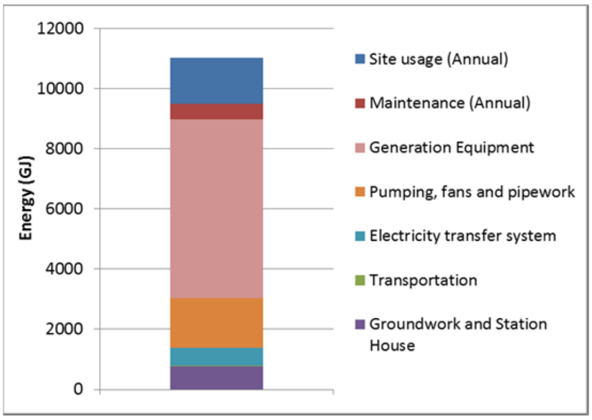

Figure 3) Relative distribution of embodied energy for the Waikite plant after one year of operation.

2.3 EROI of Waikite.

The Waikite plant has negligible costs associated with the distance from the plant to the connection point with the end user. This means that all the aspects enclosed by the $EROI_{3,i}$ are also included in the $EROI_{stnd}$. With an expected lifetime of 20 years, the Waikite plant has an $EROI_{stnd}$ and $EROI_{3,i}$ of 6.6.

Table 3) Calculated $EROI_{3,i}$(=$EROI_{stnd}$) for Waikite hot springs geothermal plant.

Year	Output (GJ)	Input (GJ)	EROI
1	6358	9485	0.7
10	78968	14156	4.5
20	157935	19346	6.6
30	236903	24536	7.8
40	315870	29726	8.6

3. CASE STUDY 2 – CHENA HOT SPRINGS, ALASKA

The Chena binary geothermal power plant is a unique case that has received much attention in literature. It is frequently noted as the lowest temperature commercial binary power generation plant in the world. The plant was built to replace expensive diesel generation in the remote region of Chena, Alaska.

The Chena power plant uses two 200 kW UTC PureCycle 200 ORC systems utilizing 73°C geothermal water as a heat source and R134a as the working fluid. These units are similar to the PureCycle 280 units investigated in the Waikite study. Unlike the Waikite plant, a large amount of surrounding infrastructure was necessary for the project, including geothermal well drilling, reinjection and an air cooled condenser (ACC). This investigation looks at the effect that this extra infrastructure has on the EROI of the project.

A third 280 kW unit has now been installed at Chena, but this is not included on the analysis. The analysis is based on data presented to January 2006 when only one of the two units used an air cooled condenser to increase net power output in winter.

3.1 Power generation at Chena.

From August 2006 until September 2009, the average gross per unit power output when running was 266 kW (Karl, 2009). In order to more accurately compare the Chena plant with Waikite, a 92% capacity factor is assumed with an average net output of 210 kW. This gives Chena an estimated annual net energy output of 15445 GJ.

3.2 Energy component calculation

The Chena project also used a US built PureCycle unit similar to Waikite, but the plant is remote and so its development required extra costs for transportation of equipment and skilled labour. As a result, the capital cost of the Chena plant is relatively expensive.

Chena has a specific capital cost of $4780 US$/kW, compared to $3690 US$/kW at Waikite . Although both sites use similar basic UTC plants, Chena has additional costs associated with extra equipment, transport, labour and a higher labour compensation rate. For comparison, the US labour cost for manufacturing in 2011 was $35.53 USD, compared to $23.38 USD for NZ (U. S. Statistics, 2011).

Transport is highly energy intensive, whereas labor is not. As a detailed budget for the Chena plant could not be found, it is difficult to properly account for the variation in energy intensity for the Chena project compared to Waikite. The study assumes that the energy intensity variation of transport and labour costs roughly negate one another, and so the energy intensity of 13.6MJ/$ (Dec, 2006) for the U.S. energy industry is used in Equation (4) as a best estimate of the energy costs.

3.2.1 Power usage at site

The Chena site is unique as it has been designed to switch between air and once-through water cooling in order to generate the greatest power output. The water cooling system requires no power as it siphons a water flow from a large well about 10 m higher in the valley.

The fans of the air condenser system require 24 kW of power when in use. The air cooled condenser is intended to be switched on during 'subzero' temperatures using manual valves. As the average air temperature at Chena Hot Springs was generally sub-zero between October 2012 to May 2013 (Weather, 2013), it was assumed that the ACC is usually switched on for 212 days between these dates. This gives the ACC an annual power draw estimate of 404 GJ.

A well pump is used in order to move the geothermal water from the well into the power plant. This pump has a variable speed drive up to 75kW, but is estimated to operate at an average of 32 kW from operational data, requiring 929 GJ annually.

The system pumps for the working fluid require 40 kW per unit during operation or 1161 GJ each annually.

The site equipment has an average total energy usage of 3656 GJ / year.

3.2.2 Maintenance

The maintenance cost was assumed to be the same as for the Waikite Hot Springs case study, at 5.8% of the embodied energy cost.

3.2.3. Transportation of plant

The transportation cost of the plant to the site was assumed to be the same 17.3 GJ requirement multiplied by 1.79 to account for the heavier weight of the plant. This gave a transportation cost of 31.0 GJ.

3.2.4. Energy transfer system to user

The transport of geothermal water from the well to the plant required 914 m of 8" HDPE pipe to be installed. The well was cased to a depth of 137 m. The reinjection well is located near the power plant building and did not require significant piping. In order to transport cold water to the once-through condenser, 820 m of 16" steel piping was required. All the piping used the Chena project was recycled or reused from other projects in Alaska (Holdman, 2007).

As the Chena system is required to be stand-alone, the inclusion of a 3MW uninterruptable power supply (UPS) battery system was necessary to supply a consistent voltage. Some modification had to be made to the marginal power distribution structure in order to support the binary power generation modules.

3.2.5. Embodied energy in plant and groundwork

The Chena plant required extensive groundwork, as it was built in an undeveloped location. The specific cost of this component is not included in the data gathered, so this was included in the overall embodied energy calculation.

Most of the surrounding geothermal resource had undergone extensive mapping prior to project commencement. The cost of this prior mapping was not included in the analysis.

The overall project expenses totaled $2,007,770 USD (Holdman, 2007). In the Waikite study, 85.5% of the total project cost was attributable to energy related expenses (i.e. excluding consultation and planning). Using this same figure for Chena, the energy related price becomes $1,716,643 USD. By using an energy intensity of 13.6 MJ/$US (Dec. 2006), converted using the consumer price index, the embodied energy for the plant and groundwork was estimated at 23,271 GJ.

3.3 EROI of Chena

Table 4) Calculated $EROI_{3,i}$ for Chena hot springs geothermal plant.

Year	Output (GJ)	Input (GJ)	EROI
1	11789	24881	0.5
10	117891	39082	3.0
20	235782	54868	4.3
30	353672	70654	5.0
40	471564	86440	5.5

4. ANALYSIS

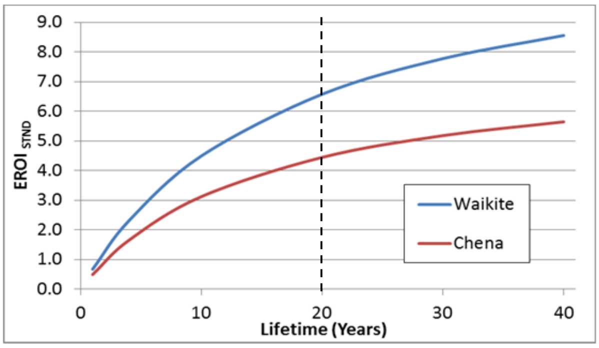

Figure 4) EROI calculated for Chena and the Proposed Waikite plant. The vertical line shows the expected twenty year lifetime of the Waikite plant.

Figure (4) shows that the EROI of Chena is less than that of Waikite at all stages throughout its lifetime. This is attributable to Chena having a larger initial energy cost, as the surrounding exploration and infrastructure requirements are significant for the Chena power plant, yet negligible for Waikite. The smaller EROI of Chena contrasts with how it has been successfully built, while no further investment has taken place into power generation at Waikite. Chena is isolated from the main grid in Alaska, and so a distributed power solution was necessary, whereas cheap grid electricity is readily available at Waikite.

The energy payback period is the time it takes for the EROI to reach a value of one. An energy transformation system will become net energy producers after this time period. The payback period is 1.5 years for Waikite and 2.5 for Chena.

Figure (4) shows that EROI of the two plants most quickly increases during the first years of operation, and grows slower when ongoing maintenance becomes a large proportion of the overall energy cost. If these binary geothermal plants were to continue operation a further twenty years past their expected lifetime, the EROI of Waikite will increase by a further 2.0, while Chena will only increase its EROI by 1.2.

A comparison of the EROI of major electricity resources with the magnitude of their use is shown in Figure (5).

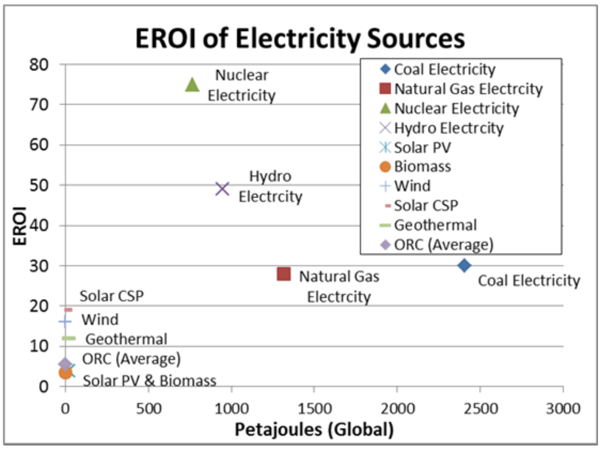

Figure 5) EROI of various electricity sources over global usage. Energy usage data from (IEA, 2012). EROI values from (Weißbach et al., 2013)

Figure (5) indicates that resources that can produce a high EROI over their lifetime are favored for electricity generation. Hydro generation is currently the only renewable resource that produces a globally significant amount of electricity, with geothermal a far second.

Renewable energies are found to be more capital intensive, with lower operational costs (C. King, 2013). This cost distribution over a project's lifetime will produce a flatter EROI curve than fuel-based generation for the same EROI in a given timeframe. A flatter EROI curve is less favorable in investment scenarios, as it implies a high capital cost.

The average EROI of the two small scale ORC plants is shown in Figure (5). The average EROI of 5.5 places it in the middle of the renewable technologies, with a greater energy return than solar PV and biomass, but less than traditional steam geothermal. Larger binary cycle plants may have an EROI approaching that of traditional steam geothermal. Case studies performed by (Felicito M, 2011) indicate that the capital cost per kW generation capacity (specific capital cost) of a larger 20MW binary plant is around 60% of a 200kW plant. A NZGA study by (SKM, 2009) estimated the specific capital cost of a 20 MW ORC plant to be 23% higher than a comparable condensing single flash steam plant. Using the methodology in this study, the EROI value of renewable power generation can be closely linked with specific capital cost, and so it could be expected that a larger ORC plant will have an EROI value close to flash steam geothermal.

5. COMPARISON WITH NESJAVELLIR POWER PLANT IN ICELAND

In order to compare the EROI figures calculated for Waikite and Chena with the figures from Nesjavellir power plant by (Atlason & Unnthorsson, 2013), a modified EROI equation had to be used. This modification places the gross output in the numerator and adds the parasitic loss to the denominator.

$$EROI_{3,i\,Nesjavellir} = \frac{D+S_1}{S_2+S_1} \quad (4)$$

Using equation (4), the (Atlason & Unnthorsson, 2013) study found that Nesjavellir power plant in Iceland has an $EROI_{3,i}$ of 9.3 if the hot water production is not included. The Waikite system analyzed had an $EROI_{3,i}$ of 3.2 after 20 years. Chena had an $EROI_{3,i}$ of 2.4.

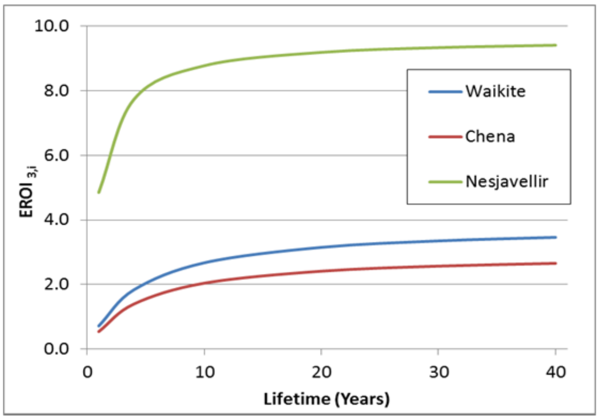

Figure 6) EROI standard for Chena, Waikite and Nesjavellir power plants, using EROI figures as calclated by (Atlason & Unnthorsson, 2013).

Figure (6) shows that the shape of all the EROI curves is similar, with all three plants nearing their respective maximum $EROI_{3,i\,Nes}$ after 20 years. The lower EROI of Waikite and Chena indicate that the small ORCs are a poorer energy investment. On top of this, the operation load is a smaller proportion of the annual energy cost for the ORCs than Nesjavellir, so Equation (4) skews the EROI comparison in favor of the ORCs.

6. CONCLUSION

The EROI of the proposed Waikite and existing Chena small scale binary plants was calculated. The $EROI_{3,i}$ was calculated as 6.6 for Waikite and 4.3 for Chena after a twenty year lifetime.

An $EROI_{stnd}$ value of 6.6 was calculated for the Waikite site, which can be used for comparison with other studies where the site-specific distribution cost is intended to be ignored. An $EROI_{stnd}$ value was not calculated for Chena hot springs power plant in Alaska as insufficient information was available.

When compared to a large scale traditional power plant at Nesjavellir, the EROI of Waikite and Chena was seen to be much smaller in comparison. The shape of the EROI over lifetime curves were found to be similar for all three plants in the investigation, indicating that the relative cost of initial capital and the continued maintenance and parasitic load was comparable for both geothermal technologies.

The EROI analysis was performed on two case studies. The Waikite case study was on a plant that is yet to exist, using information contained in a feasibility study for the site. The Chena analysis used real data to estimate its energy requirements. The comparable methodology and results of both studies show that the EROI of an energy resource may be estimated at the feasibility stage. This practice may prove to be a useful way to compare and highlight trends in the necessary level of investment required to utilise prospective energy resources.

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