Energy Return on Investment of Hydroelectric Power Generation Calculated Using a Standardised Methodology

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Abstract

The aim was to study the Energy Return on Investment (EROI) for the Fljotsdalsstod hydroelectric power plant (690 MW) using real data and a previously proposed standard. Energy return on investment is the ratio between the output and input energy. In this study we calculate the EROI within three defined boundaries, which include different parameters. Results show that over the 100-year lifetime, the plant is expected to deliver an EROI of approximately 110. The largest energy-consuming factor was the own usage, followed by the indirect energy used in the production of the construction materials. Since this study uses a standardised methodology, it can be compared to future studies. To date, this has not been possible since no standard methodology has been used in past studies.

1. Introduction

At present, pressure is put forward by society that the earth's resources should be used in the most efficient manner possible. Efficiency in the energy production sector and further utilisation of renewable energy sources is also a key factor in the battle against climate change. Energy Return on Investment (EROI) is the study of efficiency of any energy generating process. The methodology does not investigate the efficiency of certain components, such as the turbine or generator but investigates the energy efficiency of the system as a function of operational time. The methodology has mostly been used to study energy sources such as oil, coal and gas but has also been used to study energy efficiencies in food production, i.e., agriculture, aquaculture and fisheries.

EROI analysis provides a quantifiable output, which should in essence be able to be compared to other similar studies. However, most EROI studies do not follow the same methodology and are therefore not comparable. This issue is directly addressed in this study where a proposed standard put forward in 2011 by Murphy et al. [1] is used for calculations. If a resource has a relatively high EROI, it means that the energy production returns significantly more energy into the economy than was used to produce it. If a resource on the other hand provides a low EROI, less energy is available to society. It therefore provides less energy for the production of goods and services [1, 2]. EROI studies can provide a deeper insight into a resource base than only by investigating the reserves of the resource. For example, approximately 170 billion barrels of crude oil are located in the tar sands

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in Canada. However, the EROI of that resource is only around 3:1, which means that 1 quarter of the total resource goes back into recovering the other 3 quarters [1]. The production of oil from tar sands may however be feasible due to high oil prices. EROI results are often above the value of 1. This is because environmental factors such as sunlight are excluded from the boundaries. Sunlight is a public good and is not taken from the economy. EROI provides the ratio between the energy consumed from the economy and delivered back by the system in question.

In this study, the methodology was used to examine the energy efficiency at Fljotsdalsstod hydroelectric power plant, located on northeastern Iceland. Gilliland et al. [3] and Kubiszewski et al. [4] estimate the EROI of hydropower to be around 11.2 and 12 respectively for small hydro plants. Gilliand however also reported of EROI for the Fries, VA (2.1 MW) power plant to be around 33. Murphy et al. [5] estimate the EROI of hydropower to be greater than 100. Cagnon et al. [6] show that a reservoir plant can be estimated to have an EROI of 205 and a run of river plant an EROI of 267. The low EROI values reported by Gilliland can be attributed to the small size of the hydro plants under study. The smallest 1,05 MW and largest 6,5 MW. This is further underlined by Weissbach et al. [7] that state that small hydro plants (sub-MW) have a low EROI, whereas very large plants may have an EROI over 100. There seems therefore to be a link between the EROI of hydro and the size of the power plants. There is however, uncertainty around the EROI of hydro, as various studies have provided differing results. Schoenberg [8] however points out that the results from hydro power plants are very site specific and a single EROI value can hardly be used to describe the EROI of hydropower in general. Schoenberg [8] contributes the difference in EROI results for hydro to the difference in geological conditions and the use of various different technologies. Previous studies also use different methodologies and boundaries and are therefore hard to compare. The uncertainty factor the methodologies bring is however eliminated in this study.

Oil has previously been observed to have a relatively high EROI. However, this was back in the 1930's where it had an EROI of approximately 100. Today, oil has dropped down to 10 - 20 [9, 10] and is most likely heading further downwards if this trend continues. Back in the 1930's, coal had an EROI similar to oil, but has not dropped as significantly. Around 1975, the EROI for coal had dropped to approximately 50, but has risen since then and was approximately 80 in 1992 [9]. In 2000 the EROI for coal was still estimated to be around 80 [11]. The rise coal experienced after 1975 might be attributed to new coal mine discoveries or advancement in mining technology. There is some uncertainty surrounding the EROI of nuclear. Studies have shown its EROI to be around 5-15 [12], and even down to the EROI of 1 [13], while other studies have claimed it to be in the neighborhood of 100 [14]. Some have claimed that EROI studies can be coloured by prejudice, which is potentially one of the reasons nuclear has scored so low in general [15]. However, as was the case with nuclear, cases have been reported where the EROI of hydro was in the neighborhood of 100 [5], and even up to 205 and 267 [6]. In 1975, the EROI of geothermal was shown to be between 10 and 12 for an electricity producing plant [16]. This was recently confirmed by another study done in Iceland using the recently proposed standard EROI methodology [17]. The plant in Iceland also produced hot water for district heating and therefore scored a higher EROI. After integrating the hot water production, the Icelandic geothermal plant scored an EROI of approximately 33 [17]. EROI for wind turbines and wind farms have been studied where the average EROI was shown to be 25.2 [18, 19]. One must however keep in mind that wind turbines and wind farms are very location and size dependent and therefore the EROI values vary greatly between studies.

In this study the energy payback times (EPT), along with the EROI_{stnd}, $\text{EROI}_{3,i}$ and EROI_{ide} is calculated for the Fljotsdalsstod hydroelectric plant in using a previously proposed standard methodology which has at present not been used to calculate the EROI of hydroelectric power plants. Using this methodology, it is possible to compare future EROI studies with regards to hydro.

2. Methods and materials

The EROI equation can be described as follows [20]:

$$EROI = \frac{ED_{out} + \sum \nu_j O_j}{ED_{in} + \sum \gamma_\kappa I_\kappa} \tag{1}$$

Where ED_{out} is the direct energy output, ν_j is a set of well-defined non-energy co-product outputs, O_j is the energy per unit of the given non-energy output co-product, ED_{in} is the direct energy input, γ_κ is a set of well-defined non-energy input coefficient and I_κ is the energy per unit of the given coefficient. Such non-energy inputs as are described in Equation 1 can for example be regarded as material inputs for the construction of the plant. They have been allocated energy values according to their embodied energy, that is, the energy used to produce the materials. However, several factors are ignored in this equation, these include environmental, social and economic effects. It does relate to all these factors, but does not describe the efficiency of the studied plant with regards to these factors. For example, an oil field might have a favourable EROI, but the result might be extensive pollution and negative social consequences. This is generally missing in the EROI literature. Furthermore, Equation 1 does also not describe any set of boundaries. In 2011, Murphy et al. [1] proposed a standard methodology, the boundaries they proposed are used in this study, namely EROI_{stnd} and $\text{EROI}_{3,i}$.

When EROI calculations are carried out, the boundaries must be well defined in the beginning stages of the study. The boundaries represent what is to be included and excluded from the calculations. Is the energy used for transportation of materials to the building site included, maintenance of the power plant or the energy it uses in daily operation? The lack of standard boundaries have plagued EROI calculations in the past, as a result, comparison between different EROI studies is not possible. The boundaries used in this study are the same used in the study by Atlason & Unnthorsson [17] where the EROI of Nesjavellir geothermal power plant was calculated. By using the same methodology, those results can effectively be compared. These are EROI_{stnd}, $\text{EROI}_{3,i}$ and EROI_{ide}. In the EROI_{stnd} calculations the construction of the power plant itself is included, and the direct energy output from the plant. This includes the embodied energy in all the materials used for construction. This also includes the oil used on site for construction and maintenance of the plant and associated dams for the next 100 years. It further includes all energy used in road construction and all soil handling activities which took place during the production of the power plant. $\text{EROI}_{3,i}$ includes the same parameters as EROI_{stnd} but also includes the delivery of the energy to the consumer. That means that the construction of the power lines is included, that is, the embodied energy in the electric wires as well as the towers and their foundations. The energy used for groundwork in the tower construction is also included. This study also calculates a new EROI_{ide}. The EROI_{ide} includes the same inputs as the EROI_{stnd} but instead of calculating the output from the plant from real data, it assumes that the plant utilises all the potential energy in the falling water. This would in essence make the plant 100% efficient, experiencing no losses and shows an upper EROI limit which the plant can strive to reach. A much more detailed description of the boundaries can be seen in the literature [1].

The lifetime scenario in this study is 100 years which was determined by an LCA report examining Fljotsdalsstod [21]. Previous studies examining the EROI of hydro have also used 100 year time-periods [6] further strengthening the decision to use this time frame. In this study, the EROI is calculated as a function of time. Further clarification of the methodology and boundaries can be found in the article on Nesjavellir [17], since the exact same methodology was used in this study.

2.1. $EROI_{ide}$

EROI$_{ide}$ describes the highest possible EROI of a power plant when all losses due to friction and energy transformation are omitted. It essentially highlights where the room for improvement is at a particular plant. Equation 2 shows how this is to be calculated:

$$EROI_{ide} = \frac{\sum \beta}{ED_{in} + \sum \gamma_\kappa I_\kappa} \tag{2}$$

Where β is the installed capacity of the power plant, omitting all losses on the way. ED_{in} is the energy required for building, operating and maintaining the power plant, γ_κ is a set of well-defined co-efficient input and I_κ is the energy per unit of the given input co-efficient.To be able to retrieve β, one must assume that the total installed capacity of the power plant is utilised and no losses, which occur due to friction for example, are omitted. In the case of Fljotsdalsstod, the installed capacity is 690 MW. That translates to 21.76 PJ output annually. This is theoretically unachievable but shows an upper boundary for that particular power plant. One might assume that the maximum output from the power plant would equal to the maximum flow of water to the plant, this is however beyond the maximum capacity of the installed machinery, which in turn account for the inputs to the EROI calculations.

2.2. Energy payback time

The energy payback time (EPT) shows when a given plant starts to deliver surplus energy. This is the time from when the plant started operating until it has either, produced the same amount of energy it took to construct it, maintain it and operate over the lifetime of the plant. Or when a given plant reaches an EROI of 1 when energy expenditures are in chronological order. Both methods are explained in the following sections. The input in the equation can be described as:

$$x(t) = a + (b + c) \cdot t \tag{3}$$

Where x is the input energy over (t) time, a is the initial construction energy, including embodied energy within construction materials, b accounts for maintenance for a given time period, c is the power consumed by the power plant over a period of time t. The output is described as the function:

$$y(t) = d \cdot t \tag{4}$$

Where d is the output from the plant. The energy payback time is reached using method 1 when

$$y(t) = x(T) \tag{5}$$

Where T is the expected lifetime of the plant and y is the output of energy for a given time period. Using method 2, the energy payback time is reached when

$$y(t) = x(t) \tag{6}$$

2.2.1. Method 1, lifetime energy use

This method includes the energy it took to originally construct the given plants, but also includes the total energy used to maintain it and operate over its lifetime. This method will show when the plant will be producing net energy, with all energy expenditures included. In this method, the annual output is divided by the total energy used for maintenance, operation and construction over the 100 years lifetime of the plant.

2.2.2. Method 2, real time energy use

This method does not include future energy expenditures, but energy expenditures in chronological order. This method shows when the plant reaches an EROI of 1 in real time. This method might be considered to show better when the plant starts to pay off in energy terms. The difference between this method and the previous is that the total energy used in operation and maintenance is not summed up and included with the plant construction, but is considered to be ongoing throughout the lifetime of the plant. The $\text{EROI}_{3,i}$ scenario is used in both calculations. One must however keep in mind that maintenance of various parts is not conducted continually, but happens between long intervals. It is however difficult to predict when such maintenance activities occur. The Energy payback time using real time energy use gives an idea of how long the energy payback time is, but can be expected to differ to some minor extent.

2.3. Fljotsdalsstod hydroelectric power plant

Construction of dams for the Fljotsdalsstod hydroelectric power plant began in 2003, and four years later the plant was in operation. Producing 690 MW, Fljotsdalsstod consists of 6 115 MW Francis turbines. Annually, the plant produces approximately 4.600 GWh. The total fall of water is 600 meters before hitting the turbines. First, water travels from the lagoons to the plant, falling only 200 meters during the total distance of approximately 72 km, and finally falling 400 meters vertically. Two major reservoirs deliver water to the plant. These are Halslon reservoir and Ufsalon reservoir. Electricity is subsequently delivered through overhead power lines over a distance of approximately 50 km to power heavy industries. The maximum input of water possible to the plant is stated to be 144 m^3/s [22].

2.4. Parts calculated

In this study, various parts are included as an input to Equation 1. These being, 1) Own usage by the plant, 2) Maintenance, 3) Transportation to Iceland, 4) Energy transfer infrastructure, 5) Preparation stages, 6) Construction stage, 7) Production of electrical equipment. Real data was gathered from the power company with regards to energy transfer infrastructure, preparation stages, construction stage and electrical equipment. Information on the own usage by the plant was also gathered from the power company (Landsvirkjun). The assumptions on maintenance were adopted from an LCA report done specifically on this power plant [21].

2.4.1. Power usage at site

According to Landsvirkjun, the own usage of the plant can be approximated to be 0.5% of its electricity production [23]. However, this can vary between years, but can be expected to be around the given number on average. This amounts to approximately 86,400 GJ per year, or 8,640,000 GJ over the first 100 years of operation.

2.4.2. Maintenance

A life cycle analysis was done on Fljotsdalsstod where the environmental impact by the plant was examined. There, 50% of the concrete constructions are expected to be renewed after the first 100 years. Therefore 0.5% of the energy consumed in its production will be accounted for annually in maintenance [21]. Concrete maintenance is assumed to consume 7,400 GJ annually. It is also stated in the LCA report about Fljotsdalsstod that after 60 years, the engine and electrical equipment at the stationhouse have been replaced. Therefore this study will account for constant maintenance up to year 60, and then it will continue the maintenance of the new appliances. It is therefore considered that the maintenance will account for 1.6% of the original engine and electrical appliance embodied energy annually. This amounts to 3,300 GJ per year, or 331,600 GJ for the first 100 years of the plants life since it is assumed that no maintenance will occur the first year of operation.

2.4.3. Transportation

Because of the good set of data acquired for Fljotsdalsstod, the total oil consumption of transporting all relevant materials to Iceland had already been calculated. This totaled in 218.2 m^3 of oil for the three most relevant stages of the plant. These stages include Preparation (13.2 m^3), general construction (161.6 m^3) and Engines and electronic appliances (43.3 m^3). In total, transportation of materials to Iceland amounted to 8,300 GJ. However, this number is included in the embodied energy within relevant phases and are not excluded from the calculations of the total energy.

2.4.4. Groundwork

Fljotsdalslina 3 & 4, and all soil handling for the general Karahnjukar dam, amount to the biggest energy consumption in regards to soil handling. Road construction, Desjarardalur dam and Saudardalsstifla dam did not amount for such vast energy consumption as the other stages. Table 1 lists the relevant phases included in the calculations. The total energy consumption at the soil handling stage amounts to 187,200 GJ.

Table 1: General distribution of energy use at the soil handling stage.

Groundwork phase	Energy (GJ)
Fljotsdalsl. 3&4	65,410
Karahnj. dam	71,481
Desjararad. dam	21,024
Road construction	20,895
Saudardals. dam	8,409
Total	187,200

2.4.5. Embodied energy of the energy transfer system

Fljotsdalslina power lines 3 and 4 travel from Fljotsdalsstod to an aluminium plant in Reydarfjordur. The total length of Fljotsdalsslina 3 is approximately 49 km and Fljotsdalslina 4 53 km [24]. These overhead lines were fully constructed in January 2007. The lines are 400 kV high voltage lines, they were operated with 220 kV voltage to begin with. All towers are steel constructed, whilst 83 of them are constructed to withstand avalanches. In total, there are 326 towers with the average distance of 315 meters. Landsnet provided information about the lines. The towers are of various size and shape. The total weight of normal tower is 2,750 tonnes, whereas the total weight of the avalanche towers is 3,230 tonnes [24]. In total, the towers include 5,980 tonnes of steel. On average, 5.9 tonnes of steel is used for every km the line travels. Given that the embodied energy of steel is 35.3 GJ/t, the amount of energy used in production of the steel can be calculated to be approximately 211,000 GJ. In total 12,275 m^3 of concrete was used for the foundations supporting the towers [24]. 2.07 GJ is embodied within every 1 m^3 of concrete, which amounts to 25,400 GJ. Reinforcement steel used in the foundations amounts to 1,187 tonnes, which in total has 41,900 GJ embodied energy. When summed up, the total energy embodied within these two lines amounts to 278,400 GJ.

2.4.6. Energy used in the preparation stage

At the preparation stages, roads were constructed and general preparation work was done. However, not only soil was handled at the preparation stage. For example, steel was used for drainage at some stages and petroleum was used in the process. Real data was acquired about the amount of material used at these stages. The stages are listed in table 2 with the given embodied energy of each stage. The total embodied energy in the preparation stages amounts to roughly 32,000 GJ.

Table 2: General distribution of energy use at the preparation stage.

Preparation stage	Energy (GJ)
Karahnjukavegur road	13,000
Fljotsdalsheidarvegur road	6,800
Mulavegur road	1,300
Holsufsavegur road	19
Halsvegur road	3,400
Hraunvegur road	2,500
Maint. of Karahn. & Hraunv. roads	141
Bridge Jokulsa i Dal	2,200
Bridge Jokulsa i Fljotsdal	1,000
Facilities in Karahnjukar	750
Station house	408
Erection of facilities	77
Total	31,500

2.4.7. Energy used at the construction stage

At the construction phase, the embodied energy of all construction materials was calculated. The values were derived from the literature as before. Karahnjukar dam contributed to the largest amount of embodied energy, or 2,765,000 GJ. This is mostly due to the vast amount of concrete used at site. The relative distribution can be seen in Table 3. An extravagant amount of energy is associated with Hraunveita dam and the flow tunnels. Other phases like the service house only account for a minimal amount of energy embodied within the energy used in its construction. This analysis also accounts for oil used by machinery to transport the materials to site.

Table 3: General distribution of energy use at the construction stage.

Stage	Energy (GJ)
Karahnjukar dam	2,765,000
Saudardalsstifla dam	248,300
Desjarardalur dam	16,900
Flow tunnels	559,800
Station house	256,100
Drainage ditch	22,600
Service house	12,900
Hraunveita ditch	480,200
Engines & electrical	245,500
Total	4,607,300

2.4.8. Energy used in the production of electrical equipment

This stage contains of 4 different sub-stages. These are engines and electrical equipment, transformers, stationhouse cranes and cables. In total, the embodied energy amounted to 209,300 GJ. Most of which are associated to the production of engines and electrical equipment. Table 4 lists the amount of energy associated with each phase.

Table 4: Amount of energy associated with each phase of electrical and engine production at Fljotsdalsstod.

Stage	Energy (GJ)
Engine and electrical appliances	96,700
Transformers	69,800
Stationhouse cranes	1,700
Cables	41,100
Total	209,300

2.5. Sum of all energy expenditures

When all phases have been calculated, the sum of them can be seen to be just above 5,000,000 GJ within the $EROI_{3,i}$ boundaries. 187,200 GJ were estimated to have been used in the soil handling prior to the construction. Energy used in the preparation work such as road construction amounted to 31,500 GJ, maintenance is estimated to use approximately 3,300 GJ per year. Transporting all the materials to Iceland amounted to 8,300 GJ. Embodied energy in the electrical cables and their foundations amounted to 278,400 GJ. The largest energy consuming part was shown to be the construction of the dams and relevant structures, which amounted to 4,607,300 GJ when including the embodied energy. We estimate that 209,400 GJ were used in the production of the electrical equipment and that the plant uses 0.5% of its own energy for daily operations, which amounts to approximately 84,000 GJ per year. The distribution between different phases over the first 100-year lifetime of the plant can further be seen in Figure 1. It is shown that the embodied energy within the construction materials is not the largest energy-consuming factor of the plant over its lifetime. Just like Nesjavellir geothermal power plant [17], energy consumption at site is the biggest

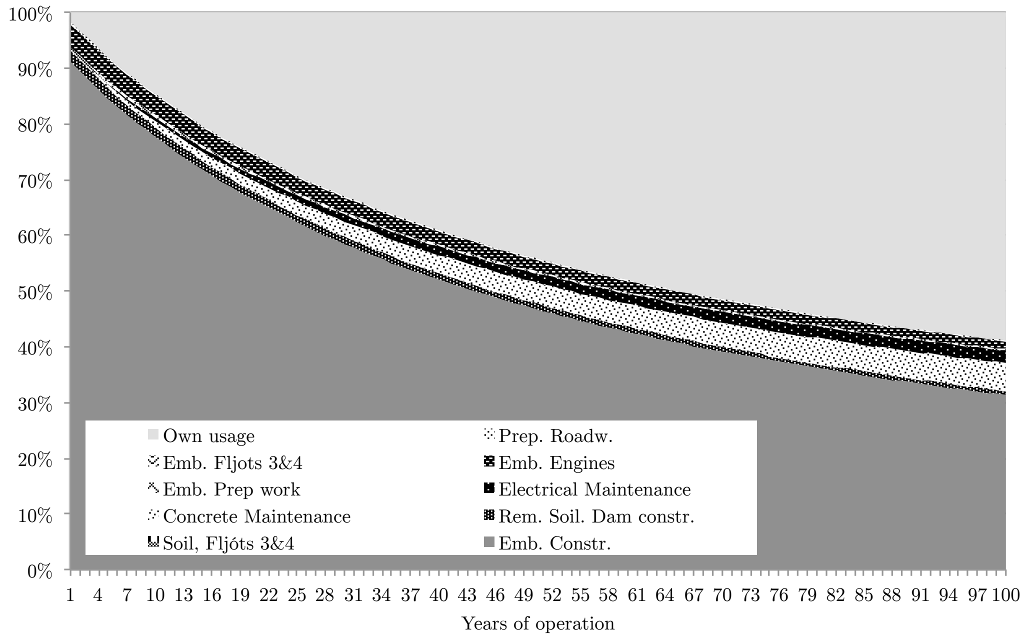

Figure 1: Relative distribution between energy usages at Fljotsdalsstod for the first 100 years. The horizontal axis shows years.

in the form of own usage, even though it is only 0.5% per year of its production. The total energy consumed within the $\text{EROI}_{3,i}$ boundaries is 15,026,200 GJ over the first 100 years of operation.

3. Results

Results were calculated for 3 EROI scenarios, EROI_{stnd}, $\text{EROI}_{3,i}$ and EROI_{ide}. Also, two scenarios calculating the energy payback time were calculated

3.1. $EROI_{stnd}$

As stated above, the EROI_{stnd} is the indirect and direct inputs to the plant, but only the energy output without delivery to the consumer. In the case of Fljotsdalsstod power plant, this will include the inputs mentioned in previous sections, but will exclude the mechanisms for delivering the energy, namely Fljotsdalslina 3 and 4. This calculation will also exclude all soil handling operations associated with the power lines. The input is calculated to be 5,057,300 GJ for the first year, which is the entire input factor summed up, plus the operational power usage; maintenance is excluded for the first year. The EROI_{stnd} scenario can be seen in Table 5.

This scenario shows that the EROI_{stnd} is 112.7 over the first 100 years of the plants lifetime of the plant. Figure 2 explains the development of the EROI_{stnd}.

Table 5: EROI values within different boundaries

$EROI_{stnd}$			
Year	Output (PJ)	Input (PJ)	EROI value
1	16.56	5.05	3.27
20	331.2	6.9	47.9
40	662.4	8.85	74.8
60	993.6	10.79	92
80	1,324.8	12.73	104
100	1,656.0	14.68	112.7
EROI3,i			
Year	Output (PJ)	Input (PJ)	EROI value
1	16.56	5.4	3
20	331.2	7.2	45.6
40	662.4	9.2	72
60	993.6	11.1	89.2
80	1,324.8	13.1	101.2
100	1,656.0	15.0	110.2
EROIide			
Year	Output (PJ)	Input (PJ)	EROI value
1	21.76	5.3	4
20	435.2	5.5	78.8
40	870.4	5.7	151.7
60	1,305.6	5.9	219.3
80	1,740.8	6.1	282.1
100	2,176.0	6.3	340.7

3.2. $EROI_{3,i}$ calculation

As before, the $EROI_{3,i}$ includes the hardware to deliver the energy to the consumer, which in this case is an aluminum smelter. These calculations will therefore include the Nesjavallalina power line 3 & 4. Table 5 further shows the EROI development over the first 100 years of the plant's lifetime. It can be seen that over the first 100 years of the operational life of the plant, the $EROI_{3,i}$ is at 110.2 but is still rising. The lifetime of the plant is however not known, but it is assumed that it will operate for 100 years. Figure 2 shows the development of the $EROI_{3,i}$ for Fljotsdalsstod.

3.3. $EROI_{ide}$

With the knowledge of the total input required to construct, maintain and operate Fljotsdalsstod power plant and the associated constructions over its lifetime, it is possible to calculate the $EROI_{ide}$ as was described in Equation 4. In the $EROI_{ide}$ calculations, it is assumed that the plant uses no energy itself and all losses are omitted hence it is 100% efficient. Table 5 shows the $EROI_{ide}$ for the same intervals as the EROI calculated previously.

The numbers provided in Table 5 show the EROI of the power plant if it was 100% efficient. This excludes all friction that can occur at the pipes when the water is on its way from the lagoons towards the stationhouse (head losses), losses in the turbine, generator and other mechanics. Table

5 illustrates that the $EROI_{ide}$ increases almost linearly the whole lifetime. The $EROI_{ide}$ is 340.7 after 100 years. This EROI represents the upper limits of the plant capacity.

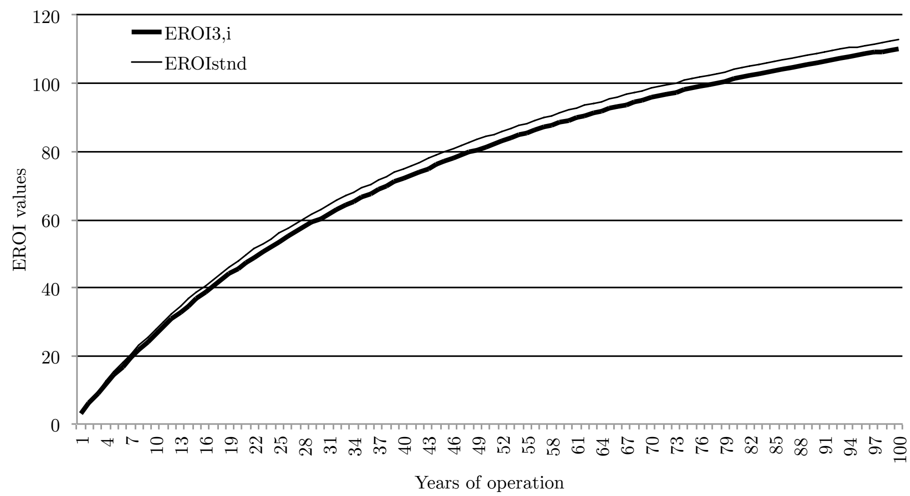

Figure 2: EROI development at Fljotsdalsstod over 100 years

3.4. Energy payback time

As was done for Nesjavellir geothermal power plant, the energy payback time was calculated for Fljotsdalsstod hydro power plant using the two methods. Method 1 shows that the $EROI_{stnd}$ and $EROI_{3,i}$ were found to have almost the same amount of energy payback time or just less than a year. Figure 3 depicts different energy payback times using method 1. Using method 2, one can

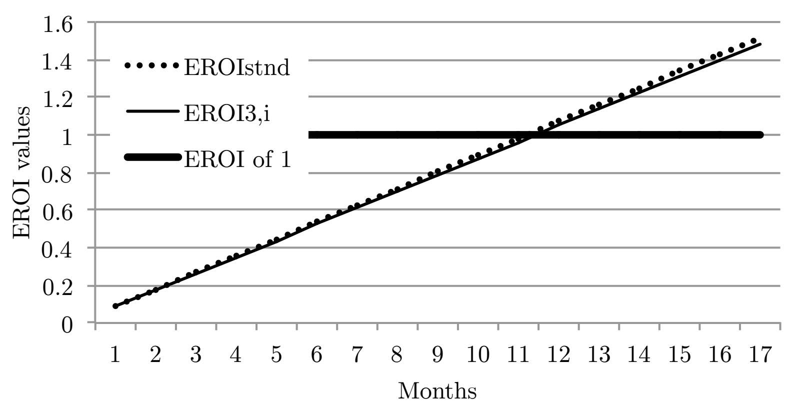

Figure 3: Different energy payback times of the different EROI scenarios calculated using method 1.

see that as was expected, the $EROI_{stnd}$ and $EROI_{3,i}$ were shown to have almost identical energy payback time, or 17 - 18 weeks. Results from method 2 can further be seen in Figure 4.

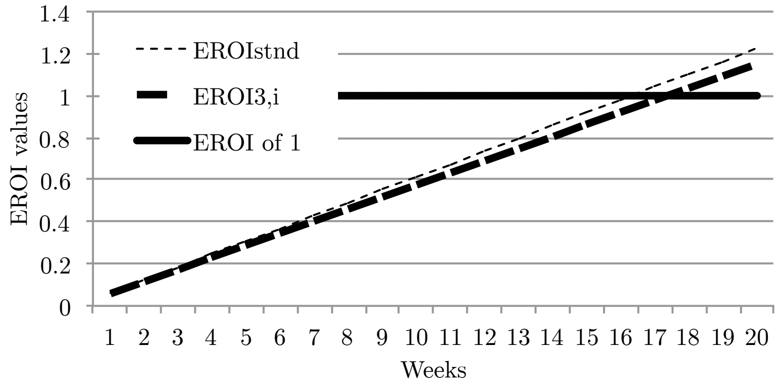

Figure 4: Energy payback time using method 2, where inputs are in chronological order.

3.5. Sensitivity analysis

To determine how much the variables affect the EROI of Fljotsdalsstod, a sensitivity analysis was conducted. Given the own consumption of Fljotsdalsstod is much less than of Nesjavellir geothermal power plant, it is not realistic to assume an increase from 0.5% of own usage to 10%. Therefore, this analysis will account for intervals of 0.2% increase up to a total of 2% of own usage, and maintenance increase from 1% per year, up to 5%. This is illustrated in Table 6. It shows that even though the maintenance is increased by 5% of the original embodied energy within electrical appliances and concrete, the $\text{EROI}_{3,i}$ does not change significantly over the 100 year lifetime of the plant. It is however shown, that if the plants energy consumption increases slightly, the EROI decreases significantly. The scenario for the sensitivity analysis was the $\text{EROI}_{3,i}$.

Table 6: Results from a sensitivity analysis. The top horizontal column shows the increase in overall maintenance and the left vertical column the amount of own usage. The variable shown is the $\text{EROI}_{3,i}$.

-	1%	2%	3%	4%	5%
0.2%	164.9	164.4	163.5	162.4	160.9
0.4%	124.0	123.7	123.2	122.6	121.7
0.6%	99.4	99.2	98.9	98.4	97.9
0.8%	82.9	82.8	82.5	82.2	81.9
1.0%	71.1	71.0	70.8	70.6	70.3
1.2%	62.3	62.2	62.1	61.9	61.7
1.4%	55.4	55.3	55.2	55.1	54.9
1.6%	49.8	49.8	49.7	49.6	49.5
1.8%	45.3	45.3	45.2	45.1	45.0
2.0%	41.6	41.5	41.5	41.4	41.3

4. Discussion

The results from this study indicates that the EROI of hydroelectric generation is higher than most other EROI's of renewable energy sources calculated so far. Such studies should however be

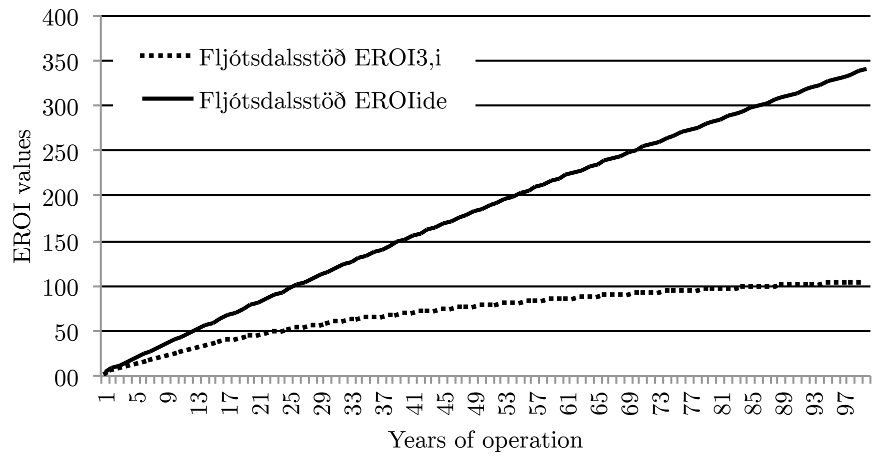

Figure 5: Room for EROI improvement at Fljotsdalsstod.

compared keeping in mind that previous studies have not necessarily followed the same methodology. This is an issue which this study addresses directly. Hydroelectric energy production has shown to provide some of the highest EROI available today, such statements should however be questioned until other renewable energy technologies have been investigated using the proposed standard.

This study showed the room for improvements available. This was shown when EROI_{ide} was calculated to be 340.7 and therefore the room for improvement at the power plant can be seen. Figure 5 depicts clearly the upper limit set for Fljotsdalsstod and the room for improvement.

It was shown by the sensitivity analysis that own consumption did have a major effect on the EROI. If the plants energy consumption increased slightly, the EROI decreased significantly. Therefore, stakeholders were contacted and the own consumption clarified. The own consumption might be a little more one year, but a little less the next. On average, the own consumption is only 0.5%. Increase in maintenance does not show to have any great impact on the EROI, even if overall maintenance went up by 5%, the EROI only dropped by approximately 4. This indicates that maintenance should be of high priority, since appropriately working mechanism will keep the own consumption at minimum. If the own consumption would be decreased even more, the EROI would rise substantially. The results show that own consumption accounts for the most amount of energy, this is in conjunction with Nesjavellir geothermal plant, where own consumption was shown to be the biggest input factor [17]. However, embodied energy and direct energy used in the construction of the plant amounted almost for as much energy as the own consumption. Energy payback time was calculated to be around one year using method 1, and around 4 months using method 2. This proved to be a little shorter period of time than at Nesjavellir geothermal power plant, where the plant was shown to pay back its energy expenditures in approximately 1 year and 3 months using method 1. However, using method 2, where energy expenditures are put in chronological order, Nesjavellir paid back its energy quicker, where the EROI_{stnd} and $\text{EROI}_{3,i}$ scenarios where shown to pay the energy back in 2 - 3 weeks [17]. Further EROI research in the field of renewable energy sources using the proposed boundaries is suggested, this would allow for a clearer comparison of energy sources and allow stakeholders to make better informed decisions on which energy source to pursue.

5. Conclusions

Methods for harnessing energy that have high EROI's are preferable over those that have low EROI's as they provide more energy to society than they consume (during construction and operation). This paper calculated the EROI of a 690 MW hydroelectric plant located in Iceland using a standardised methodology proposed by Murphy et al [1]. Standardised methodology is essential in order to effectively compare EROI studies. This means, that the results of this paper can be compared to other EROI studies if the same methodology is followed. Such comparison is important when evaluating and choosing between different energy production technologies. Hence the EROI calculations presented both in this article and the one by Atlason & Unnthorsson [17] can prove beneficial to policy makers involved in energy policy making, and strengthen their decision making. The use of the EROI_{ide} can also prove beneficial to locate low hanging fruits where efficiency can be improved. The EROI_{ide} can also assist policy makers by providing a clearer image of which electricity producing technology has potential for improvements in its production life cycle and where these potentials are.

This study confirmed that the Fljotsdalsstod hydroelectric power plant delivers an EROI of approximately 110 during its operational lifetime. This means that for every 1 unit of energy that is t used for the construction and operation of the power plant is returned 110 fold back into the economy.

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References

[1] D. J. Murphy, C. A. Hall, M. Dale, C. Cleveland, Order from chaos: A preliminary protocol for determining the eroi of fuels, Sustainability 3 (10) (2011) 1888–1907.

[2] F. Kreith, Bang for the buck, Mechanical Engineering 134 (5) (2012) 26–31.

[3] M. Gilliland, Net energy of seven small-scale hydroelectric power plants, Tech. rep., U.S. Department of Energy (1981).

[4] I. Kubiszewski, C. J. Cleveland, P. K. Endres, Meta-analysis of net energy return for wind power systems, Renewable Energy 35 (1) (2010) 218–225.

[5] D. J. Murphy, C. A. S. Hall, Year in review—eroi or energy return on (energy) invested, Annals of the New York Academy of Sciences 1185 (1) (2010) 102–118.

[6] L. Gagnon, C. Belanger, Y. Uchiyama, Life - cycle assessment of electricity generation options : The status of research in year 2001, Energy Policy 30 (14) (2002) 1267.

[7] D. Weissbach, G. Ruprecht, A. Huke, K. Czerski, S. Gottlieb, A. Hussein, Energy intensities, erois (energy returned on invested), and energy payback times of electricity generating power plants, Energy 52 (0) (2013) 210 – 221. doi:http://dx.doi.org/10.1016/j.energy.2013.01.029.
URL http://www.sciencedirect.com/science/article/pii/S0360544213000492

[8] Schoenberg, The energy return on investment of (industrial) solar - passive solar, pv, wind and hydro (2008) [cited 08.11.2012].
URL http://www.theoildrum.com/node/3910

[9] C. Cleveland, Net energy from the extraction of oil and gas in the united states, Energy 30 (5) (2005) 769–782.

[10] C. J. Cleveland, R. Costanza, C. A. S. Hall, R. Kaufmann, Energy and the u.s. economy: A biophysical perspective, Science 225 (4665) (1984) 890–897.

[11] F. Blanch, S. Schels, G. Soares, M. Haase, D. Hynes, Biofuels driving global oil supply growth, Global Energy Weekly 6.
URL http://ethanolrfa.3cdn.net/18ecc0a8e735d5e936_30m6i2xo5.pdf

[12] L. Manfred, Life cycle energy and greenhouse gas emissions of nuclear energy: A review, Energy Conversion and Management 49 (8) (2008) 2178–2199.

[13] G. T. Sr, R. Costanza, R. G. Fowler, The net-energy yield of nuclear power, Energy 13 (1) (1988) 73–81.

[14] Nuclearinfo, Nuclear power education - the benefits of nuclear power (n.d.) [cited 11.03.2011].
URL http://nuclearinfo.net/Nuclearpower/TheBenefitsOfNuclearPower

[15] N. Hagens, The energy return of nuclear power (eroi) (2008) [cited 01.02.2012].
URL http://www.theoildrum.com/node/3877

[16] M. W. Gilliland, Energy analysis and public policy, Science 189 (4208) (1975) 1051–1056.

[17] R. S. Atlason, R. Unnthorsson, Hot water production improves the energy return on investment of geothermal power plants, Energy 51 (0) (2013) 273–280. doi:http://dx.doi.org/10.1016/j.energy.2013.01.003.
URL http://www.sciencedirect.com/science/article/pii/S0360544213000121

[18] I. Kubiszewski, C. J. Cleveland, P. K. Endres, P. Saundry, Energy return on investment (eroi) for wind energy, The Encyclopedia of Earth, last updated June 18.

[19] I. Kubiszewski, C. J. Cleveland, P. K. Endres, Meta-analysis of net energy return for wind power systems, Renewable energy 35 (1) (2010) 218–225.

[20] K. Mulder, N. J. Hagens, Energy return on investment : toward a consistent framework, Ambio 37 (2) (2008) 74–79.

[21] R. Olafsdóttir, Vistferilsgreining raforkuvinnslu med vatnsafli - fljotsdalsstod, Tech. rep., EFLA verkfraedistofa (2011).

[22] Landsvirkjun, Fljotsdalsstod (n.d.) [cited 06.06.2012].
URL http://www.landsvirkjun.is/starfsemin/virkjanir/fljotsdalsstod/

[23] R. Jónsdóttir, E-mail communication (2012).

[24] Efla, Fljotsdalsslinur 3&4, Tech. rep., Landsvirkjun (2010).