Energy return on Investment of Geothermal and Hydro power plants and their respective energy payback time

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60 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Environment and Natural Resources

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Abstract

The purpose of this study was to compare the energy efficiency between hydro and geothermal power plants. The plants analysed were Nesjavellir (geothermal), and Fljótsdalsstöð (hydroelectric) power plants. The Energy Return on Investment (EROI), which is the ratio between output and input energy, was calculated for both plants. A recently proposed methodology was used, so the boundaries are consistent to other similar studies and can therefore be compared. Real data was gathered from stakeholders regarding construction, maintenance and operation of the plants. Therefore close to accurate results can be expected from these calculations. Results show that Nesjavellir geothermal plant returned approximately 33 units for every 1 unit that was used for construction, maintenance and operation at the plant over 40 years. Fljótsdalsstöð hydro station however, returned approximately 112 units for the same criteria. Own consumption was shown to be the largest consuming factor at both sites when looking at the whole lifetime of the plants. A scenario was calculated where hot water production was excluded at Nesjavellir, where the EROI dropped to approximately 9:1. These results are very close to the results published in 1975 and 1979 when the EROI for electricity production from a geothermal power plant was last calculated. This scenario underlines the efficiency improvement hot water production has. Energy payback time was calculated, where geothermal was quicker to reach an EROI of 1, but Hydro quicker to pay back the total energy consumed over its lifetime. The EROI is considerably higher for hydroelectric plants compared to geothermal. EROI is particularly low for electric production alone at geothermal power plants and has arguably not improved over 30 years.

Útdráttur

Í ritgerð þessari er orkuarðsemi Nesjavallavirkjunar og Fljótsdalsstöðvar borin saman. Í ritgerðinni er notast við aðferðafræði sem nýverið var sett fram svo samanburður sé mögulegur á samskonar rannsóknum. Orkuarðsemi jarðvarmavirkjunar hefur ekki verið birt síðan 1979. Gögnum varðandi byggingarefni, viðhald og eigin notkun virkjananna var safnað frá eigendum virkjananna sem og tengdum fyrirtækjum staðið hafa í rekstri og byggingu tengdra mannvirkja. Þannig má ætla að nákvæm niðurstaða hafi fengist þar sem raungögn voru notuð. Niðurstöður sýna að Nesjavallavirkjun skilar um það bil 33 einingum til baka til samfélagsins fyrir hverja eina sem fór í að byggja hana og reka yfir fyrstu 40 ár hennar. Fljótsdalsstöð skilaði betri niðurstöðum þar sem hún skilar um það bil 112 einingum fyrir hverja eina sem hún notar fyrir fyrstu 100 ár hennar í rekstri. Eigin notkun virkjananna var langt um orkufrekasti partur rekstrarins. Athuguð var orkuarðsemi Nesjavalla ef framleiðsla á heitu vatni væri ekki til staðar, niðurstaðan leiddi í ljós að orkuarðsemi á rafmagnsframleiðslu frá jarðvarma hefur lítið aukist síðan 1979, þar sem mjög líkar niðurstöður fengust, eða um það bil 9:1. Hinsvegar má á sama hátt sjá hvernig framleiðsla á heitu vatni eykur orkuarðsemi gríðarlega. Endurgreiðslutími orku var einnig reiknaður, þar kom í ljós að Nesjavallavirkjun var sneggri að ná EROI 1:1 en Fljótsdalsstöð var fljótari að greiða til baka alla þá orku sem hún notar yfir líftíma sinn. Sem almenna ályktun, má halda því fram að Vatnsaflsvirkjanir skili mun betri orkuarðsemi en jarðvarmavirkjanir.

This thesis is dedicated to John Galt

Preface

During my undergraduate studies in Australia, and later my post-graduate studies in Iceland, I became increasingly interested in the environmental impact mass production has. Associated with this interest, energy consumption in mass production also intrigued me. I was lucky enough to participate in a research project at the University of Iceland where energy efficiency in agriculture was examined, it was during that time when my interest in energy analysis grew immensely. Although energy efficiency in agriculture is very interesting and relevant today I wanted to dig even deeper, to the core of it all. So I asked the question, what is the energy efficiency in the energy production itself? During the agricultural research project I was exposed to the EROI methodology, which had mostly been used to study viabilities of energy sources. With a slight experience in energy analysis, there was nothing to stop me from answering this question. This thesis is a part of the answer.

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Abbreviations

cm	–	Centimeter
EJ	–	Exajoule
EPT	–	Energy Payback Time
EROI	–	Energy Return on Investment
GJ	–	Gigajoule
GWh	–	Gigawatt hour
HDR	–	Hot dry rock
Km	–	Kilometer
KWh	–	Kilowatt hour
LCA	–	Life Cycle Assessment
M	–	Meter
MJ	–	Megajoule
mm	–	Millimeter
n.d.	–	No date
PJ	–	Petajoule
°C	–	Degrees Celsius

Acknowledgements

This thesis would not be real if it was not for the motivation provided by my advisor Dr. Rúnar Unnþórsson and Dr. Brynhildur Davíðsdóttir, those two are a reminder that the productive characters of Ayn Rand are not only found in her novels. My former lecturer Wilma Van Boxtel deserves my gratitude for sparking my interest in environmental impact from mass production, which ultimately lead to this thesis. My significant other, Anna Bryndís Einarsdóttir has patiently discussed this work when we should be sleeping, to her I give my gratitude and apologize for the lost hours of sleep. Gratitude goes to Orkusjóður, which provided financial support. Njörður Ludvigsson at Landsnet, Edda Sif Aradóttir and Kristinn Rafnsson at Orkuveita Reykjavíkur, Ragnheiður Ólafsdóttir at Landsvirkjun and Gyða Mjöll Ingólfsdóttir at Efla Engineering contributed substantially to this work in the form of data. Gratitude goes to Annalisa De Cia and Marta Rós Karlsdóttir who assisted with problems related to general physics and Arnaldur Smári Stefánsson for productive discussions on mathematics. Dr. Einar Stefánsson gets my gratitude for reviewing this thesis and provide some very useful comments. Last but not least, my parents have always supported me, no matter how outlandish and unrealistic my goals are, my gratitude to them can hardly be explained in words.

1 Introduction

Until agriculture was invented, around 12 thousand years ago, human population numbers were considered to be stable. This was the time of hunters and gatherers (Common & Stagl, 2005), where the global population was not in clumps of towns and cities, but rather made of individuals in search of food. Agriculture changed the population scenery, when humans discovered that food could be grown and animals domesticated. The global population grew slightly after the invention of agriculture, but a real increase can be recognized in the mid 18^{th} century where human population began its exponential growth (World Population to 2300, 2004). This exponential growth, and the effects humans have on the ecosystem, can easily be related to the fact that humans gained relatively easy access to energy, mostly fossil fuels (Vitousek, 1997). In conjunction with the industrial revolution, this allowed agricultural practices on previously unimaginable scale that had the potential to feed much greater numbers of inhabitants than ever before in human history. Since then, humans have relied on easy access to energy to maintain exponential population growth. This cheap fossil energy has not only allowed humans to maintain its growth, but has also fed its industrial activities. Economic growth has been fuelled by cheap energy throughout the years, which further improves the well being of humans. A question has however been dominant in recent literature and media regarding peak oil (that access to oil will become more difficult from now on), and when cheap energy, such as fossil fuels, will drain out. The effects such an event can have could be dramatic, and should therefore be investigated, mitigated and hopefully avoided. Today, humans possess the knowledge on how finite the resource is they exploit for their survival, they must however also make intelligent decisions on how the resource is to be used.

In order to retrieve energy, such as fossil fuels, some energy needs to be used in the process. For example, to pump oil up from an oil well, the machines on location require some amount of oil themselves. This has always been the case in energy generation. In early agriculture for example, energy was needed in form of various food to feed humans and animals, and sunlight for photosynthesis. Today, agriculture (in addition to sunlight) relies mostly on fossil fuels for energy so heavy machinery can be used. This ideology is even present in biology (Hall, 2011), where animals (and humans) need to use energy in order to retrieve energy. The energy is used in the process of getting or hunting the food. The animal must, in order to survive, retrieve more energy from the food than it used in the process, otherwise it will go extinct.

Many energy sources have been proposed to replace the conventional fossil oil, and some have been developed. In Iceland, geothermal and hydro power plants have been constructed and are at present being used to power heavy industries and households within the country. No study has previously compared how much energy has gone into producing these two forms of power plants within Iceland, and calculated the ratio between the energy that went into the production of the given plant and the energy that it will deliver over its lifetime.

In modern literature, the ratio between the amount of energy retrieved and the amount of energy used in the process of retrieving that energy is called Energy Return on Investment (EROI). EROI has shown its usefulness as a methodology to assess the viability of energy sources and will be the methodology used in this study to assess the

EROI of two recently built power plants, Nesjavellir, which started operating in 1990 (hereafter referred to as the geothermal plant) and Fljótsdalsstöð, which started operating in 2007 (hereafter referred to as the hydroelectric plant).
The concept has in recent times mostly been used to study energy sources such as oil, coal and natural gas. It has gained much interest in recent years, especially with discussions on how long the oil will last for. Less interest has been in the EROI of renewable sources such as geothermal and hydro. However, although interest has increased in recent years in EROI's, there have been very few new studies since the 1980's. This can perhaps be partially contributed to the lack of methodological standardisation (Murphy, 2011). Therefore, to this date, studies of the same energy source might have given different results since they did not follow the exact same method, as will be discussed in chapter 1.2.6.

1.1 Energy Return on Investment (EROI): concept and history

This chapter will discuss how EROI has been evident in the literature and what results have been derived from different studies regarding different energy sources. It will further discuss where the concept is originated from and who the main researchers on the subject are. Energy payback time will also be explained.

In essence EROI is the ratio between the output and input energy from a given power source, but has for example also been used to calculate the efficiency in aquaculture and agriculture. When EROI is calculated, a clear set of boundaries are drawn which clarify what is to be included within the calculations and what excluded. Time is another factor that in many cases has a big influence on the results as is shown in this thesis. The EROI concept is often credited to Charles A. S. Hall, where he used the concept in his PhD dissertation and resulting publications (Hall, 1972, 1975, 1981). Similar concept was put forward by Herendeen & Plant, who described the term "Energy Ratio" which in essence is the same as EROI (Herendeen & Plant, 1979). Murphy and Hall claimed in 2010 that hydro powered electricity generation had an EROI of >100 and that no data exists on geothermal EROI (Murphy & Hall, 2010). This was further demonstrated by Mansure (2011) who further stressed that no studies have been done on the subject of geothermal EROI in recent times and an up to date analysis has yet to be made. However, EROI of approximately 4 might be a reasonable guess for wet steam geothermal energy production according to Herendeen & Plant (1979). Gilliland (1975) did however calculate the EROI to be 12.6 for a dry steam reservoir and 10.7 for a wet steam reservoir over a 30-year lifetime. Murphy & Hall and Mansure either overlooked the reports by Herendeen & Plant (1979) and Gilliland (1975), or merely consider them out-dated. Murphy & Hall (2010) further showed that while hydropower has such an extravagant EROI as mentioned, it is only a fraction of the energy produced by oil globally (Murphy & Hall, 2010). EROI's of various energy sources are discussed in chapter 1.2. Murphy & Hall (2010) estimate that in 1999 world oil production was around 200 EJ/year, with the EROI of 35, compared to hydropower, which only provides around 9 EJ/year but has a significantly higher EROI.

Energy payback time is in essence the time it takes the power plant or the energy generating equipment, to produce as much power as went into producing, maintain and operate the plant or equipment over its lifetime (Nieuwlaar & Alsema, 1997). The papers above do not mention energy payback time at all, even though it is highly interlinked with EROI. The energy payback time has not been located of any major energy sources in the literature, and seems only to have been estimated on photovoltaic installations to be 7.4-12.1 years (Wilson & Young, 1996). Even though this might not be directly related to the payback time of hydro or geothermal, it shows that energy payback time can be used as a measure between options, as well as EROI. Kessides and Wade (2010) stated that the energy payback time should be much less than the expected lifetime of a given project. In Kessides and Wade's paper, they demonstrated that according to their calculations a hydro power plant can be expected to have the EROI around 50. A significantly higher EROI can therefore be expected in my study from the selected hydro plant compared to the geothermal. The literature shows that EROI has been thoroughly studied by only a handful of people, including, Hall, Murphy, Cleveland and Costanza.

1.2 Previous EROI studies

As mentioned above, Charles Hall originally proposed the term energy return on investment in a series of papers in the 70's. Since then various studies have been published describing the EROI of various fuels. This section will discuss which energy sources have been of most interest to researchers in the past.

1.2.1 Oil

In a paper by Cutler Cleveland (2005) the EROI of oil extraction in the United States from 1954 to 1997 is demonstrated. The EROI fluctuates as new oil wells are found and technology develops. The EROI, according to Cleveland, was at 100 in 1930´s, 17 in 1954 and rises to 25 in 1970 and is around 12 at present (Cleveland, 2005). Cleveland demonstrates in his paper how fast the EROI of domestic U.S. oil has declined from the 1930's when it was around 100. A sharp decline is quite obvious from 100 in the 30's to 25 in the 70's to 12 in '97. These results are further demonstrated by Cleveland et al. (1984) where it is demonstrated that the in 1970's the EROI of already established oil wells was around 23 (meaning that the whole process delivers 23 barrels for every barrel used to acquire the oil). Gagnon et al. (2009) assessed the EROI of global oil at the wellhead.

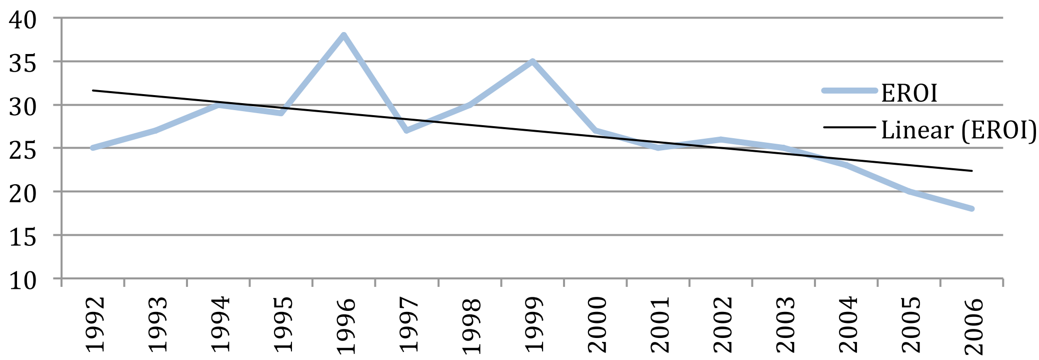

Figure 1.1 - EROI of oil from 1992 - 2006 and a trend line (Gagnon et al. 2009)

They demonstrate that the EROI of global oil was around 26 in 1992, it rose subsequently in 1999 to 35 and has since then decreased to 18 in 2006, which is considerably higher than was demonstrated by Cleveland et al. in the United States. Figure 1.1 shows the EROI of global oil using the data derived from these studies. What can be seen in this figure is the overall trend of EROI, where it is declining in spite of sudden increase in 1996 and 1999, which may be contributed to new discoveries in the years leading to the rise.One can see that the EROI of global oil production is declining, where in 2006 it was around 18. This EROI will be compared to other energy sources later in this study.

1.2.2 Coal

According to Cleveland (2005), the EROI of coal in the 1930's was around the same as oil, or roughly around 100, in the same study it is shown that the EROI has dropped to 80 in 2000. This drop is not as big as was seen in the EROI of oil between the 1930's

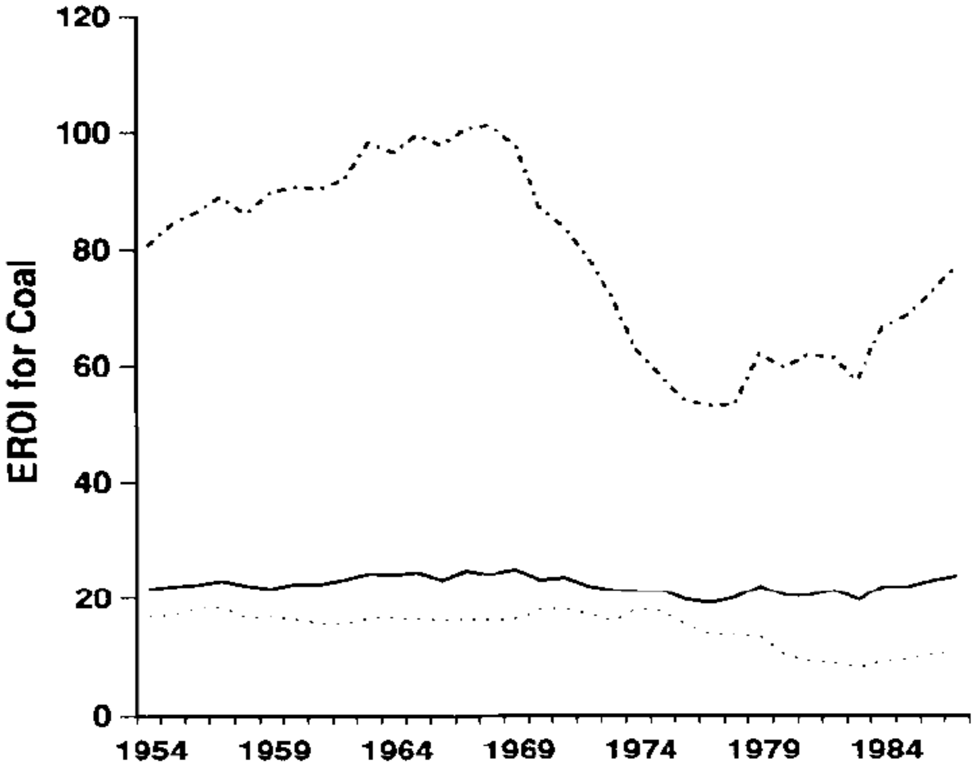

Figure 1.2 - EROI development of coal from 1954, the solid line represents energy quality corrected EROI (Cleveland, 1992)

and 2000 (from 100 to around 20). With the knowledge of the EROI around 2000 being 80, one can see that the EROI has actually increased since 1974 where it was actually heading downwards rapidly. What is however more interesting is the huge difference in the energy of coal before and after quality correction where quality is the ability of the given resource to perform physical work. This is mostly due to the fact that when extracting coal, a relatively low quality fuel, higher quality fuels are used in the process (Cleveland, 2005). The EROI of coal in the United States between 1954 and 1984 can be seen in Figure 1.2. The increase in the EROI from 1979 can perhaps be credited to new discoveries of easy reachable coal and technological innovations in extraction, in mixture with lower energy intensity in the extraction process. Cleveland does however credit this increase to substitutions of input energy from high-grade energy to lower grade (Cleveland, 1992).

1.2.3 Nuclear

Probably the most debated energy source of recent times in regards of the danger that it poses in production is nuclear energy. When calculating the EROI of power plants, such as nuclear, hydro or geothermal, the methodology often consists of all the energy it takes to produce the plant against the energy that the plant delivers over its lifetime (Gagnon et al. 2009). It is therefore often hard to estimate the EROI of the given energy source since the lifetime of the plant is never fully known. The EROI has therefore to be estimated on certain given parameters. With regards to nuclear, the EROI was considered to be around 4 according to Cleveland et al. (1984) but 5-15 according to Manfred (2008), note that no timeframe is supplied by Cleveland but in the study by Manfred, the lifetime of the plant is expected to be 35 years. This variation in outcomes illustrates the uncertainty in the lifetime of the power plants and different boundaries. However, the differences in the EROI of nuclear can be so intense that no way is to know precisely what the EROI can be estimated to be. This can be seen in a study on the Forsmark nuclear power plant, which is said to have the EROI of 93 over the lifetime of 40 years (Nuclearinfo, n.d.). As mentioned by Nate Hagens (2008), the studies of nuclear EROI are often biased and the study from Forsmark seems to be one of them, where the benefits of nuclear are illustrated to the extreme, for example with extremely high EROI.

1.2.4 Hydro

Icelanders mostly use hydropower, along with geothermal power to produce electricity and heat for industry (93) and households (17%). The same problem arises when calculating the EROI for hydro power plants as has been demonstrated with nuclear, which is the uncertain lifetime of the plant, which will significantly change the EROI of a given plant. As an example: the hypothetical plant requires X amount of energy to construct, given the boundaries that have been chosen. Say that this X number is 10 for convenience sake. This number will give a baseline for the EROI calculation. Assuming that the plant produces 1,5 units of energy per year (could be mega joules, gigajoules, GWh or whatever is chosen) it can be seen that it takes the plant 7 years to pay back the energy it took to produce the plant itself (The Energy Payback Time). After 10 years the plant has the EROI of 1.5, which is not considered sustainable by Hall et al. However, over the whole lifetime the plant has the EROI of 5.85, which is considered sustainable. The lifetime is however hard to predict as has been mentioned and therefore the EROI has to be estimated. Cleveland et al. (1984) calculate the EROI of hydropower to be around 11.2 (33.6 when quality corrected). The paper by Cleveland et al. is however since 1984, and could therefore be considered out dated since the technology has most likely improved and the production of power plants requires less energy. This is however not the case according to Kubiszewski et al. (2010) where he calculates the EROI for hydro to be around the same magnitude, where it is considered to be around 12. Kessidies & Wade (2010) showed that hydropower could be expected to have an EROI around 50 after the first 30 years of operation. However, like was observed with nuclear power, there are extreme cases in the EROI calculation for hydro. It has been observed to be greater than 100 (Murphy et al. 2010). Gagnon et al. investigated a hydro power plant in Quebec, Canada. Their results show that over a period of 100 years, the plant had an EROI of 205 for a plant with reservoir and 267 for run of river (Gagnon et al. 2002). These results make hydropower the most efficient energy source available to humans at present time. The difference can be contributed to the fact that the EROI for hydropower is very site specific and one EROI value cannot be used to describe hydropower in general (Schoenberg, 2008). In this study, the EROI for hydroelectricity production is calculated using real data, gathered from stakeholders such as Landsvirkjun and Landsnet, who own the plant and the energy grid system respectively.

1.2.5 Geothermal

Gilliland (1975) calculated the EROI to be 12.6 for a dry steam reservoir and 10.7 for a wet steam reservoir. Herendeen & Plant (1979) claim that an EROI of 4 (±1) might be a reasonable guess for a wet steam geothermal energy production over a 30 year lifetime. Herendeen & Plant (1979) also estimate that hot dry rock systems have an EROI of 1.9 to a maximum of 13, geopressure systems an EROI of 2.9 and vapour dominated systems an EROI of 13. Both studies, which had looked into geothermal EROI, are more than 30 years old and are considered out dated in the literature. This is confirmed by both Murphy and Hall (2010) and Mansure (2011), which claim that no data exists on geothermal EROI and data analysis on the EROI of geothermal has yet to be made. This study attempts to provide new data on wet steam geothermal and hydro EROI (among other objectives) using real data, comparing with the older studies and filling the gap claimed by Murphy and Hall (2010) and Mansure (2011). When investigating a geothermal reservoir, not all the energy coming out of the ground is usable, therefore it is also useful to investigate and compare the exergy of that particular system to the total energy coming out of the system, as is done in this thesis.

1.2.6 Comparing EROI's

Remarkably, EROIs of the same energy source can vary greatly between studies; this can be due to the fact that no standard methodology is present to guide researchers through their studies. A standard method has however been proposed recently by leading figures in the field of EROI analysis (Murphy et al. 2011), time will however only tell if researchers will make use of this methodology when conducting their analysis. Analysis on the EROI of geothermal power production is however missing in recent times; this is of some surprise since the topic on geothermal power production has been popular in the recent past. The literature shows that only a handful of researchers can be considered experts on EROI analysis, this can be attributed to the fact that the field is still relatively young and rapidly developing. The EROI results are hardly ever presented in the public debate but are rather stuck within scholarly literature and do not reach the mainstream media. Charles Hall did however try to counter this problem by posting a series of short essays on the internet (theoildrum.com) and promoting public discussion on the topic with some success.

1.2.7 Summary of previous studies

Looking at previous studies further demonstrates the difficulties that arise since there are no standards that have guided researchers in the past. The research shows that oil at present time can be expected to have an EROI around 12, Coal was found to have a significantly higher EROI, or around 80. Nuclear was found to have a much lower EROI, around 4-15, even though extreme case analysis was found where the EROI was claimed to be 93. Hydro was found to have an EROI around 12, also along with significantly higher EROI greater than 100. Geothermal is yet to be examined in recent times but was found in the past to have an EROI around 12. These five energy sources were examined because of two factors, 1) because of their magnitude of usage (such as oil and coal.) 2) because of their controversy in recent times (such as nuclear and geothermal.) Figure 1.3 demonstrates the results between the various energy sources. This shows that coal is likely source to have high energy return on investment of the studied energy sources. There are however extreme cases where very high EROI of nuclear and hydro has been measured to be greater than 100. However, some studies do not clarify the expected lifetime of the plant studied or the boundaries. Sensitivity analysis has not been conducted in most of these studies, so minor changes with regards to technological advancements might have great impact on the EROI values listed in figure 1.3.

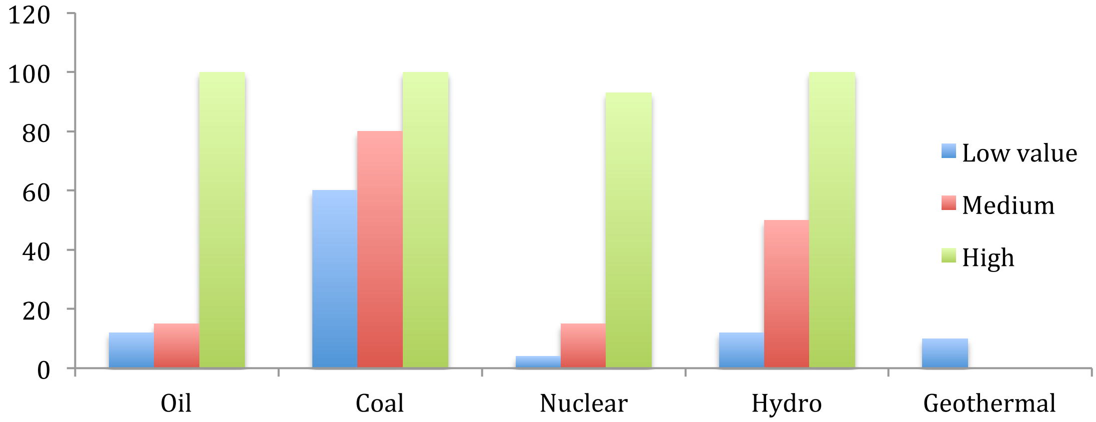

Figure 1.3 - EROI for various studied energy sources. Each column represents an individual study. Different colours show if a given study shows low, medium or high EROI value in relation to other studies of the same source.

1.3 Energy payback time

Relevant to energy return on investment is the energy payback time (EPT). EPT can be explained as the time it takes a certain energy production process to generate the same amount of energy as was used in the process of constructing the plant, maintain it and operate. As was mentioned above, the energy payback time has not been studied in most energy production processes. Photovoltaic installations are estimated to have the EPT of 7.4-12.1 years (Wilson & Young 1996). When all data has been acquired to calculate the EROI of a given power plant, within the boundaries decided, one should be able to calculate the EPT of the plant. This study will use two methods of calculating the EPT. Methods of doing such calculations are explained in chapter 2.10.

1.4 The research questions

When choosing an alternative to produce energy, many factors come into account. Economic costs, environmental effects, social aspects and the amount of energy the plant is capable to produce and for how long. Low net energy can indicate massive energy consumption in the construction or operation phase, which can lead to environmental degradation locally or even globally. A study of this sort will therefore provide an important guide on the feasibility to construct a certain type of power plant and hopefully allow decision makers to make better-informed decisions on this matter. With the knowledge of previous studies in the field of net energy analysis and EROI, one can see which factors are missing from the literature, and which would be interesting to have a further look at.

This study therefore looks at, and answers the following research questions

What are the different EROI's for the chosen geothermal (Nesjavellir) and hydro (Fljótsdalsstöð) power plants in Iceland, within the boundaries chosen? And what is their energy payback time?

1.5 Contribution

This study will contribute substantially to the existent EROI literature, mostly in the terms that the EROI of geothermal has not been calculated in detail since 1975 (Gilliland, 1975) and 1979 (Herendeen & Plant, 1979). It will also determine the energy payback time of the chosen power plants, creating an indicator of which type of power plant has less energy payback time. This study will also allow policymakers to make use of the information when deciding on which power plant to construct. Deepening the understanding of the decision makers on which plant to choose (also considering environmental, economic and social factors). The more information decision and policy makers have on a given subject, the better and more informed decision they will hopefully make. A new concept will be introduced to the literature, $EROI_{ide}$, calculating the maximum EROI; this is further explained in chapter 2. In Icelandic context, work of this sort may shed stronger light on the differences between the power plants studied, which can prove to be a valuable substance to the on going public discussion.

1.6 Chapter summary

In this chapter the EROI was briefly explained. EROI is in essence the ratio between output energy and input energy over a lifetime of a given power plant. Leading figures in the field, such as Cleveland, Murphy and Hall were introduced and results derived from their studies. Oil was shown to have an EROI of approximately 15, which had declined from around 100 in the 1930's. Coal has an EROI of approximately 80. Studies showed that the EROI of Nuclear can be expected to be between 4 and 93, hydro between 12 and >100 and geothermal around 10-12. These results can be misleading and difficult to compare. Energy payback time was briefly explained, which is the time it takes a given plant to produce the same amount of energy as it took to construct it, maintain and operate. The research questions were: what are the EROI's of two Icelandic power plants, one geothermal and one hydroelectric and what is their energy payback time.

2 Methods and materials

This chapter will introduce the methodology used in this study (Energy Return on Investment, or EROI), the underlying principles behind the methodology and the practical use of it in modern society. How the concept has developed is slightly explained. It will further demonstrate how EROI is calculated, which problems can be encountered and suggested methods how to solve these problems. Mathematical equations are provided to calculate the EROI and variants of these equations, which include different parameters depending on what is included within the given boundaries. This chapter also looks at the relative use of energy, especially geothermal and hydropower within Iceland. Sectors mostly using these sources are subsequently studied. The chapter ends by introducing the two power plants to be studied, Nesjavellir and Fljótsdalsstöð.

2.1 Methodology

When conducting an EROI analysis, several objectives must be kept in mind from the beginning. One of the biggest discussions around EROI is the lack of standardization, and therefore each study can have different parameters. First and foremost are the boundaries, in the beginning of the study, a clear set of boundaries regarding the data collection shall be set. This has to be set very clearly especially since this study compares two plants. Since already constructed plants are studied, data was collected from their respective firms on quantities of material used in the construction, amount of oil used, where material was constructed, relative to the set of boundaries chosen. The total energy needed to create a given power plant formed a baseline for the EROI calculations. When the EROI scenario has been calculated, it is possible to see the energy payback time, which is when the EROI reaches 1.

2.1.1 Equations and boundaries

The following section will explain different boundaries and equations; this is done in the same section because different equations describe different boundaries. Therefore these two are inseparable.

The original concept of EROI, the ratio between energy delivered against the energy required in the process can be described as follows (Cleveland, 2008):

$$EROI = \frac{Quantity\ of\ energy\ supplied}{Quantity\ of\ energy\ used\ in\ supply\ process} \quad (1)$$

This equation may seem straightforward at first, but complicates when deciding what is to be included in the numerator and denominator. For example: will the energy needed to transport all the material to a given location be included? What about the energy that was used to create all that material? What about the energy needed to create the machines, which were used for material production? And so forth.

Since various factors can be included within an EROI study, and no standard exists on what should be included or where the boundaries should be set, an attempt has been put forward by at least two parties to standardize the method.

Mulder & Hagens (2008) claim that since no consistent framework exists around the EROI concept, it can be manipulated to give the desired results. Mulder & Hagens try to prevent this by supplying a standard to which calculations should be derived from.

At the beginning of Mulder & Hagens description, a graph is provided, which depicts an energy production process (see Figure 2.1).

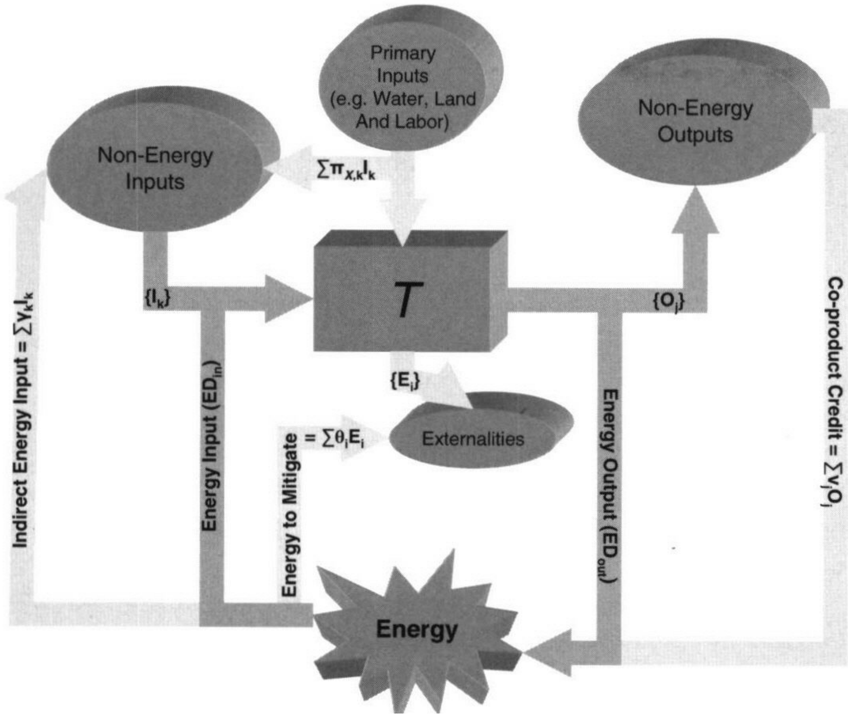

Figure 2.1 - Various inputs and outputs from a theoretical energy production process

Figure 2.1 shows the physical flows of a theoretical energy producing process (T), Such as a geothermal plant. Inputs, such as energy (ED_{in}) and various other inputs ($\{I_k\}$) are used in the process to produce the energy on site (ED_{out}) and any co-product ($\{O_j\}$). The parameters supplied by Mulder & Hagens do however only scratch the surface in terms of standardisation. According to Mulder & Hagens, non-energy inputs are often left out of EROI calculations (the light grey arrows in Figure 2.1 but perhaps should not be. The following equation is therefore provided:

$$EROI = \frac{ED_{out}}{ED_{in} + \Sigma\gamma_K I_K} \qquad (2)$$

Where:

ED_{out} is the direct energy output
ED_{in} is the direct energy input
γ_k is a set of well defined co-efficient
I_k is the energy per unit of the given co-efficient

This equation is however not including parameters such as indirect energy outputs, non-energy outputs, land, ground water or time. Some of these parameters can be very hard to convert to energy equivalents (or perhaps impossible). Most of the time however, co-products do have energy content (such as co-products from farming to produce oil seeds, or hot water from a geothermal plant) and can therefore be accounted for. Mulder & Hagens (2008) therefore provide an EROI equation that does so:

$$EROI = \frac{ED_{out} + \Sigma v_j O_j}{ED_{in} + \Sigma y_k I_k} \quad (3)$$

Where:

ED_{out} is the direct energy output
v_j is a set of well defines co-efficient output
O_j is the energy per unit of the given output co-efficient
ED_{in} is the direct energy input
γ_k is a set of well defined co-efficient input
I_k is the energy per unit of the given input co-efficient

Still, factors such as soil erosion, ground water pollution and loss of food production are not included within these equations, neither are any fixed set of boundaries. Mulder & Hagens do provide a method to calculate the loss of such factors, but they are irrelevant to the goal of this study, so they will not be discussed any further.

Mulder & Hagens do suggest three versions (levels) of EROI calculations, depending on the boundaries they include.

1) First order EROI includes only direct inputs and outputs. This is the most superficial of the three levels but is the most precise. It does not include any co-products

2) Second order EROI includes indirect energy, as well as non-energy inputs. It also includes co-products. This is the methodology used currently in the LCA literature. Using the 2^{nd} order EROI two assumptions must be defined: i) how co-products are allocated (heat content, mass etc.) and ii) what boundaries are to be drawn. Mulder & Hagens suggest that the boundaries are to be drawn where the input is less than 1% of the total energy used (invested).

3) The 3^{rd} level EROI incorporates all additional costs and benefits for the process. This is the most accurate method. Mulder & Hagens do not provide any standardisation in regards to the boundaries of EROI. They merely mention that boundaries should be drawn and well defined (except on 2^{nd} level EROI where they mention that boundaries can be drawn where the energy input is less than 1% of the energy invested). This is however discussed in detail by Murphy (2011) who introduced more detailed definition of boundaries.
Figure 2.2, taken from Murphy's article, shows that the larger the boundary gets, the smaller the EROI will be.

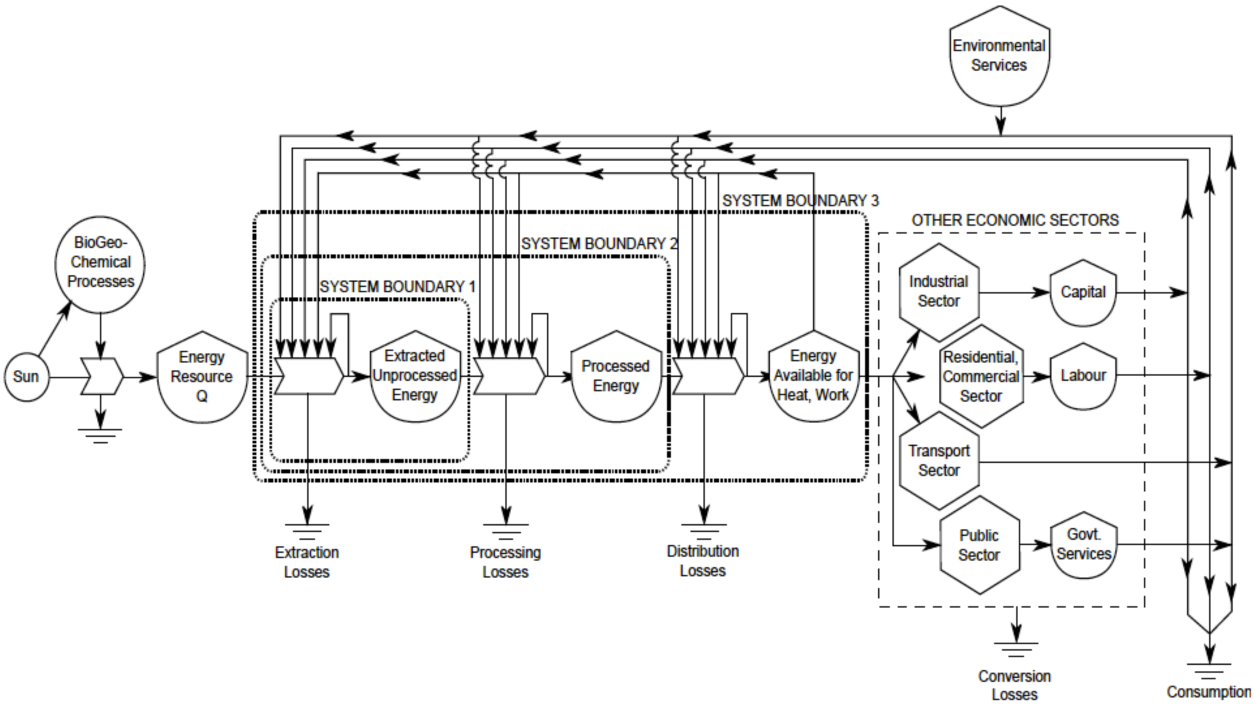

Figure 2.2 - Three system boundaries provided by Murphy et al. (2011). The larger the boundaries are, more energy is lost and the EROI declines.

This is evident by the fact that the larger the boundary is, the more inputs will go into the process, at the same time energy is lost in every step after its extraction (when refined, transported etc.). Murphy et al. (2011) put the economy into four sections, industrial, residential, transport and public. Where each sector has its output. Murphy (2010) states that for comparisons sake, all EROI studies should include at least $EROI_{stnd}$ so different studies can be compared. This includes indirect energy and material inputs and the energy retrieved in the extraction before processing. This does provide some clarification but nowhere nearly enough. To what extend should the data reach and so forth? Should one attempt to calculate the proportion of oil it took a ship to transfer parts between continents to their final location or point of extraction? This is not clearly identified, but if data allows, the <1% rule provided by Mulder & Hagens can be used. Murphy states that data access is in most cases the factor that will determine the boundaries.

Table 2.1 - System boundaries provided by Murphy et al. (2010)

Boundary for Energy Inputs	1. Extraction (Output)	2. Processing (Output)	3. End Use (Output)
1. Direct energy and material inputs	$EROI_{1,d}$	$EROI_{2,d}$	$EROI_{3,d}$
2. Indirect energy and material inputs	$EROI_{stnd}$	$EROI_{2,i}$	$EROI_{3,i}$
3. Indirect labour consumption	$EROI_{1,lab}$	$EROI_{2,lab}$	$EROI_{3,lab}$
4. Auxiliary services consumption	$EROI_{1,aux}$	$EROI_{2,aux}$	$EROI_{3,aux}$
5. Environmental	$EROI_{1,env}$	$EROI_{2,env}$	$EROI_{3,env}$

However, with no further boundary clarification EROI studies are hard to compare, therefore, system boundaries provided by Murphy et al. (2010) and shown in Table 2.1 should be used. The table, provided by Murphy et al. (2010) gives a very easy understanding of the boundaries, where a given researcher can state which boundary he has set for his research. This will also make comparisons easier and the risk of studies with different boundaries being compared will be reduced. No misunderstanding will occur when $EROI_{stnd}$ is compared to an $EROI_{2,i}$ study of the same energy source.

2.2 $EROI_{ide}$

The previously explained EROI equations show what they are intended to show, various output/input ratios of the energy source being studied. They do however not show the potential EROI of the source studied. To be able to calculate this, the EROI equation needs to be modified. An entirely new concept, Ideal EROI is therefore introduced in this thesis, or $EROI_{ide}$. This EROI variant gives the decision maker a tool, which shows clearly how much potential for improvement is available at the given resource, when all losses have been omitted.

The following equation is therefore introduced:

$$EROI_{ide} = \frac{\Sigma\beta}{ED_{in} + \Sigma y_k I_k} \tag{4}$$

Where:

$\Sigma\beta$	Is the total energy at wellhead, omitting all losses in the process. This is after construction to access, e.g. borehole for geothermal.
ED_{in}	Is the direct energy input for construction, maintenance and operation.
γ_k	Is a set of well-defined co-efficient input.
I_k	Is the energy per unit of the given input co-efficient.

However, to be able to retrieve β one must calculate the total geothermal energy at wellhead or the maximum energy within a flow of water in a hydro power plant (or whatever source is being studied)

There are various ways to capture such values. For water, the following equation describes the energy released:

$$E = mgh \tag{5}$$

Where:

E	is energy measured in watts
m	is the amount of water per second, measured in litres
g	is gravity, which under normal circumstances is $9.81 m/s^2$
h	is the total fall of water from mouth to turbine

For geothermal power, steam tables provide data that is comfortable to use.

To take an example of how $EROI_{ide}$ would be measured for a theoretical hydro power plant, the following parameters are going to be assumed. The plants lifetime is 100 years, the height of the head is 100 meters and it delivers 50m^3 (50,000 litres) of water per second. To retrieve the $\Sigma\beta$, one must first get the results from equation 5. $100 \times 50000 \times 9.81 = 49{,}050{,}000$ or 49.05 MW. This would equal to 429,678 MWh annually, or 429.68 GWh over its lifetime. Let's at the same time say that the production of the given plant (within the boundaries given) would amount to 12.92 GWh (or 46,512 gigajoules). The following $EROI_{ide}$ can therefore be calculated

$$EROI_{ide} = \frac{429.68}{12.92} = 33.25$$

Even though the $EROI_{ide}$ shown above is 33.25, it is theoretically impossible to reach such EROI. This is due because no energy production process can be 100% efficient. This hydro power plant would most likely reach around 80-90% efficiency, and therefore an EROI of 26.6.

A geothermal power plant usually consists of more than one borehole, therefore the energy value needs to be calculated for every hole (for steam and water), and then summed up to retrieve the β value.

As one can observe, the denominator in equation 4 is the same as in the equation provided by Mulder & Hagens (2010) in equation 3. This is due to the very reason that future technology cannot be used to construct a power plant in present time. One can therefore not say that maximum theoretical future efficiency should be used for construction of a given power plant in present time.

With the results from this equation, in co-ordinance with the results from an EROI study with the same boundaries, parties can observe the possibilities of a given energy source. This will provide them with information about future possibilities, but will of course include speculations about the future of technological advancements.

The introduced $EROI_{ide}$ provides information that is not directly applicable to the current state of a given resource, but rather gives stakeholders practical information, which can be used in decision-making. For example which energy production system should be incentivised by the government since the room for improvement at a given source is greater and allows for improvements. The $EROI_{ide}$ will however prove meaningless if it is not in combination with another EROI calculation of the same source for comparisons sake.

2.3 Comparison

A problem arises when EROI's of different energy sources are to be compared. This is due to different boundaries set for each study. This problem can however be avoided if the method proposed by Murphy et al. (2011) is followed and $EROI_{stnd}$ is always shown in the study conducted. $EROI_{stnd}$ is a good comparative method, especially because it excludes the delivery system, which might set energy sources apart. For example, two hypothetical power plants are studied, a coal plant and a hydroelectric plant. The coal plant might have the EROI of 80 after extraction and processing, however, after transporting the coal to its final destination, the EROI declines to 70. Located further away from the destination, is the hydro power plant, which after harnessing the power has the EROI of 100. After transferring the power through power lines over a vast distance, the EROI has dropped to 70 since the energy used in the production of the power lines decreases the EROI. The $EROI_{stnd}$ in this hypothetical case is 80 for the coal, but 100 for the hydro plant, whereas the $EROI_{3,i}$ is 70 for the coal plant but 70 as well for the hydro plant. Even though both energy sources are delivering the same amount of energy to the consumer, shown in the $EROI_{3,i}$ calculations, it is a good insight and a better comparative factor to see the $EROI_{stnd}$. In a case like this, it is vital to see both the $EROI_{stnd}$ and the $EROI_{3,i}$ and analyse where the EROI is dropping if that is the case. In the hypothetical case described above, it is obvious that the transportation of energy to the consumer is holding the hydro plant down. Policy makers might therefore, with regards to this factor, promote hydro power production closer to the consumer.

2.4 Boundaries and data within study

This section will discuss the various boundaries used within this study. It will further explain the quality of the data acquired from stakeholders and how energy values were gathered to calculate the embodied energy of various construction materials. It will further explain how energy use was calculated for trucks, excavators and ships. Estimation had to be done for shipping of construction materials to Iceland for the geothermal power plant since no data on oil consumption during transportation was provided. Oil consumption for transportation to Iceland for the hydro power plant did however not need to be estimated since data was provided for that segment.

2.4.1 Boundaries

As mentioned before, the boundaries of what to include in the EROI calculations need to be very clear. These are often determined by available data, as is the case in this study. The data acquired does allow for the $EROI_{stnd}$ boundaries, the data for the geothermal plant includes all oil and material use for borehole drilling, and all material used in the plant production. At the hydro plant, data was very reliable and allowed also for $EROI_{stnd}$ as well as $EROI_{3,i}$ to be calculated. Embodied energy within these materials are gathered from the literature and transportation was estimated. As explained, the $EROI_{stnd}$ includes indirect material and energy inputs and direct energy output. For example, embodied energy of a given material includes how much energy goes into producing that given material. This information is gathered from the literature, transportation energy to Iceland is estimated as well as within Iceland. Total oil usage for both sites was also provided. This does therefore include indirect energy (the production of the steel) as well as direct energy that went into construction at site. This is in conjunction with equation 2, which describes direct and indirect material and energy usage and the direct energy output. Figure 2.3 depicts the boundaries. The energy source delivered to the system under examination, for example falling water or geothermal energy, is not considered as an input to the EROI ratio. This is because the question posed is how much energy will the system deliver to society for the energy it took from society rather than how much energy does the system deliver in general for all the energy it took from the biosphere. For this reason, the energy source is not considered as an input.

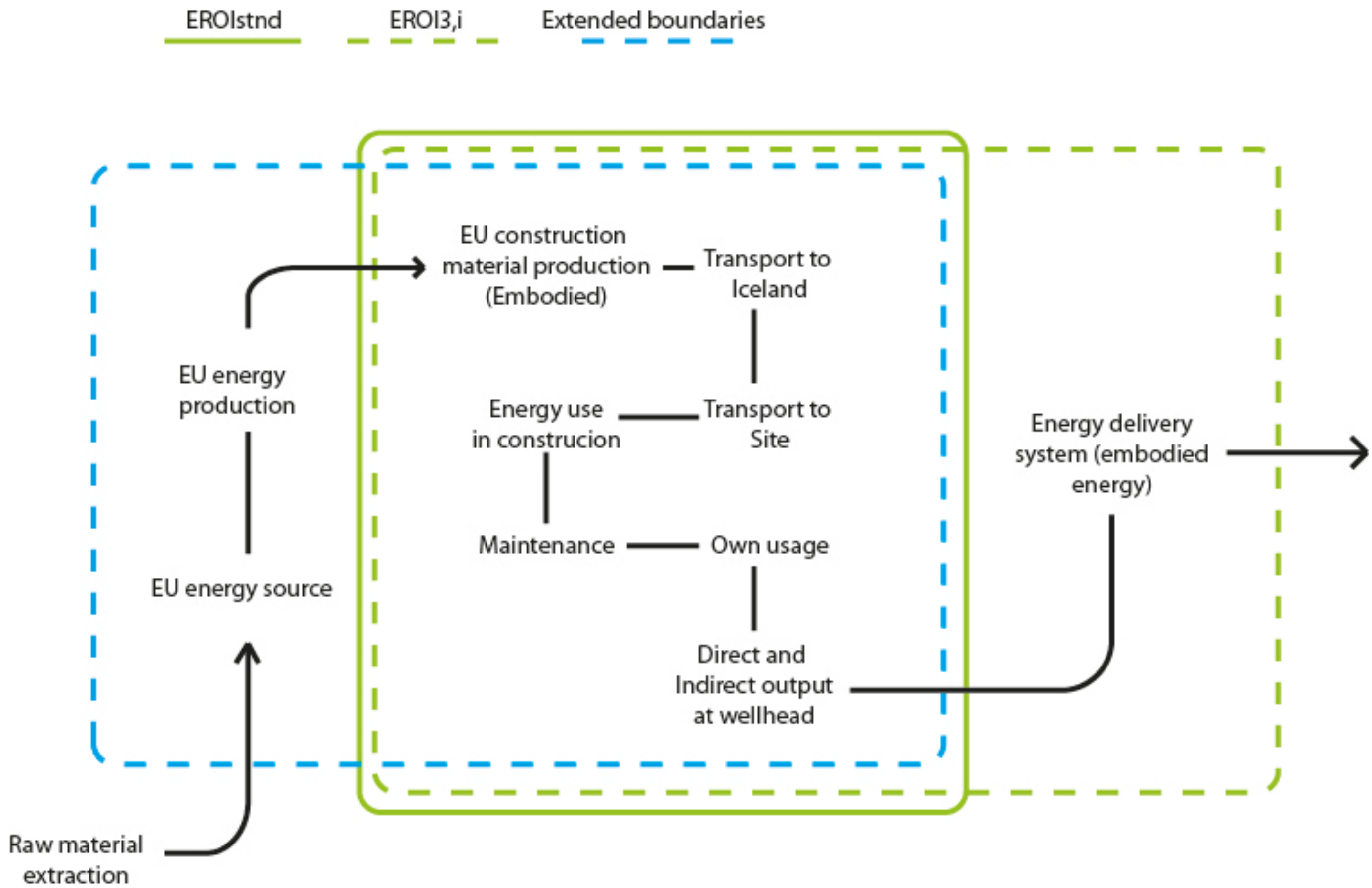

Figure 2.3 – Three main boundaries studied within this study. The solid green line represents the $EROI_{stnd}$ boundaries, which excludes the energy delivery system. The dotted green line is the $EROI_{3,i}$ boundary, which includes energy delivery system. The blue dotted line includes the energy embodied in the energy sources originally used to create the embodied energy.

As Figure 2.3 shows, there are three boundaries to be studied, boundary 1 (solid green) which includes material production, transport to Iceland, construction at site and the energy produced at site, this boundary is in essence the $EROI_{stnd}$. Boundary 2 (green dashed line) stops when the energy has been processed and delivered to the user, which in essence is $EROI_{3,i}$. The main difference between these boundaries is the delivery system associated with each power plant, whether these are power lines or pipes containing hot water. These two boundaries are independent of the $EROI_{ide}$, which is also examined in this study and will follow in this case the $EROI_{3,i}$ calculations. The dashed blue line indicates a set of boundaries, which includes the energy lost in the power generation destined for the factories manufacturing the construction materials. These boundaries are further explained and calculated in chapter 3.3. Calculating the $EROI_{stnd}$ will, as mentioned by Murphy et al. (2011) allow this study to be compared to other EROI studies that also include the $EROI_{stnd}$. Maintenance is accounted for within these boundaries as being 2% of total amount of construction material annually for the geothermal plant but the maintenance scenario complicates slightly at the hydro station as is explained in section 3.2.7. These numbers are derived from the relevant LCA reports (Ólafsdóttir, 2011, Kristjánsdóttir & Jónsdóttir, 2008). In order to calculate the denominator in the EROI equation, one must obtain data from the power plant studied about the amount of construction materials used. When these are known, as well as the quantities of them, one must obtain how much energy went into producing them, the embodied energy in the materials. Embodied energy is the energy used in direct production of given materials. This study looks at the literature and average values, since the origin of the materials are not known. For example, it was not known where the steel used in the construction was produced; one must therefore simply use the world average intensity. Since the average energy intensity value of given products (steel, concrete etc.) are known, they will be used both for the hydro power plant as well as the geothermal plant. Relatively low difference is between the energy intensities of these constructions and therefore the same values are used. The oil used in producing the plants is a special case for itself. If given the information that 1,000 litres are used in the production, one can assume that number to be 1,200. This is due to the reason that 200 litres were used in the process to acquire these 1,000 litres (that the oil has an EROI of 20 at present). This will be accounted for in this study.

2.4.2 Data gathering, quality and relation to boundaries

Both power plants studied have been the subject of LCA analysis in recent times. LCA, or Life Cycle Assessment investigates the environmental impact a certain product or process has. The LCA reports do have similar boundaries and therefore should data be available for the same power plants to be studied with regards to their EROI. It is however recognised that some variability will occur and has to be addressed. One case is the shipping of materials to Iceland. The energy used for this activity was provided in the data acquired for the hydro power plant, but had to be estimated for the geothermal power plant.

To calculate the embodied energy within the construction materials, real data was gathered from stakeholders. Excel sheets were provided with detailed information; however, the data regarding Fljótsdalsstöð was more detailed in the sense that oil used for shipping was included. Data regarding shipping to Iceland was not provided for the geothermal plant and was estimated instead. However, after calculating the energy used for shipping at the hydroelectric plant, one can see that the assumption made for the geothermal plant was relatively close to the reality at the hydroelectric plant. Even though the amount of energy was increased or decreased by a significant amount, no effects would be visible in the final EROI result due to the minimal amount of energy used for shipping. The stakeholders providing data were Orkuveita Reykjavíkur, Landsvirkjun, Efla, Landsnet and Steypustöðin.

2.5 General Assumptions

Many assumptions have to be made for various parts, such as trucks, excavators, concrete trucks, embodied energy etc. This has mostly to do with the oil usage and amount of time the machinery uses in its operations. Other specific assumptions that are site specific are detailed in relevant chapters. General assumptions will at this stage be detailed.

2.5.1 Trucks and excavators

To standardize the average truck, the comparative study by Nylund & Erkkila (2005) was used. The paper simulates a truck that takes 60 ton load, and consumes 53 litres per 100 km fully loaded and 30 litres per 100 km empty. This data was used throughout the study. Excavators were also used in the constructions; this study used the data from Volvo EC210, which bucket capacity is 1 m^3 and it is estimated that transferring the bucket from a truck, to the pile and back takes 15 seconds, resulting in 240 m^3 per hour. The Volvo EC210 consumes 26 litres of oil per hour (EC210 – Volvo, n.d.). The consistency of the soil was estimated to be 1600 kg/m^3 (Earth or Soil, n.d.) which amounts to 37.5 m^3 per truck. The average concrete truck was estimated to contain 7,5 m^3 of concrete and consume 70 litres per 100 km fully loaded, it was also estimated to consume 25 litres when empty per 100 km (Guðmundsson, 2012).

2.5.2 Shipping

Since Iceland is an island, most materials for construction need to be transported by sea to Iceland. This study assumes that relevant parts are transported from mainland Europe through the normal route of the Icelandic shipping company Eimskip (Siglingaáætlun, n.d.), which is Rotterdam – Immingham - Reykjavik. For the allocation of energy usage in the transportation, it is assumed that the ship fully loads in Rotterdam. In reality this is however not the case, since the ship transports various products to Iceland. However, to associate the energy cost of transporting these materials to Iceland, these simplifications are made. To justify this, an example can be made: in theory, the ship was loaded 50% with products destined for the power plant, and 50% with other products. One could therefore allocate 50% of the oil consumption to the power plant. This would however mean that the ship would have to make more trips from Rotterdam. One can therefore simply add up the total weight of all the material needed to transport, and calculate the amount of energy the ship uses for transport. This method should therefore give a good idea of how much energy it takes to transport these materials to Iceland. It is also assumed that the ship is used for other business when departing Iceland. Energy will not be counted for when the ship returns to Rotterdam. Only the energy used for transportation of the fully loaded ship, from Rotterdam to Immingham and from there to Reykjavík where the sea route was estimated to be ca. 3,000 km. General information about Dettifoss, one of the company ship, shown in Table 2.2, was provided by Eimskip shipping company and are as follows (EHO/MAO, n.d.).

Table 2.2 - Specific properties of one of Eimskip ships, Dettifoss

SPEED AND CONSUMPTION:	a.b.t knots	a.b.t 24 hours.	
		Heavy Oil	Gasoline
Max speed	N/A	60 T	
Full speed	20.0	56.5 T	
Economy speed	17.0	40 T	
In port		4-5 T	1-2 T
Fuel tank capacity		2009 m^3	186 m^3
Consumption above in tons per 24 hours			
Fuel grade : 380 cst, RMG 35, ISO 8217:1996(E)			
Dead weight 17034 T			

Given these parameters, one can calculate that 17 knots are 31 km per hour that the ship travels, which would equal to 97 hours of traveling between Rotterdam and Reykjavík. By using 40 tonnes of oil every 24 hours, one can also see that the ship would use 161 tonnes of oil on this route, transporting 17,034 tonnes. This number does however also include the oil used by the ship. Given the fact that the ship has a full tank, the amount of oil is 2009 m^3. This accounts for 881 kg/m^3 (aqua-calc, n.d.) or 1,769 tonnes of oil. This then leaves 15,265-ton allowance for other materials to be transported.

2.6 Energy use in Iceland

At present, most of the energy used within Iceland is either from geothermal or hydro power plants (Orkustofnun, n.d.). According to Orkustofnun, electricity production from hydro began in 1920, with less than 1 GWh hour produced. Subsequently, electricity production from geothermal began in 1969 with 2 GWh produced (Orkustofnun, n.d.). The amount of power produced in GWh has increased rapidly and in 2010, 17059 GWh were produced in total from hydro and geothermal. This can further be seen in Figure 2.4. Interestingly, power usage dropped significantly for the first time in the history of Iceland's power production in 2008.

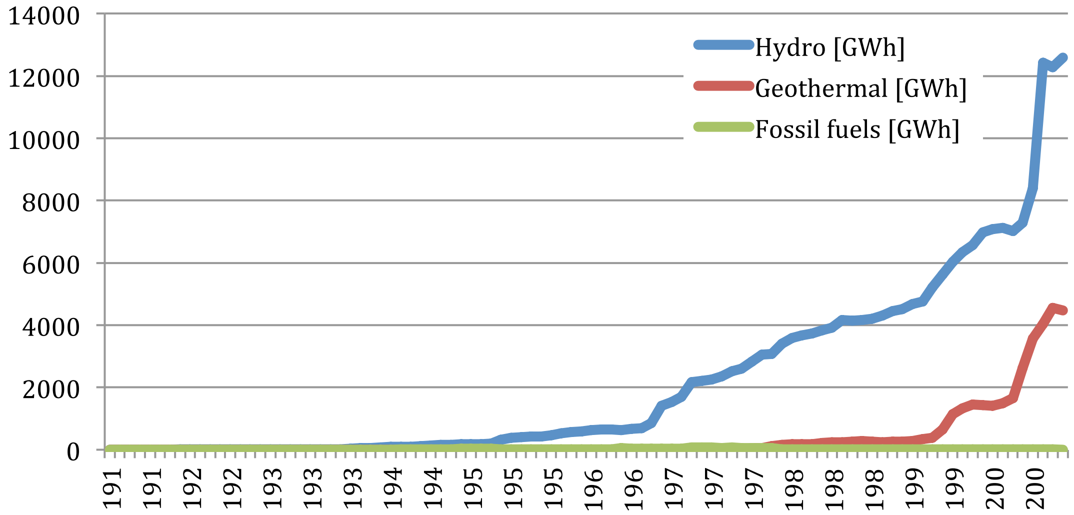

Figure 2.4 - Development of power utilization from 1915 in Iceland (Orkustofnun, n.d.)

The energy production process of both these sources will now be briefly explained.

2.7 Hydro

Hydropower is an energy source, which originates in the energy stored within water that flows from higher elevation to a lower one under the earth's gravity (Tester, 2005). This process is highly interlinked with solar energy and the hydrological cycle of evaporating water from oceans and lakes, which is then delivered to higher elevations as rain or snow. Rivers from higher altitudes, which are flowing towards the ocean, are constantly converting their potential energy into kinetic energy (Tester, 2005). This power can be harnessed by building a dam within a given river, where the power of the river is converted into electricity as the water is diverted towards turbines. This is the method mostly used today, where turbines produce rotating shaft work, which then turns an electric generator (Tester, 2005). Hydro power plants can produce from few KW to over 10,000 MW. Hydropower produces at present around 20% of the world's electricity (Tester, 2005). In the developing countries, hydropower has the potential to supply 1/3 of their total power whereas today only 10% of the potential power is being exploited. Hydro power plants can last over a century and are in general considered robust and durable (Tester, 2005). The 10 largest electric producing power plants today are hydroelectric. The biggest controversy around hydropower is the impact it can have on fish migration, water quality, land inundation and aquatic ecology (Tester, 2005). Even though much controversy is also around the reservoirs that often are associated with hydro, it is an important major renewable and a potential non greenhouse emitting source of electricity (Tester, 2005) which is a great economic factor in many countries, such as Iceland. In Iceland, aluminium companies are the biggest consumers of electricity from hydropower, where the general public only consumes around 15% of the power generated by Landsvirkjun (Landsvirkjun, n.d).

2.8 Geothermal

The stored energy within the earth's crust is what in general is considered to be geothermal energy. The energy is distributed between the host rock and the fluids that are contained within the crust which are above ambient temperature (Tester, 2005). These fluids are mostly water and dissolved salts. They also come across as steam when in a saturated or superheated steam vapour phase (Tester, 2005). The hot crust heats the fluids, which then build up pressure within the crust. This heat and pressure can be harnessed by drilling holes into the ground; this is done by similar methods as used by the oil industry in the exploration and extraction of oil wells (Tester, 2005). The reservoir also has to produce enough power for the plant to feasible. Not all areas on the planet are viable for geothermal energy production. Such areas accompany often tectonic plate boundaries and volcanic activity. That is why geothermal energy is often related to places such as New Zealand, Japan, Iceland (Plate boundaries), Yellowstone national park and the Lardarello field in Italy where volcanoes have been active in recent times (Tester, 2005). HDR or hot dry rock systems lack fluids within the hot rocks, but are still warm enough to be utilized. This is done by drilling a hole to sufficient depths, then fracturing the rocks to increase the heat transfer surface. After this has been done, a second hole is drilled, where water is injected to the well, which is then heated by the earth (Tester, 2005).In Iceland, geothermal energy has been used for various activities, Figure 2.5 shows the relative distribution between different sectors using hot water.

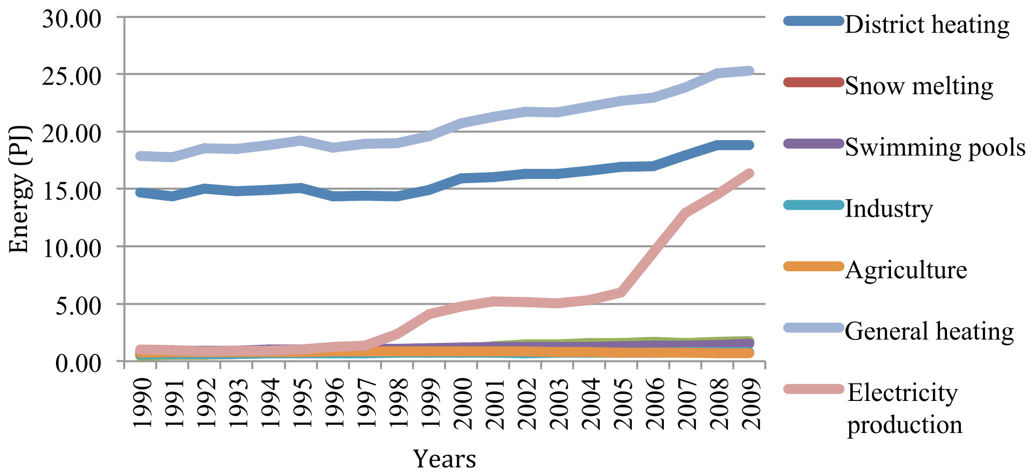

Figure 2.5 - Relative distribution between users of geothermal water (Y-axis shows PJ). (Orkustofnun, n.d.)

2.9 Case studies

This study looks at and calculates the EROI and the energy payback time for two power plants within Iceland, one geothermal and one hydro. These plants will now be described.

2.9.1 Case study 1: Nesjavallavirkjun geothermal plant

Claimed by Orkuveita Reykjavíkur to be Icelands biggest technological achievement, Nesjavallavirkjun is located in the southwest part of Iceland. The construction of the plant began in 1987. On 29th of September 1990, it was officially operating. The geothermal power plant currently produces 120 MW of electricity and 300 MW of heat power. At the site, 25 holes have been drilled to harness the geothermal power. The depth varies between 1000 – 2200 meters with temperatures up to 380°C. The average hole produces over 60 MW of power, which, according to Orkuveita Reykjavíkur is enough to heat the homes for 7500 people. Excess steam is used for electricity production (Nesjavallavirkjun, n.d.).

2.9.2 Case Study 2: Fljótsdalsstöð hydro station

Construction of Fljótsdalsstöð started in 2003 and it began operating on 30th of October 2007 (Fljótsdalsstöð, n.d.). The plant is set up to deliver 690 MW but delivers approximately 4,600 Gigawatt hours annually (against 6,044 GWh if producing 690 MW constantly). It is located on Iceland's eastern highlands and is the islands biggest power plant. The fall height from the reservoirs to the plant is 599 m and the average flow is 110 m^3/s. The maximum flow possible is 144 m^3/s. The reservoir (Hálslón) covers 57 km^2 when full and the flow to the reservoir is approximately 107 m^3/s. The main dam, Kárahnjúkar dam, is 198 m high and 700 meter long. Two horizontal Francis turbines are used to produce electricity. Two other dams divert water to Fljótsdalsstöð; these are Desjarár dam (68 m high and 1.100 m long) and Sauðárdalur dam (29 m high and 1.100 m long) (Landsvirkjun, n.d.)

2.10 Energy payback time

The energy payback time shows when a given plant starts to deliver surplus energy. This is the time from when the plant started operating until it has produced the same amount of energy it took to construct it, maintain it and operate. However, over the lifetime of the plant, it is constantly consuming energy for maintenance and operation. But these expenditures are mostly made after the plant reaches an EROI of 1. Therefore two methods will be calculated in this study. These methods will now be explained.

2.10.1 General description of EPT

In general, the input in the energy payback time can be described as follows:

$$x(t) = a + (b + c) \cdot t \qquad (6)$$

Where:

x Is the total input energy
a Is initial construction energy, including embodied energy within construction materials.
b Maintenance
c Own consumption
t Time factor

The output is described as the function

$$y(t) = d \cdot t \tag{7}$$

Where:

d is output energy

y is the output energy for a given time period

The energy payback time using method 1 is reached when:

$$y(t) = x(T) \tag{8}$$

Where:

T Is the expected lifetime of the plant

y Is the output of energy for a given time period

When this point in time is reached, one can see when the plant has produced the same amount of energy as took to construct it, operate and maintain over its lifetime. This method, hereafter referred to as method 1 is further explained in Chapter 2.10.2.

Method 2 is described as:

$$y(t) = x(t) \tag{9}$$

In this scenario, one can see when the plant has reached the EROI of 1 in logical time order. The x and y values in equation 8 and 9 are the same as used to describe the general input and outputs before. This method, hereafter referred to as method 2, is further explained in Chapter 2.10.3. A figure, showing the development of a theoretical system is provided in appendix 7.

2.10.2 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 total energy used for maintenance, operation and construction over the lifetime of each plant is summed up and divided by the annual output. This method can further be described as follows:

$$EPT_1 = \frac{Energy\ output\ per\ time}{Energy\ in\ over\ lifetime} \tag{6}$$

2.10.3 Method 2, Real time EPT

This method will not include future energy expenditures, but energy expenditures in logical order. This method will show when the plant will reach an EROI of 1 in real time. This method might be considered a more realistic one and 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, but is a changing variable. Same EROI scenarios will be used in both calculations. This method can be described as follows:

$$EPT_2 = \frac{Energy\ out\ per\ time}{Energy\ in\ at\ point\ in\ time} \quad (7)$$

2.11 Chapter Summary

The EROI boundaries used in this study are the $EROI_{stnd}$ and $EROI_{3,i}$, Also a new concept was introduced to the literature, named $EROI_{ide}$ which explains the maximum EROI possible at a given plant omitting any energy losses. To study the given plants, real data is used, gathered from stakeholders, which allows for very accurate results. Assumptions however needed to made for transportation to Iceland in regards to oil consumption of ships and trucks for the geothermal plant. It was shown that heavy industries are the biggest consumers of hydropower, where as the public only consumes a small portion of the power generated by Landsvirkjun. Energy payback time shows the time it takes the plants to produce the same amount of energy as they consume.

3 Results

A portion of this chapter resulted in an article, titled Energy Return on Investment of a Geothermal Power Plant (Atlason, Unnthorsson, 2012). It has been peer reviewed and accepted for the ASME 2012 International Mechanical Engineering Congress and Expo, Houston, TX.

3.1 Nesjavellir Geothermal Power Plant

This section shows the results from Nesjavellir geothermal power plant. It calculates the $\Sigma\beta$ results, $EROI_{3,i}$, $EROI_{stnd}$ as well as the $EROI_{ide}$. It further explains how transportation to Iceland was calculated. Subsequently, the energy payback time was calculated.

3.1.1 Phases calculated

This study includes different phases for Nesjavellir, which were calculated as an input to the equation 2. These are 1) energy the plant uses directly at site. 2) The energy used to maintain the plant. 3) The energy used to transport the materials to Iceland from mainland Europe. 4) All groundwork done in the construction phase. 5) Embodied energy involved in producing the parts to transfer the electricity from the plant, this includes masts and underground cables. 6) Grámelur pump station. 7) The embodied energy in the pipe and its foundations transporting the hot water produced at the plant to Reykjavik over approximately 25 km. 8) This accounts for all the major parts of the plant itself and the embodied energy that went into producing these parts.

3.1.2 Assumptions

The biggest assumption for Nesjavellir, in regards to energy consumption, is on maintenance. Two percent of the original material cost is accounted for annual maintenance. This number is however an unknown but was used in the LCA report by Kristjansdottir & Jonsdottir (2008) and will therefore be used in this study. The effects of this percentage changing can be seen in the sensitivity analysis. Future work, such as drilling other holes is excluded in this analysis. Calculations however showed, that if these factors are included, the EROI would only change slightly. These operations could have been kept in the study, but due to uncertain data regarding drilling (and if drilling would be needed) it is kept out. Other assumptions are general, such as the oil consumption allocated to shipping and oil usage for soil work and handling.

3.1.3 Ideal output ($\Sigma\beta$) from Nesjavellir

Reykjavík Energy provided all information about the boreholes currently in use for the $\Sigma\beta$ in the $EROI_{ide}$ equation to be calculated. The steam table in Appendix 5 was used in these calculations. The properties of the boreholes are provided in Table 3.1. The sum of all the energy from these holes will eventually form the $\Sigma\beta$, which will allow for the $EROI_{ide}$ to be calculated.

Table 3.1 - Pressure and temperature from bore holes in use at the geothermal Power plant

Hole	Pressure	Temp.	Enthalpy steam KJ/Kg	Enthalpy water KJ/Kg	Amount of steam Kg/s	Amount of water Kg/s	KJ/s of Steam	KJ/s of Water
NG-5	19	210	2798	897.8	8	9	22384	8080.2
NG-6	19.7	210	2798	897.8	21	9	58758	8080.2
NG-7	23.1	220	2802	943.6	5	16	14010	15097.6
NG-9	23.9	220	2802	943.6	18	18	50436	16984.8
NG-10	21.1	212.4	2800	908.8	6	26	16800	23628.8
NJ-11	21.4	212.4	2800	908.8	26	18	72800	16358.4
NJ-13	19.4	210	2798	897.8	28	23	78344	20649.4
NJ-14	20.6	212.4	2800	908.8	15	36	42000	32716.8
NJ-16	20	212.4	2800	908.8	11	11	30800	9996.8
NJ-19	22.5	220	2802	943.6	32	21	89664	19815.6
NJ-20	24	220	2802	943.6	5	12	14010	11323.2
NJ-21	19.5	210	2798	897.8	14	2	39172	1795.6
NJ-22	20.6	212.4	2800	908.8	27	34	75600	30899.2
NJ-23	20.8	212.4	2800	908.8	22	1	61600	908.8
NJ-24	20.1	212.4	2800	908.8	15	37	42000	33625.6
NJ-25	22.1	220	2802	943.6	32	2	89664	1887.2
Total					285	275	798042	251848.2

Table 3.1 calculates the total energy embodied in the saturated steam coming from these holes, as well as the thermal energy in the hot water. These amounts are summed up in a more comfortable way in Table 3.1.2. One can see that for the geothermal plant the following can be stated $\Sigma\beta = 33{,}112{,}000\ GJ/Year$. Table 3.2 shows that the utilization at the plant is 40%, meaning that the plant is using 40% of the energy that is available at the boreholes.

Table 3.2 – Energy from bore holes at the geothermal plant

	Steam	Water
MJ/s	798.042	251.848
MJ/m	47,882.52	15,110.88
MJ/h	2,872,951.2	906,652.8
MJ/day	68,950,828.8	21,759,667.2
MJ/Year	25,167,052,512	7,942,278,528
GJ/Year	25,170,000	7,942,000
		Plant output
Water		9,461,000 GJ/Y
Electricity		3,784,000 Gj/Y
Max (Ideal) output	Total GJ/ Year	33,112,000
Real Output	Total GJ/Year	13,245,000
Utilization		**40% efficiency**

However, since not all energy is possible to harvest, calculating the exergy from the plant can perhaps provide a more accurate and realistic approach to see the Ideal output. The exergy calculations can be seen in appendix 8

3.1.4 Embodied Energy

To produce all the materials used in the construction of the Nesjavellir power plant, energy was needed in the production process. The energy used in production for given materials is referred to as embodied energy. Information was available for the vast majority of materials used for the construction of Nesjavellir power plant, hot water pipe and other associated phases of the plant. The energy used to produce the pipes for the water transport was the biggest single consumer of energy. The 5980 tonnes of steel are the biggest factor of that matter. This section will look at individual phases and how the energy was consumed.

Embodied Energy of Nesjavellir plant and hole drilling

This phase was calculated to be the largest energy-consuming phase, with all the components added together. The energy used in the drilling and construction of the geothermal holes was the biggest factor in this phase, using, when put together, a total of 134,648 GJ. No other part of this phase amounted for such vast amount of energy. The construction of the station house came next with the total amount of 36,044 GJ used. The stages are further shown in Figure 3.1.

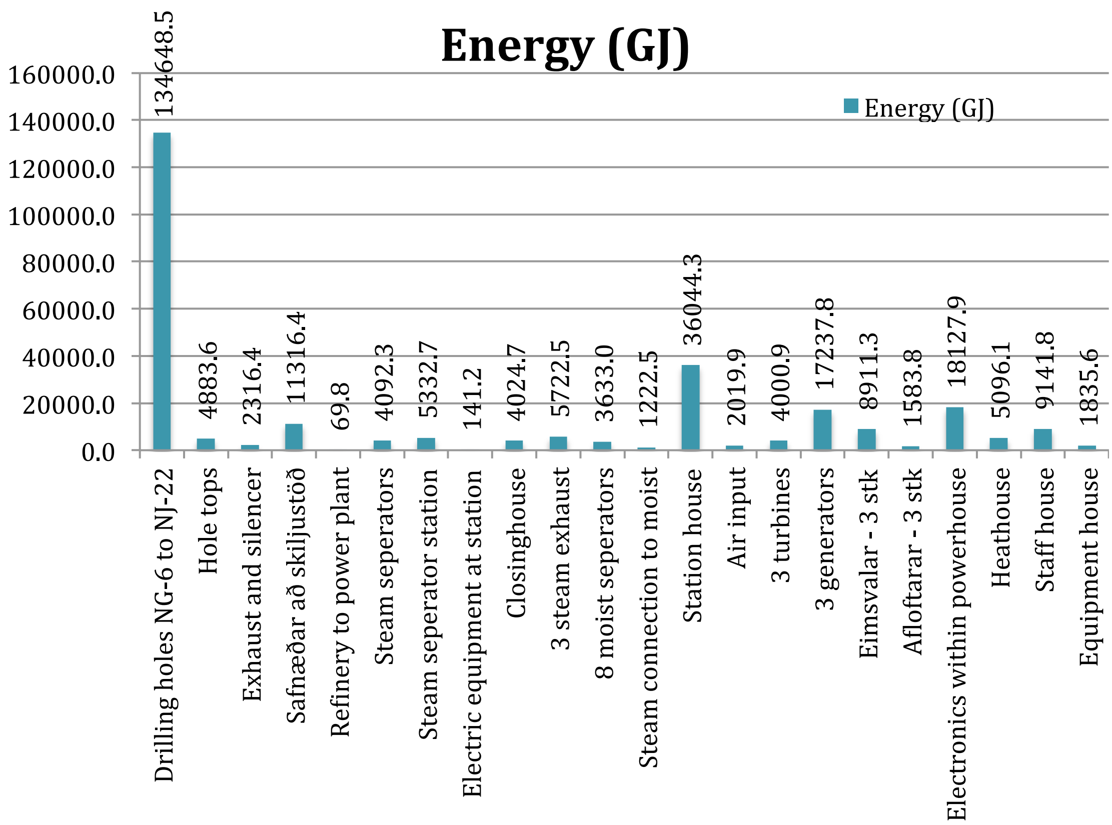

Figure 3.1 - Embodied energy in the Nesjavellir station and drilling phase

Figure 3.1 illustrates clearly which factors are the largest contributors in the plant phase and hole drilling. This does however not include any groundwork. Each of these stages included production of various materials, which in total add up to the given number for each stage, for example, the drilling of the holes included steel, oil, cement and other materials. The embodied energy of these materials is gathered from the literature. In total, the embodied energy of this phase amounted to 307,866 GJ.

Embodied Energy of Nesjavallaæð hot water pipe

Nesjavallaæð is the tube that transfers the hot water from the power plant to the city of Reykjavík. It consists mostly of steel and concrete but also a vast amount of wool, or 631 tonne. The energy used for the different parts of Nesjavallaæð can be seen in Figure 3.2. The phase of Nesjavallaæð also includes the storage tank at Háhryggur, which only amounts to a fraction of the total energy consumption.

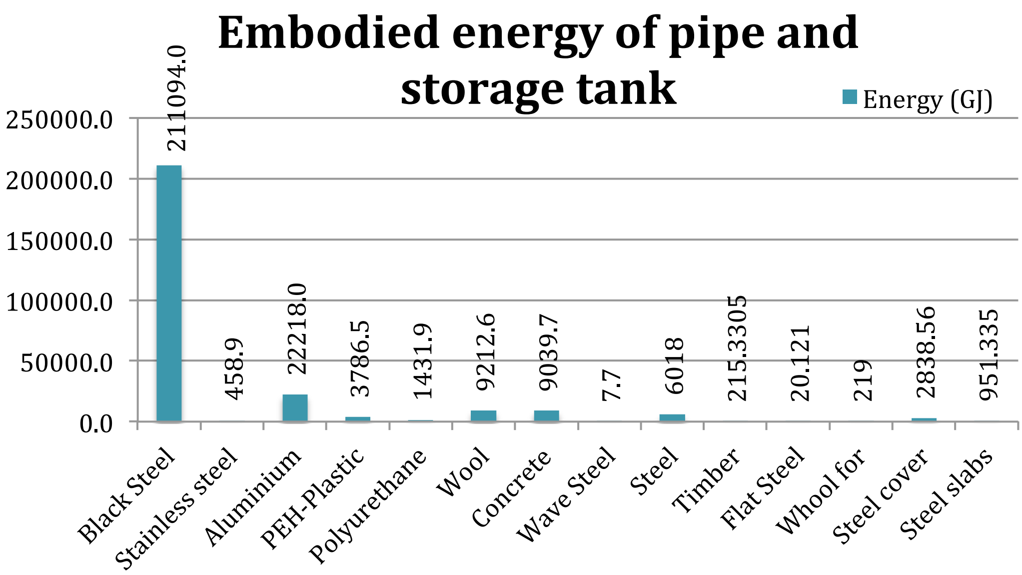

Figure 3.2 - Embodied energy within different parts of the pipe and storage tank at Nesjavellir

Figure 3.2 shows that the most amount of energy is used in the production of steel, or more than 211,000 GJ of the total 267,511 GJ. This can be directly attributed to the production of hot water at the plant. Steel is the largest single contributing factor within all these three phases. Aluminium is however counting for more than 22,000 GJ, which is a significant amount of energy considering that only 210 tonnes were used. The amount of energy used in aluminium production is however much greater than in steel production, or 105.8 GJ/Tonne of aluminium (U.S. Energy Requirements for Aluminum Production: Historical Perspective, Theoretical Limits and Current Practices. 2007) against 35.3 GJ/Tonne of steel (Hammond, 2008).

Embodied Energy in Grámelur pump station

Grámelur is a pump station, that pumps cold water from 6 boreholes and transfers towards Nesjavellir power plant. The cold water is then used to cool down steam among other purposes (VGK, 2000). The water is then transferred to the city of Reykjavík through Nesjavallaæð pipe. The total energy used in part production of Grámelur pump station amounts to 62,697 GJ. This shows that Grámelur is a minor part of the construction. Again, it is steel that amounts for the greatest energy consumption in Grámelur pump station. This is mostly due to the steel within a pipe that transports cold water. Figure 3.3 shows the energy consumption of various parts within Grámelur.

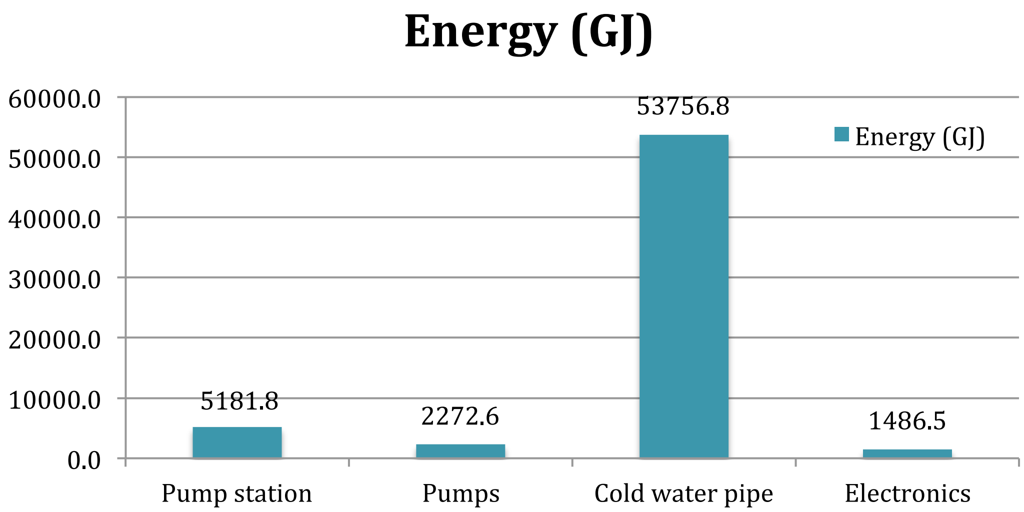

Figure 3.3 - Different parts of Grámelur pump station and the embodied energy therein

Comparison of embodied energy between phases

The three phases all needed different amounts of energy for their parts to be constructed. For further analysis it is helpful to look at Figure 3.4, which depicts the total amount of embodied energy of the three phases comparative to each other.

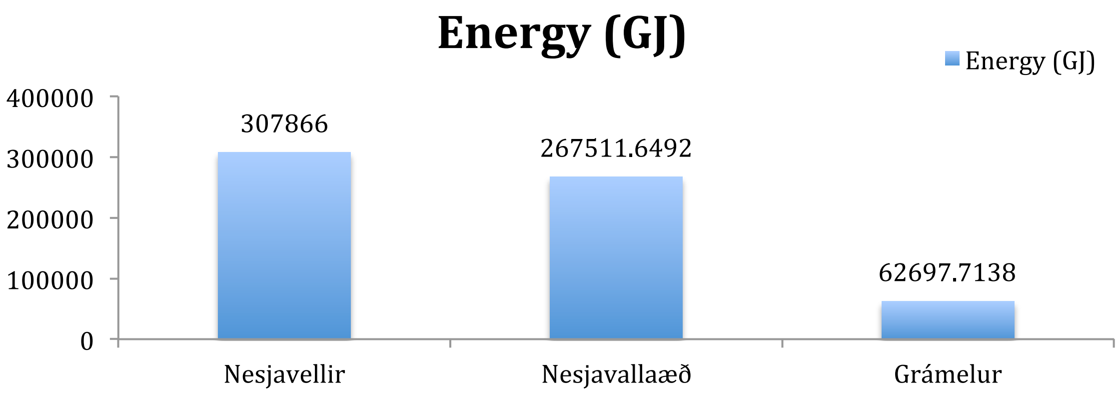

Figure 3.4 - Comparison of the embodied energy between the three different phases of the geothermal power plant

3.1.5 Transportation to Iceland

Heavy amount of polyurethane is used in the transportation pipes from the power plant to the city; polyurethane is given the mass of 946 kg/m^3 (aqua-calc, n.d.). Iron is also given the weight of 5,150 kg/m^3 (aqua-calc, n.d.). The total weight of all materials used in the construction amounts to approximately 21,000 tonnes. This is a rough estimate though, since many materials have not been accounted for due to their minimal weight. This number accounts for the largest proportion of materials. This accounts for 1.37 trips to Iceland from Rotterdam and 220 tonnes of oil. Within the calculations, it has been estimated that oil has the average energy value of 41.87 GJ/ton (Energy Units, n.d). Therefore approximately 9,211 GJ where needed to transport the materials to Iceland from mainland Europe.

3.1.6 Energy transfer from Nesjavellir geothermal power plant to Reykjavik

At Nesjavellir geothermal power plant, energy in form of hot water and electricity is produced. The hot water is delivered through a pipe, which stretches from the plant to the city of Reykjavik. Electricity is delivered through two power lines that are in three sections. Nesjavallalína power line 1 consists of 15.642 km of overhead power line running through masts and 15.65 km of underground cable. A map provided by Landsnet, showing where line 1 lies, is supplied in annex 4. Nesjavallalína power line 2 consists solely of an underground cable and is 24.6 km long.

Nesjavallalína power line 1

This line is divided into two sections, firstly an overhead power line, and secondly an underground cable. The overhead line consists of 51 masts, masts 1-10 on Hengilsvæði and 11-51 on Mosfellsheiði. The total length of the overhead line is 15.6 km. The underground line goes from Nesjavellir to Selklettar (2.45 km) and from Bringur to Korpa (13.2 km), the line is 15.65 km in total. The total weight of the masts is 180.3 tonnes, with the average weight of 3.535 tonne. (Línuhönnun, 2002.) Soil that had to be removed for the construction of masts 1-10 at Hengilsvæði amounts to 2,006 m^3 and 315 m^3 of soil was transferred to the site for construction. 618 m^3 where used for road construction. For masts 11-51 at Mosfellsheiði 1,514 m^3 of soil was removed and 408 m^3 of soil was imported for mast construction. At Mosfellsheiði however, 43,610 m^3 of soil was imported for road construction, which is a significantly higher number than was imported for road construction at Hengilsvæði (Línuhönnun, 2002).

Nesjavallalína power line 1 Underground Cable

Information provided by Landsnet (Icelandic Energy Grid) on the properties of the underground cable are as follows:

Total length: 15.65 km
Conductor:
    Aluminium: nominal diameter of 26 mm.
Insulation:
    Extruded cross-linked polyethylene: nominal diameter 18 mm.
Over sheath:
    Extruded polyethylene, nominal diameter of 3.3 mm.

The volume of these materials can be calculated using the cylindrical formula as follows:

$$V = \pi h r^2 \tag{10}$$

Where:
V is Volume
π is 3.141519 (approximately)
h is Height
r^2 is the radius in the power of two

One can therefore calculate that the amount of aluminium is 0.0005 m^3 per meter. This line however runs for 15,650 meters, and the volume is therefore 7.825 m^3 of aluminium in total. The amount of energy used in production of such amount of aluminium is 542,700 MJ/m^3 (U.S. Energy requirements for aluminium production, n.d.). This amounts to 4,246,627 MJ, or 4,247 GJ in total for the aluminium.

Polyethylene is then used as insulation; it has the nominal thickness of 18 mm. the volume of the plastic insulation can therefore be calculated to be 0.0002 m^3 per meter. This line runs for 15,650 meters and the volume can therefore be calculated to be 3.13 m^3. The amount of energy used in production of this amount of polyethylene is 97,340 MJ/m^3, which is in total 304 GJ.

The third element calculated in this cable is the polyethylene cover. The nominal thickness of the sheath cover is 3.3 mm. This amounts to another 0.12 m^3 of polyethylene over the total distance of the cable. In total 11.6 GJ were used in the production of the polyethylene.
The total energy used in production of this part of the electricity line Nesjavallalína power line 1 is in total 4,568 GJ. It should be noted however that the energy used in the construction of the line, that is raising the masts, digging the ditches and so forth have not been calculated in this. These calculations are not to be excluded but are done independent of the embodied energy calculations in the production of specific parts.

Nesjavallalína power line 1 Overhead Line

According to Landsnet, the owner of the Icelandic electrical power grid, the total weight of the 51 masts running from Nesjavellir is 180.300 tonnes. The embodied energy in this amount of steel is approximately 6,364 GJ, This does, like before, not include the construction energy on site (which is covered in Chapter 3.1.9). The overhead line is aluminium based; it consists of 37 threads, each with the diameter of approximately 4 mm (some parts go down to 3.49 when some parts go to 4.02). It has the average total diameter of 26.2 mm and stretches for 15.642 km. Using equation 6 the total volume of the aluminium cable can be calculated to be 0.0005 m^3 per meter of cable. This will then in total amount to 8.29 m^3 of aluminium. The embodied energy of 1 m^3 of aluminium is approximately 542,700 MJ (Embodied Energy coefficients, n.d.), which amounts to 4,498,983 MJ, or 4,499 GJ. The masts needed approximately 168 m^3 of concrete, which only uses 2.07 GJ per m^3. This amounts to 347.76 GJ for the concrete. Another 14,020 kg of steel were used in reinforcements of the base slabs. 494 GJ of energy was used in the production of this reinforcement steel. In total, 11,706 GJ were used in the production process of the overhead line in Nesjavallalína power line 1.

Total energy embodied in Nesjavallalína power line 1.

When adding the total amount of energy of these parts of Nesjavallalína 1 the total energy amounts to 16,274 GJ. Where the underground cable amounted for 4,568 GJ with the entire major components included. The overhead cable, including the masts amounted for 11,706 GJ.

Nesjavallalína power line 2

This underground cable is 24.6 km long, and is in most parts the same as the underground part of Nesjavallalína 1. It will therefore be calculated using the same parameters. 291.8 GJ were used in the total production process of that line per km. The same number will be used for Nesjavallalína power line 2. This will then amount to 7,180 GJ over the whole distance of 24.6 km.

Nesjavallaæð hot water pipe

Nesjavallaæð hot water pipe transfers the hot water from the power plant to the city. It contains various parts, such as concrete, steel, wool, polyurethane and timber. The largest portion of the embodied energy lies in the 5,980 tonnes of steel used. The steel amounts to 211,094 GJ of energy used in its production, this is calculated estimating that each tonne uses 35.3 GJ. The total energy in the production phase of Nesjavallaæð hot water pipe is estimated to be 267,511 GJ with all major parts included.

3.1.7 Total Embodied energy in Nesjavallalína power line 1, 2 and Nesjavallaæð hot water pipe

The total energy used to produce Nesjavallalína power line 1, 2 and Nesjavallaæð hot water pipe amounts to 290,965 GJ. It was shown that the transportation of hot water from the plant amounts to the greatest energy consumption in production. This is mostly due to the large amount of steel needed in the pipe or 5,980 tonnes.

3.1.8 Energy usage in operation

The own energy usage at the plant is 12 MW at the current production rate (Rafnsson, 2012). This equals to 105,120 MWh every year, or 378,432 GJ per year, which makes the own usage of the plant the biggest energy-consuming factor of the plant. Pumps, pumping water to and from the plant, consume most of this energy. However, if no hot water production for consumption would be present at the power plant, the own energy consumption would stay relatively close to present state. This is because of the cooling that takes place at the plant, which would still require this amount of water.

3.1.9 Machinery in construction

As mentioned previously, the energy in producing individual parts of the power plant are not the total amount of energy used. Soil was removed and replaced, both for mast construction as well for the underground cable to be laid. This stage was energy consuming and will be explained in detail now. For the transport of concrete from Reykjavík to Nesjavellir, the distance of 100 km was estimated.

Transport from harbour

After all parts arrive to Iceland, they must be transferred to Nesjavellir. This was calculated by summing the weight of most significant components and dividing them to fully loaded trucks. The distance used for this was 100 km. This estimate should be relatively close since some materials needed to travel further but some shorter. The total weight is calculated to be 20,816 tonnes, which means that a fully loaded 60 tonne truck would drive 347 trips to Nesjavellir. It is assumed that the truck would drive empty back to the harbour. This amounts to 18,387 litres when driving full to the location, and 10,408 when driving empty back. In total, it is estimated that transporting the materials would need 28,795 litres of oil, or 1,117 GJ.

Nesjavallalína power line 1

Nesjavallalína power line 1 consists of two main parts, the overhead line and the underground cable. For masts 1-10 of the overhead line, 2,006 m^3 had to be removed for the masts, 315 m^3 were then used to replace the pre-existing soil. Also, 618 m^3

were used to create roads. For masts 10-51, 1514 m^3 was removed for the masts, 408 m^3 imported and 43,610 m^3 used for road construction. To lay the underground cable, a ditch of 200 X 120 cm was dug. This ditch covered the distance of 16.65 km and therefore 37,560 m3. In total, 86,031 m3 were removed or imported to that location. 168 m^3 of concrete was used in the construction of the masts.

It is estimated that the trips per truck are 50 km. This would require 2,294 trips for a 60 tonne truck which would consume 60,795 litres of oil fully loaded and 34,412 litres driving empty. In total, this amounts to 95,207 litres of oil usage by the truck. The excavator on site did two jobs; first of all it removed soil for the masts. Second, it dug the ditch for the underground cable. It is estimated that the excavator removed 4 m^3 per minute. This amounts to 21,507 minutes when removing or importing the soil for the masts. This amounts to 358 hours, and 9,320 litres of oil in total for this stage, assuming that the excavator consumes 26 litres per hour. For digging the ditch, it is estimated that the total hours amount to 156, which equals 4,069 litres of oil. To transport the 168 m^3 of concrete from Reykjavík, the concrete trucks needed 23 trips, which amounted to 2,128 litres of oil, or 82 GJ. By summing the oil usage of these phases, one can see that the total amounts to 110,724 litres of oil. The energy content of oil is considered in this study to be 38.4 MJ per litre. This amounts then to 4,251 GJ for the machinery usage of Nesjavallalína power line 1. Table 3.3 further outlines the energy consumption at this stage.

Table 3.3 - Energy used in ground construction of Nesjavallalína power line 1

Machinery used	**Amount of oil**
Truckload (masts and ditch)	95,207 litres
Excavator (Mast work)	9,320 litres
Excavator (Ditch)	4,069 litres
Concrete truck	2,128 litres
Total	110,724 litres
Gigajoules	4,251

Nesjavallalína power line 2

Unlike Nesjavallalína power line 1, power line 2 is solely underground and goes for 24.6 km. The same parameters are used for this line as is for the underground part in line 1. That is that the ditch is 200 cm wide and 120 cm deep.

The same parameters are used for all trucks in this study. For this part of the line, 59,040 m^3 were to be removed. This amounts to 1,574 trips of 50 km. It is estimated that the truck used 41,721 litres driving fully loaded, and 23,616 litres driving back empty. In total, the fuel usage by the truck on this phase was 65,337 litres. In this phase, the excavator removed 59,040 m^3, this required at least 14,760 minutes of operation time, or 246 hours. This leads to 6,396 litres of oil consumed to dig the ditch to lay the underground cable. By summing up the oil usage of line 2, it is evident that the trucks used 65,337 litres and the excavator 6,396 litres. This amounts to 71,733 litres of oil or 2,783 GJ in the total construction phase of Nesjavallalína power line 2. As mentioned, Nesjavallalína 2 is an underground cable that stretches the whole way from the power plant to Reykjavík. Table 3.4 further outlines the energy use at this stage.

Table 3.4 - Energy used in ground construction of Nesjavallalína power line 2

Machinery used	**Amount of oil**
Trucks	65,337 litres
Excavators	6,369 litres
Total	71,706 litres
Gigajoules	2,753

Nesjavallaæð hot water pipe

A pipe, which delivers hot water from the power plant, runs from the geothermal plant to the city of Reykjavík. For this, some 76,150 m^3 of soil needed to be removed or imported to the site. 8,023 m^3 of concrete was used in the construction of the water pipe. This amounted to 2,030 trips by trucks, where the trucks used 53,812 litres of oil driving fully loaded and 30,460 driving empty back, in total the trucks consumed 84,272 litres of oil. This amounts to 3,269 GJ of energy. The excavators needed 317 hours of operating time to handle the 76,150 m^3 of soil and deliver them to the trucks; this amounted to 8,249 litres of oil or 320 GJ. To transport the 4,414 m3 of concrete from Reykjavík, 588 trips were needed. This amounts to 55,910 litres of oil usage by the concrete trucks. Table 3.5 outlines the energy used by machinery in the construction of the hot water pipe.

Table 3.5 - Energy used in ground construction of the water pipe at Nesjavellir

Machinery used	**Amount of oil**
Truckload	84,272 litres
Excavators	8,249 litres
Concrete trucks	55,910 litres
Total	148,431 litres
Gigajoules	5,759

General plant

In the construction of the physical plant, some 76,020 m^3 of soil needed to be handled, either imported or exported from site. This amounted to 2,027 trips by trucks, which in total consumed 53,720 litres driving fully loaded, and 30,408 driving empty back. This in total amounted to 84,128 litres consumed by the trucks. The excavators needed 316 hours of operating time to handle this amount of soil, using 8,235 litres of oil in total. To transport the 8,023 m^3 of concrete for the construction of the plant, 1,069 trips were needed from Reykjavík, consuming 101,624 litres of oil by the concrete trucks. In total, 7,526 GJ of energy were consumed at this phase. The energy used by machinery in the construction is further outlined in Table 3.6.

Table 3.6 - Energy used in ground construction of the general geothermal plant

Machinery used	**Amount of oil**
Truckload	84,128 litres
Excavators	8,235 litres
Concrete trucks	101,624 litres
Total	193,978 litres
Gigajoules	7,526

Grámelur pump station

At Grámelur, 3,500 m3 were either imported or exported from the site at the construction phase and 162 m^3 of concrete was used. In total, the trucks needed 93 trips to handle this amount of soil. Using 2,473 litres driving fully loaded and 1,400 litres driving empty. In total, the trucks used 3,873 litres of oil. The excavators needed 14.5 hours to deliver this amount of soil, resulting in 379 litres of oil. To transport the concrete to site, 22 trips were needed, requiring 2,052 litres of oil. In total this amounts to 6,309 litres of oil, or 244 GJ. Table 3.7 sums the energy used at the construction site at Grámelur pump station.

Table 3.7 - Energy used in ground construction of Grámelur pump station

Machinery used	Amount of oil
Truckload	3,878 litres
Excavators	379 litres
Concrete trucks	2,052
Total oil	6,309 litres
Gigajoules	244

3.1.10 Sum of energy in construction

When all the energy consumed by removing and replacing soil, transporting materials from the harbour and transporting concrete from Reykjavík to various sites is put together, the result is 21,725 GJ. Table 3.8 sums up the energy used in various phases for soil handling and transport of materials.

Table 3.8 - Energy used for groundwork at different stages of the plant construction

Phase	Energy (GJ)
Transport from harbour	1,117
Nesjavallalína power line 1	4,296
Nesjavallalína power line 2	2,783
Water pipe	5,759
General Plant	7,526
Grámelur	244
Total	21,725

The distribution can further be seen in Figure 3.5. This shows that most energy went into the plant construction, or 35%, following by the groundwork form the water pipe, which amounted to 26%. Electricity transport amounted to 33% in total as is shown by Nesjavallalína power line 1 and 2.

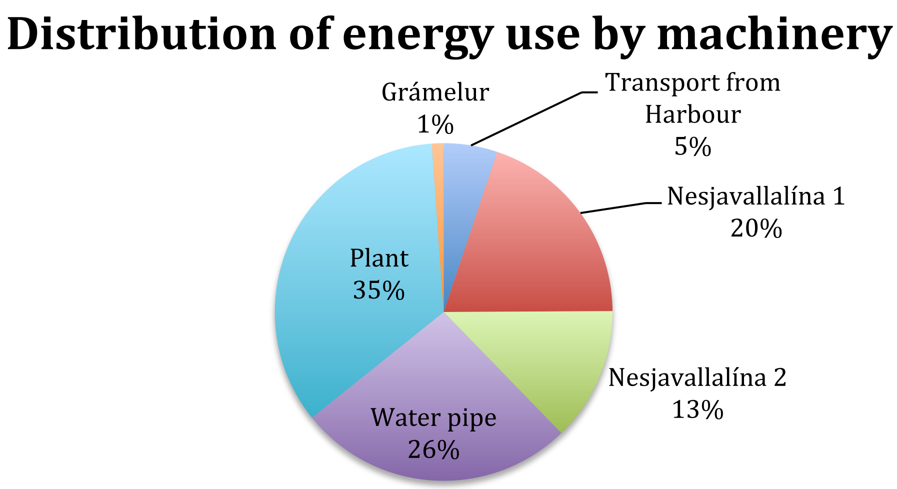

Figure 3.5 - Relative distribution of energy use by machinery in construction of various phases of the geothermal power plant

3.1.11 Total energy used in Nesjavellir

After calculating all the main phases of the production and construction of this power plant and the main components, one can add up the total amount of energy consumed. These include:

a) Embodied energy of all the major components of the plant. That is, the energy it took to produce these parts
b) The energy it took to transport all parts from mainland to Europe
c) The energy it took to transport all parts from Reykjavík to Nesjavellir
d) How much energy was consumed while removing and importing soil at site
e) The energy used to transport all the concrete from Reykjavík to sites.
f) Energy used for maintenance (2% of original energy cost per year)
g) 12 MW own usage

This can be clearly seen in Table 3.9 which sums these factors up.

Table 3.9 - Energy consuming factors included in the construction, operation and maintenance of the geothermal power plant

Phase	**Energy (GJ)**
Total embodied energy	661,527
Transport Europe – Iceland	9,211
Transport Reykjavík – Nesjavellir	1,117
Soil and concrete handling	21,725
Power usage per year	378,432
Total used Energy (excl. own usage)	**699,854**
Maintenance per year (2%)	13,849

The input is distributed as depicted in Figure 3.6 where the own usage of power by the plant is the biggest contributing factor, or 378,432 GJ per year (which will run for 40 years). This is followed by the embodied energy in the plant and hole drilling. The third largest contributor is the pipe, transporting the hot water from the plant to the city of Reykjavik. What should however be noted as well, is that all these factors are fixed, meaning that they occurred only once and will not result in further energy usage, except the operation and maintenance. However, as has been noted, the LCA report regarding the plant assumes for some hole digging after 2002, these operations would only amount for a minimal change in the EROI results and are therefore excluded. The two factors (maintenance and operation) prove to be, in the long run, the biggest energy consuming factors of the plant. Electricity transport seems to be minimal compared to the general construction of the plant and the hot water pipe construction. Groundwork associated with the construction is also minimal, but is however higher than the transport of the ingredients from mainland Europe to Iceland.

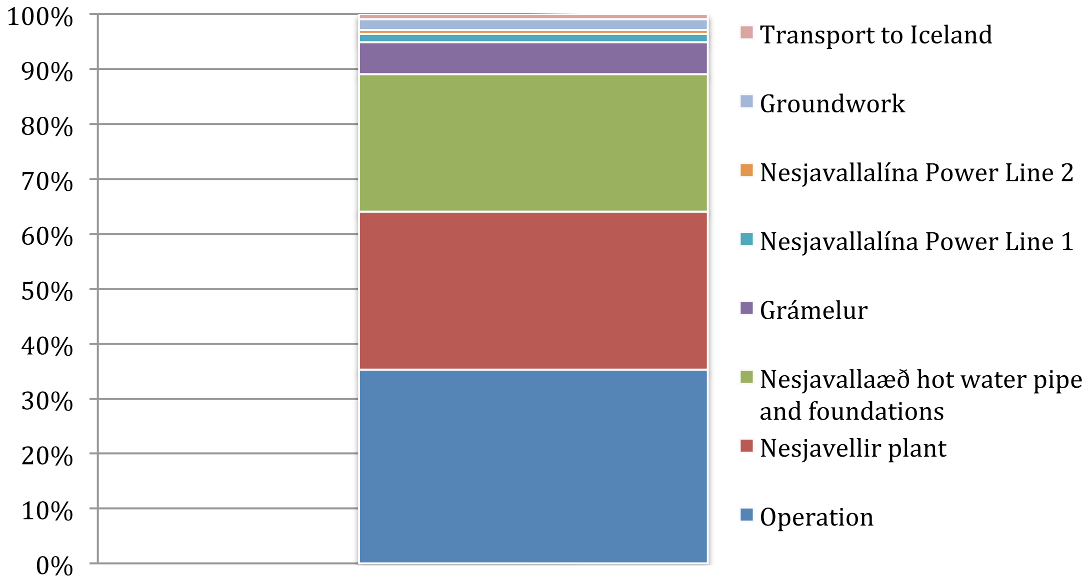

Figure 3.6 - Associated energy with different phases of the geothermal plant construction and operation over the first year

As described before, it is estimated that the maintenance of the plant will account for 2% of the original material cost annually. The overall impact of the operation and maintenance factor is not linear as one might think, it can be further observed in Figure 3.7 where the operation cost in energy term increases from year to year, as well as the maintenance cost. This can be observed by looking at the thickness of the horizontal bars in Figure 3.7, the fixed energy use get narrower the further time passes, but the increasing energy use gets thicker (operation and maintenance). Figure 3.7 shows clearly that the own power consumption at the plant is by far the largest energy consuming factor over the plants lifetime, followed by the maintenance, which becomes a larger portion than total embodied energy after approximately 27 years.

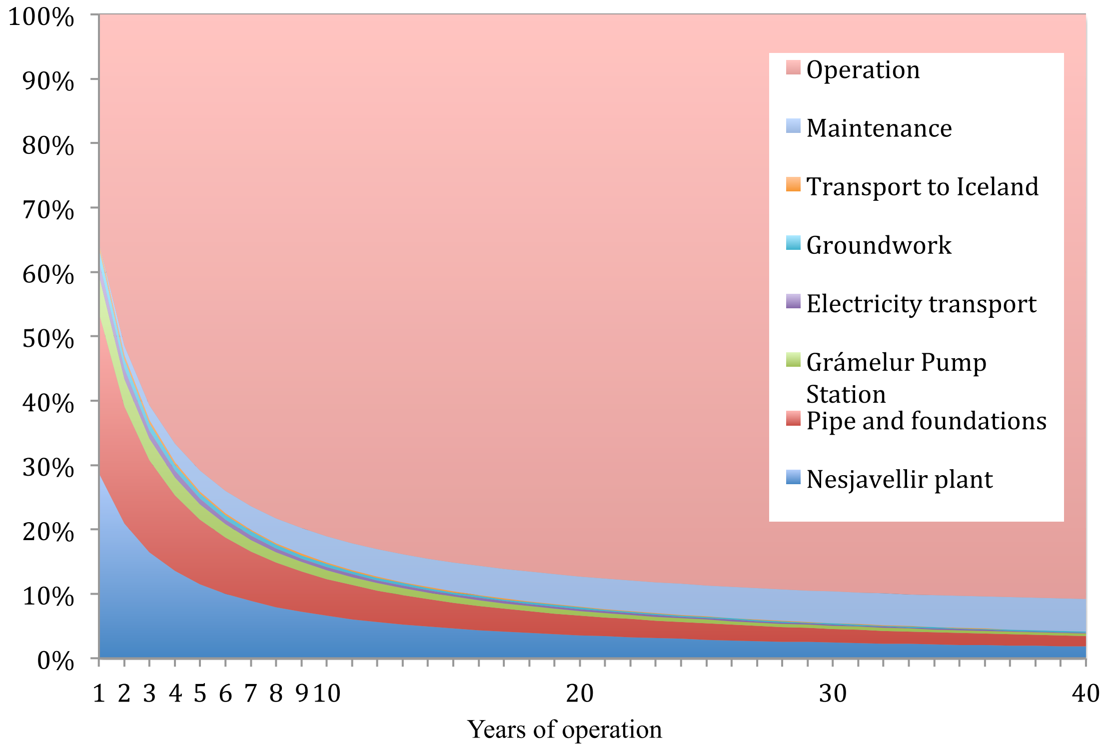

Figure 3.7 - Development of energy use of different phases in the construction and operation of the geothermal power plant over 40 years.

3.1.12 EROI of Nesjavellir

This section will calculate the EROI for the geothermal power plant; different scenarios will be calculated since the lifetime of the plant is not known in beforehand. The $EROI_{ide}$ explained before, will also be calculated. Scenario excluding hot water will also be calculated, to show the EROI of the plant if it produced solely electricity. Answer to the research question will be given in this chapter, which is the $EROI_{stnd}$, $EROI_{3,i}$, $EROI_{ide}$ and the energy payback time for the power plant.

3.1.13 $EROI_{stnd}$

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. This is a good factor for comparison of energy sources since the plants may need more or less distances for transport of the energy. The distance might disadvantage some energy sources even though the source might have a relatively good EROI. In the case of Nesjavellir power plant, this will include the same inputs as before, but will exclude the mechanisms for delivering the energy. That is the pipe, which delivers the hot water, as well as the mechanisms for delivering the electricity, namely Nesjavallalína power line 1 and 2.

The input was 779,931 GJ for the first year, which are the input factors summed up, plus the operational power usage. The $EROI_{stnd}$ scenario can be seen in Table 3.10 over the lifetime of the plant.

Table 3.10 – Different output and input scenarios for the $EROI_{stnd}$ calculations for the geothermal plant over the first 40 years of operation

Year	Output (GJ)	Input (GJ)	$EROI_{stnd}$
1	13,245,000	779,931	17
10	132,451,200	4,310,463	30.7
20	264,900,000	8,233,276	32.2
30	397,353,600	12,156,089	32.7
40	529,804,800	16,078,902	33

This scenario shows that the $EROI_{stnd}$ is around 33 over the lifetime of the plant. Figure 3.8 explains the development of the $EROI_{stnd}$ over the lifetime.

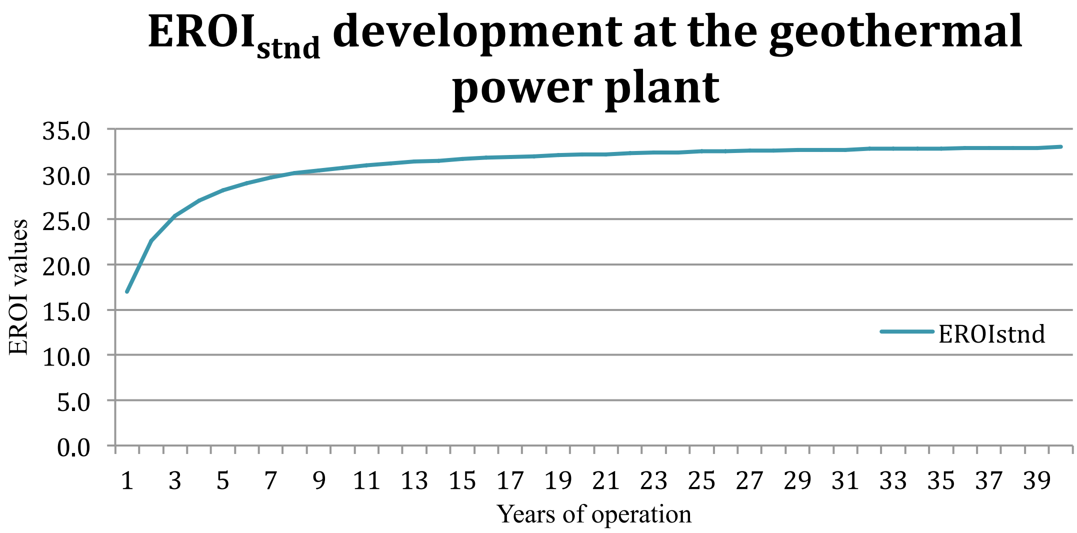

Figure 3.8 - Development of the $EROI_{stnd}$ for the geothermal power plant over the lifetime of 40 years. The x-axis shows years, the y-axis shows the EROI

3.1.14 $EROI_{3,i}$

With the knowledge compiled, then following calculation can be made from equation 3. This includes the direct energy for the operation of the plant, as well as the indirect energy used for construction of materials and groundwork. $EROI_{3,I}$ also includes the direct energy output from the plant as well as the co-efficient energy output, which in this case is hot water. Summing all these factors up, the scenario shown in Table 3.11 is the result. After the first year, 2% maintenance of original energy cost will occur annually and operational cost is a constant 12 MW. This will therefore be calculated in the EROI of the plant. Table 3.11 shows the EROI for every 10 years, for 40 years, which is the expected lifetime of the plant.

Table 3.11 – Different output and input scenarios for the $EROI_{3,i}$ calculations for Nesjavellir geothermal power plant over the first 40 years of operation.

Year	Output (GJ)	Input (GJ)	EROI
1	13,245,000	1,070,896	12.3
10	132,451,200	4,601,428	28.8
20	264,900,000	8,524,241	31.1
30	397,353,600	12,447,054	31.9
40	529,804,800	16,369,867	32.4

One can therefore see that over the lifetime of the plant, the EROI will be just a little more than 32. It increases rapidly in the beginning but as times goes by and operational and maintenance costs increase it levels off. This can be seen in Figure 3.9 where the development of the EROI is visualised.

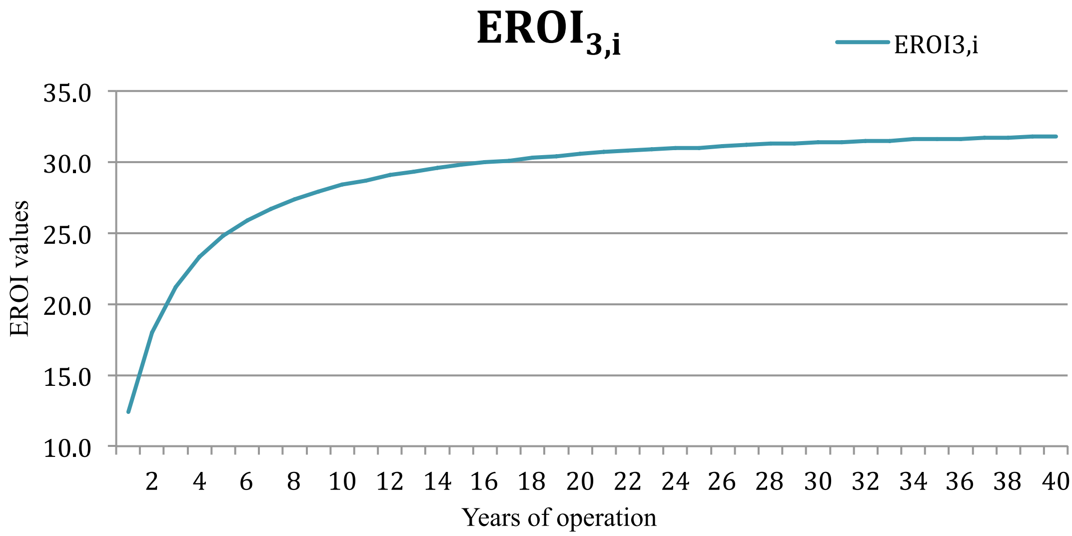

Figure 3.9 - Development of Nesjavellir geothermal power plant $EROI_{3,i}$ over 40 years. The x-axis shows years, the y-axis shows the EROI

3.1.15 $EROI_{3,i}$ scenario without hot water

Since a vast amount of hot water is delivered from the plant, and the part, which has the largest embodied energy associated to it is the pipe, which delivers the hot water. It is therefore interesting to see how the plant would perform without the hot water production. The plant produces 300 MW equivalent of hot water of the 420 total MW produced at the plant (Nesjavallavirkjun, n.d.). In this scenario, the plant only produces 120 MW but still uses the same amount of operation energy. The results from that scenario are shown in Table 3.12. One might however conclude that since hot water production has been removed, the energy needed for water pumping would be less (own usage). This was however clarified with Orkuveita Reykjavíkur, where the conclusion was that nonetheless, water needed to be pumped towards the plant and from it for cooling. Therefore, approximately the same amount of energy would be consumed at the plant. However, the best-case scenario was that the own consumption went down to 10 MW. The difference in results where the own usage is changed from 12 MW to 10 MW is shown in Figure 3.10. The amount of energy embodied in Nesjavallaæð hot water pipe is also removed.

Table 3.12 - Different scenario calculations for the $EROI_{3,i}$ without hot water

Year	Output (GJ)	Input (GJ)	EROI
1	3,784,000	803,385	4.7
10	37,840,000	4,285,765	8.8
20	75,680,000	8,155,076	9.3
30	113,520,000	12,024,386	9.4
40	151,360,000	15,893,697	9.5

Table 3.12 shows the EROI development if hot water production at Nesjavellir power plant was not present and the plant consumed 12 MW. This shows that the EROI declines from earlier results and stagnates at around 9.5. This shows that the hot water production increases the efficiency at the plant almost threefold, where the EROI with the hot water production and associated energy costs and benefits is around 33, whereas without the hot water production it is from around 9.5 to 11.2. The development of the EROI is similar in this scenario as compared to the earlier EROI's, this can be observed in Figure 3.10.

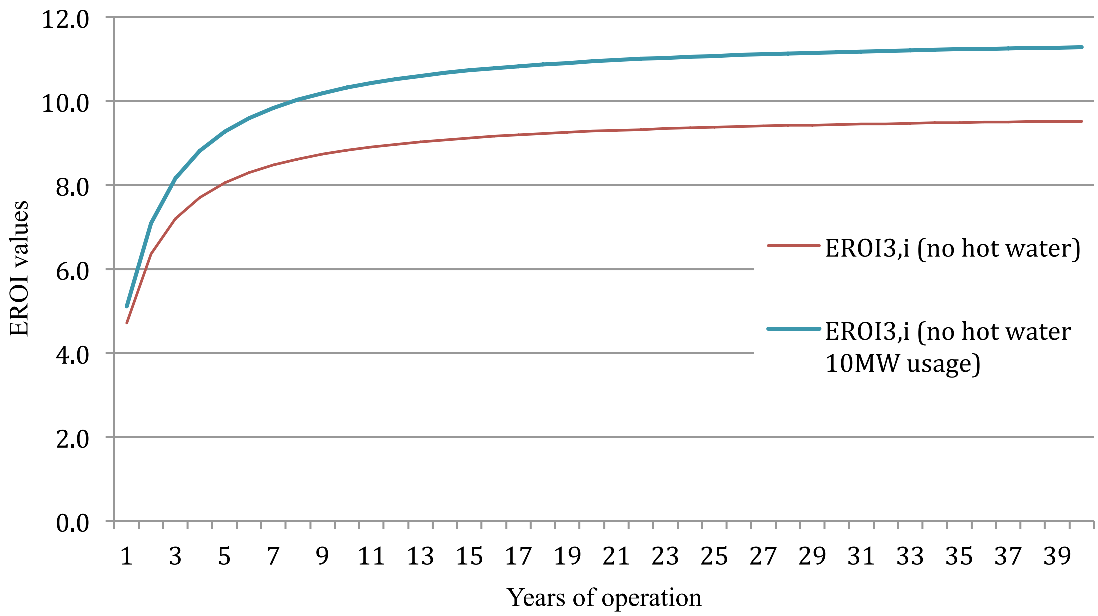

Figure 3.10 - EROI of the geothermal power plant without hot water production. X-axis shows years, Y-axis shows EROI values. The blue line shows the results if own usage went also down to 10 MW.

With the knowledge of the total input required to construct, maintain and operate Nesjavellir power plant over its lifetime, it is possible to calculate the $EROI_{ide}$ as was described in equation 4. Table 3.13 shows the $EROI_{ide}$ for the same intervals as the EROI was calculated previously.

Table 3.13 - Different output and input scenario calculations for the $EROI_{ide}$ at the geothermal power plant

Year	**Total Output (GJ)**	**Input (GJ)**	**$EROI_{ide}$**
1	33,112,000	1,070,896	30.9
10	331,120,000	4,601,428	72.0
20	662,240,000	8,524,241	77.7
30	993,360,000	12,447,054	79.8
40	1,324,480,000	16,369,867	80.9

The numbers provided in Table 3.13 show the EROI of the power plant if it was 100% efficient, which according to modern physics can never be achieved. It is illustrated that as before, the $EROI_{ide}$ increases rapidly the first decade, but then the increase slows down and stabilizes just above 80.

3.1.16 Energy payback time

As explained before, the energy payback time is the time it takes the power plant to produce the same amount of energy it took to produce the plant, maintain it and operate. With all the knowledge needed to calculate the EROI scenarios calculated above, it is possible to calculate the energy payback time. This will be calculated with the different input scenarios as were used in the different EROI calculations using the two methods listed in the methods chapter.

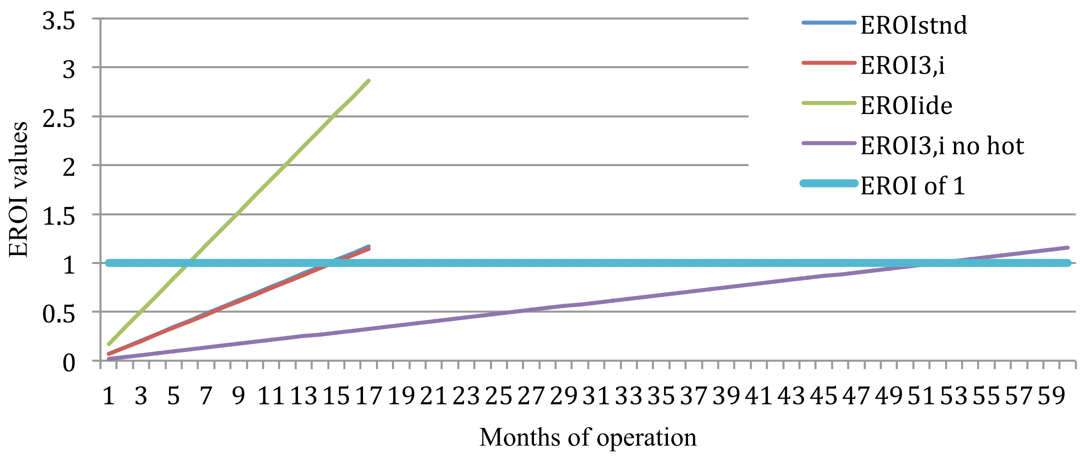

Figure 3.11 - Different energy payback times at the geothermal power plant when method 1 is calculated. X-axis shows months and y-axis EROI values.

The $EROI_{ide}$ has the shortest payback time, or almost exactly half a year using method 1. The scenario with no hot water production was found to have the longest energy payback. However, the $EROI_{stnd}$ and $EROI_{3,i}$ were found to have almost the same amount of energy payback time, or around 1 year and 3 months (1.21 and 1.23 years). These results are further put in context in Figure 3.11. However, when the scenarios are put in logical order of energy consumption and method 2 is used, where the energy for maintenance and operation is not summed up, the result is very different.

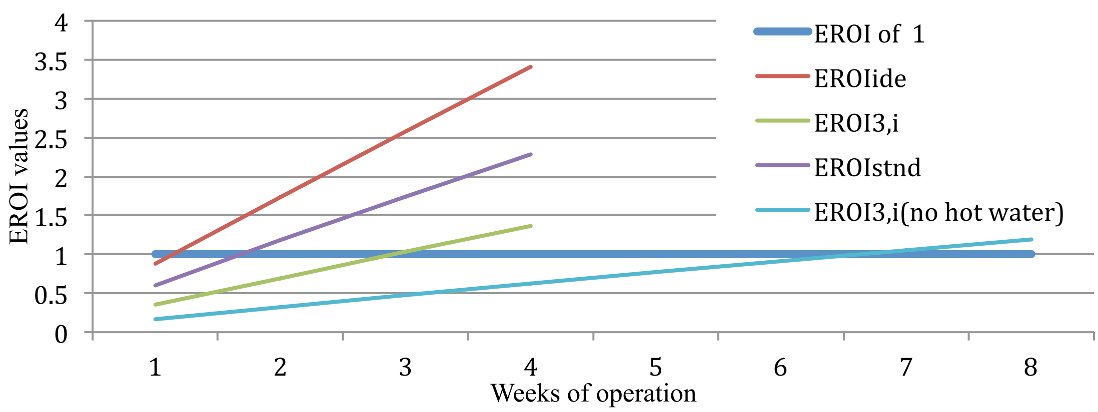

Figure 3.12 - Energy payback time of different scenario at Nesjavellir geothermal power plant using method 2. X-axis shows time in weeks, y-axis shows EROI values.

As Figure 3.12 shows, the development of the EROI's seems to be linear, it is however not, since the figure is merely showing the development in weeks. It does however show when the EROI reaches 1, where the same amount of energy so far used in the construction, operation and maintenance has been produced by the plant. Using method 2, $EROI_{ide}$ is only just more than a week to pay back its energy. $EROI_{stnd}$ is just a little less than 2 weeks. $EROI_{3,i}$ was found to pay back its energy in 3 weeks, whereas the $EROI_{3,i}$ scenario paid back its energy in 7 weeks.

3.1.17 Sensitivity Analysis

A sensitivity analysis was conducted, to see the effects on the EROI if the uncertainty factors (own usage and maintenance) would change over time. The parameters included lowering the maintenance from 2% of the original material cost as was calculated in the EROI scenarios down to 1% and up to 10%. It also included lowering the own usage by 10%, and increasing the own usage by 10% and all the intervals between. The scenario used in the sensitivity analyses was the $EROI_{3,i}$ over 40 years time. The analysis shows that if maintenance remains at 2%, but the operational cost decreases by 10%, the EROI increases from 32.4 to 35.7. It also shows that if the operational cost increases by 10% from the current status the EROI lowers down to 29.6. It was shown that if the operational usage remains as predicted (12 MW consumption) but the maintenance cost decreases down to 1% from the predicted 2% cost, the EROI increases slightly up to 32.9. If however the maintenance cost increases up to 10% per year of the original energy cost, the EROI declines down to 28.6. The best-case scenario of the analysis, where maintenance had decreased down to 1% and operational cost had decreased by 10%, the EROI reached 36.3. However, in the worst-case scenario where the maintenance cost was 10% per year and the operational cost had increased by 10%, the EROI dropped down to 26.4. The sensitivity analysis is further depicted in Table A.2. The equation to modify these parameters is as follows:

$$EROI_{3,i} = \frac{ED_{out} + \Sigma v_j O_j}{((Op * y) + E + (E * x * 39))} \tag{11}$$

Where:

ED_{out} Is the total output energy over the lifetime of the plant.
Op Is the total operational use.
y Is the percentage if the original use to be calculated.
E Is the total embodied energy of the plant.
x Is the fraction of the embodied energy used for maintenance.
39 accounts for the years of maintenance over the 40 years lifetime of the plant.

To visualise further how the EROI changes with different parameters, Appendix 2 is provided which shows different results within each parameter.

3.1.18 Summary of Nesjavellir

It was shown that shipping to Iceland amounts to only a small portion of the total energy consumed in the production of the plant. It was however shown that the own usage of the plant amounted to the largest portion, consuming 12 MW, followed by the maintenance, over the 40-year lifetime of the plant. Pipes and foundations, for delivering hot water to Reykjavik consumed enormous amount of energy, which was mostly used in the steel production for the pipes. Four EROI scenarios were calculated and the energy payback time of the Nesjavellir power plant. The $EROI_{stnd}$ was found to be 33 over a 40-year lifetime of the plant. The $EROI_{3,i}$ was found to be slightly lower, or 32.4 since it included the energy needed to transfer the electricity and hot water to Reykjavik. To see how much difference the hot water made, the $EROI_{3,i}$ was also calculated excluding the hot water production. This resulted in a much lower EROI of 9.5 over the lifetime of the plant and 11.2 when the own consumption was reduced by 2 MW. A new concept was introduced to the literature in this chapter, $EROI_{ide}$, which calculates the maximum theoretical EROI possible. The $EROI_{ide}$ was calculated to be 80.9 over the 40-year lifetime of the plant. Figure 3.13 further illustrates the differences between the EROI scenarios, clearly illustrating that the efficiency can be improved at the plant significantly, but only up to the limit that the $EROI_{ide}$ indicates.

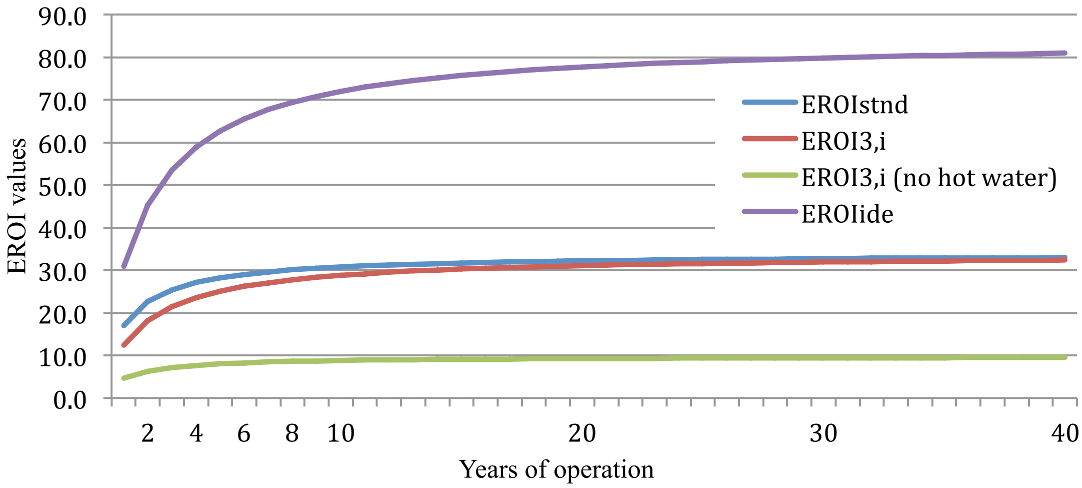

Figure 3.13 - Development of different EROI scenarios calculated for Nesjavellir geothermal power plant. The x-axis indicates the years and the y-axis the EROI values.

The energy payback time was calculated using method 1 to be 1.24 years in the $EROI_{stnd}$ scenario and 1.26 years in the $EROI_{3,i}$ scenario, which is around 1 year and 3 months it would take the plant to produce the amount of energy it consumed to be constructed and used during its operational lifetime. The energy payback time was however only 6 months (0.5 year) for the $EROI_{ide}$ scenario. This underlines the increase in efficiency when hot water is produced at the plant as well as electricity, where the energy payback time went from 4.3 years down to 1.26 years. This can further be seen in Figure 3.11, where the fastest possible payback time was shown to be only 6 months (or 0.5 years) in the case of the $EROI_{ide}$ calculation. Using method 2, the energy payback times were calculated to be much less than when using method 1. Using the second method the EPT was around 2 weeks for the $EROI_{stnd}$ and $EROI_{3,i}$ scenarios. This can be seen in Figure 3.12, where the lines cross an EROI of 1.

3.2 Fljótsdalsstöð hydro power plant

This section shows the results from Kárahnjúkar hydro power plant. It calculates the $\Sigma\beta$ results, $EROI_{3,i}$, $EROI_{stnd}$ as well as the $EROI_{ide}$. It further explains how transportation to Iceland was calculated. Subsequently, the energy payback time was calculated using the two methods described in Chapter 2.

3.2.1 Phases calculated for Fljótsdalsstöð hydro power plant

Since much of the data used for this study derives from an LCA study, which investigated Fljótsdalsstöð hydro power plant, it will calculate the same phases as was done in the LCA study. The same boundaries are to be used as were used when

Nesjavellir geothermal power plant was studied so both plants can be compared to each other and also provide a valuable contribution to the literature. The phases included are 1) Kárahnjúkar dam, 2) Desjarár dam and Sauðárdalur dam, 3) Hraunveita (drainage), 4) Station house, 5) Tunnels, 6) drainage ditch, 7) Service buildings, 8) workers housing, 9) Roads and bridges.

3.2.2 Assumptions

As was for Nesjavellir, various assumptions have to be made. This includes maintenance and renewable of equipment on site. The biggest difference in this case, is that the predictable lifetime of Fljótsdalsstöð hydro power plant is anticipated to be at least 100 years, opposed to the 40 years expected of Nesjavellir geothermal plant. The projected lifetime of electronics and engines at the plant is expected to be 60 years, and has after that time been renewed fully. This can be transferred to be 1.6% maintenance per year of the original energy used in the electrical appliances and converters. These assumptions are in fact different from the Nesjavellir geothermal plant, where maintenance was simply considered to be 2% of the original material usage per year, but should however give very clear results. Maintenance is also accounted for in the concrete of the plant, this amounts to 50% replacement over the first 100 years.

3.2.3 Ideal output ($\Sigma\beta$) from Fljótsdalsstöð hydro power plant

Different from Nesjavellir geothermal plant the energy at Fljótsdalsstöð hydro power plant comes from falling water. At this hydro power plant, water is retrieved from three lagoons, Hálslón, Ufsalón and Kelduárlón lagoons. Pipes transfer the water towards Fljótsdalsstöð over 72 km. While travelling that distance, the water falls around 200 meters. When the water finally reaches Fljótsdalsstöð, it falls almost vertically 400 meters on to the Francis turbines before being drained away. When calculating the $EROI_{ide}$. Equation 5 is used to calculate the power resulting in the falling water at Fljótsdalsstöð. The maximum flow to the station is 144 m^3 per second, or 144,000 litres, while the average flow is 110 m3 per second. The total drop given by Landsvirkjun is 599 meters. With the flow of 144,000 m^3/s the amount of energy consists of 847.6 MW. This calculation assumes that no friction is present in the pipes, the temperature does not change during the travel from the lagoon to the turbines and the water leaves the lagoon at no velocity. As with Nesjavellir geothermal plant, the $EROI_{ide}$ represents the upper EROI limit the given plant is bound to. This amounts to 7,425 GWh or 26,730,000 GJ per year.

3.2.4 Own usage

According to Landsvirkjun, the own usage of the plant can be approximated to be 0.5% of its electricity production (Jónsdóttir, 2012). This does however vary between years, but can be expected to be around the given number on average. This means that of the 4,800 GWh the plant produces annually, it consumes 24 GWh. This amounts to 86,400 GJ per year, or 8,640,000 GJ over the first 100 years of operation. This parameter would however change if the plant produced more or less energy, as is demonstrated with the $EROI_{ide}$ calculations.

3.2.5 Embodied energy at Fljótsdalsstöð hydro power plant

As with previous power plant, the embodied energy of Fljótsdalsstöð and the relevant parts shall be calculated, this chapter calculates this, using figures from the literature as a reference to the energy content of each material. Data sets were provided by relevant stakeholders on the quantities of materials.

Fljótsdalslína power line 3 and 4

Fljótsdalslína power lines 3 and 4 travel from Fljótsdalsstöð to Alcoa's aluminium plant in Reyðarfjörður. The total length of Fljótsdalslína power line 3 is approximately 49 km and Fljótsdalslína power line 4 is 53 km (Efla, 2010). 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 masts are steel constructed, whereas 83 of them are constructed to withstand avalanches. In total, there are 326 masts with the average distance of 315 meters. Landsnet provided information about the lines. The masts are of various size and shape. The total weight of normal masts is 2,750 tonnes, whereas the total weight of the avalanche masts is 3,230 tonnes (Efla, 2010). In total, the masts 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 211,094 GJ. In total 12,275 m^3 of concrete were used for the foundations supporting the masts (Efla, 2010). 2.07 GJ is embodied within every 1 m^3 of concrete, which amounts to 25,409 GJ. Reinforcement steel used in the foundations amounts to 1,187 tonnes, which in total has 41,901 GJ embodied energy. When added up, the total energy embodied within these two lines amounts to 278,404 GJ. Exported soil amounts to 76,647 m^3 and imported soil amounts to 58,762 m^3. Soil imported to create roads amounted to 598,237 m^3. The energy used in machinery for soil handling is however covered separately in another chapter.

Preparation stages

At the preparation stages, roads were constructed and general preparation work was done. However, not only soil was handled at the preparation stage. Steel was used for example for drainage at some stages and petroleum was used in the process. Very reliable data was acquired about the amounts of material used at these stages. The stages are listed in Table 3.14 with the given embodied energy of each stage. The total embodied energy in the preparation stages amount to 32,032 GJ.

Table 3.14 - Distribution of embodied energy in the preparation stages of Fljótsdalsstöð hydro power plant

Preparation Stage	**Energy (GJ)**
Kárahnjúkavegur road	13055
Fljótsdalsheiðarvegur road	6859
Múlavegur road	1364
Hólsufsarvegur road	19
Hálsvegur road	3490
Hraunavegur road	2521
Maint. Of Kárahn. & Hraunv. roads	141
Bridge Jökulsá í Dal	2253
Bridge Jökulsá í Fljótsdal	1085
Facilities Kárahnjúkar hydro power plant	756
Stationhouse	408
Erection of facilities	77
Total	**32,032**

Construction phase

At the construction phase, the embodied energy of all construction materials was calculated. The values were derived from the literature as before. Kárahnjúkar dam contributed to the largest amount of embodied energy, or 2,765,087 GJ. This is mostly due to the vast amount of concrete used at site. The relative distribution can be seen in Figure 3.14.

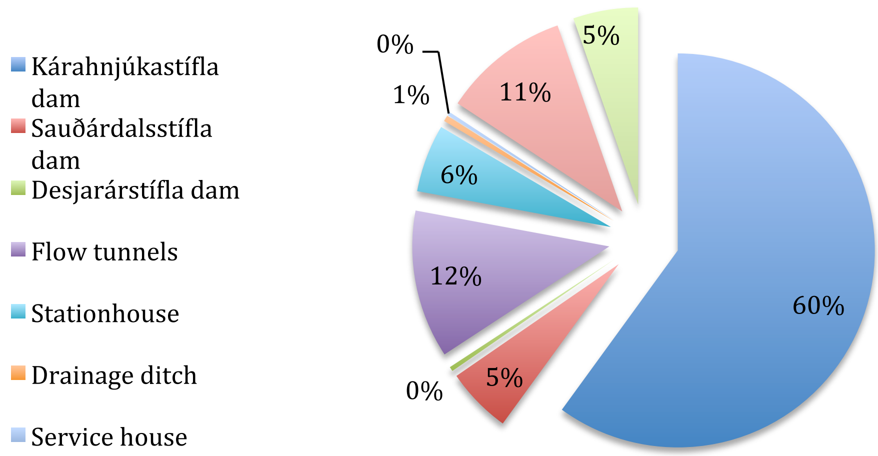

Figure 3.14 - Relative distribution of embodied energy of the construction materials associated with Fljótsdalsstöð hydro power plant

Table 3.15 lists the amount of energy embodied in the construction materials at the construction phase at Fljótsdalsstöð hydro power plant and relevant phases. It further shows the extravagant amount of energy associated with Hraunveita drainage ditch and the flow tunnels. Other phases like the service house only amount 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 3.15 - Amount of energy embodied in different phases associated to Fljótsdalsstöð hydro power plant

Stage	**Energy (GJ)**
Kárahnjúkar dam	2,765,087
Sauðárdalur dam	248,354
Desjarárdalur dam	16,922
Flow tunnels	559,836
Stationhouse	256,134
Drainage ditch	22,635
Service house	12,932
Hraunveita drainage	480,229
Engines and electrical	245,531
Total	**4,607,663**

Engine and electrical devises

This phase contains of 4 different stages. These are engines and electrical appliances, transformers, stationhouse cranes and cables. In total, the embodied energy amounted to 209,409 GJ. Most of which are associated to the production of engines and electrical appliances. Table 3.16 lists the amount of energy associated with each phase.

Table 3.16 - Amount of energy associated with each phase of electrical and engine production at Fljótsdalsstöð hydro power plant

Phase	Energy (GJ)
Engine and electrical appliance	96,721
Transformers	69,847
Stationhouse Cranes	1,720
Cables	41,119
Total	**209,409**

Sum of embodied Energy at Fljótsdalsstöð and relevant phases

When all factors have been calculated together, the total amount of embodied energy is approximately 24,945,446 GJ. The largest proportion of energy was used in the construction of the plant. Table 3.17 further shows the distribution of embodied energy between different stages of the plant and its relevant stages.

Table 3.17 - Distribution of embodied energy between different stages of the hydro power plant

Phase	Energy (GJ)
Preparation	32,032
Construction	4,607,663
Engines and electricals	209,409
Fljótsdalslína powerline 3 & 4	278,404
Total	**5,127,510**

3.2.6 Machinery usage in construction

As with the previous power plant studied, the energy usage in all soil handling will be accounted for. Same assumptions regarding the oil consumption of various machinery are outlined in the boundaries chapter are used in these calculations. This will further strengthen the ability for a comparative analysis.

Fljótsdalslína power lines 3&4

Fljótsdalslína 3&4 are handled as a single entity since the data acquired does not allow for further diagnosis. The amount of removed soil is 76,647 m^3, whereas imported soil to site is 58,762 m^3. Soil for road construction amounted to 598,237 m^3. Concrete for premade foundations amounted to 1,012 m^3, concrete for foundations made on location amounted to 940 m^3. The largest proportion of concrete went to avalanche foundations, or 10,323 m^3. In total, 745,921 m^3 of material was handled. For Kárahnjúkar dam, most soil was retrieved from the lagoon area, so in the case of Fljótsdalslína power lines 3&4 this will be estimated as well. The lagoon is approximately 70 km away from Fljótsdalsstöð hydro power plant, which is also approximately 50 km away from its final destination. It will therefore be estimated that on average the trucks will drive

100 km from the lagoon area to their destination. In total, the soil handling trucks used approximately 1,036,886 litres when driving with a full load. These trucks used approximately 586,916 litres driving empty. The total energy used by these trucks amounts to 62,354 GJ. The concrete trucks drove 1,636 trips, and used 116,228 litres of oil, which amounts to 4,463 GJ. The excavators used in total 3,056 hours transferring the soil, this excludes the concrete since it was most likely not handled with an excavator. The amount of oil used by excavators amounts to 79,478 litres, or 3,051 GJ. These results are further listed in Table 3.18.

Table 3.18 - Distribution of energy used in soil handling for Fljótsdalslína power lines 1 & 2

Truckload	1,623,803 litres
Excavators	79,478 litres
Concrete trucks	116,228 litres
Total oil	1,819,509 litres
Gigajoules	**65,410 GJ**

Roads at preparation stage

In the preparation stage of the construction of Kárahnjúkar dam, soil was removed at various stages. Most of it was transferred to the Lagoon area. Landsvirkjun provided the total amount of kilometres driven by the trucks so they did not need to be estimated. The trucks, while transferring the materials consumed approximately 544151 litres of oil. These are only for road construction in the preparation stage of the plant construction. The relative distribution of energy use by different road construction can be seen in Table 3.19.

Table 3.19 - Relative distribution between energy usages in soil handling in the preparation process of Kárahnjúkar dam

Soil handling	**Oil consumption**	**Energy (GJ)**
Kárahnjúkavegur road	84,992	3,263
Fljótsdalsheiðarvegur road	177,284	6,807
Múlavegur road	52,732	2,024
Hólsufarvegur road	44,454	1,707
Hálsvegur road	44,454	1,707
Hraunavegur road	132,088	50,72
Kára & Hraunav. Shoulder maint.	8,143	3,12
Total	**544,151**	**20,895**

In total, 20,895 GJ were used in the process of soil handling in the preparation of the hydro project.

Soil for dams

Several mines were used to get soil for the dam constructions. Most of them were however located in the lagoon area so the distance driven by the trucks was only minimal. After estimating the length from a map, the driving distance is only estimated to be 5 km from the lagoon area to the place of delivery.

Kárahnjúkar dam

In total, 8.5 million m^3 of soil was used in the construction of Kárahnjúkar dam; most of this material was retrieved from dams located in the lagoon area. This amounts to 226,666 trips for the trucks, using 600,666 litres of oil fully loaded, and 340,000 driving empty back. This amounts to 940,666 litres of oil, or 36,121 GJ. Excavator work for this stage amounts to 35,416 hours, or 920,833 litres of oil. This results in 35,360 GJ for the excavator. 71,481 GJ were used by machinery handling soil in the construction of Kárahnjúkar dam. The distribution of the energy use in soil handling at Kárahnjúkar dam can be seen in Table 3.20.

Table 3.20 - Distribution of energy consumption in soil handling for Kárahnjúkar dam

Machinery used	**Amount of oil**
Trucks	940,666 litres
Excavators	920,833 litres
Total oil	1,861,499 litres
Gigajoules	**71,481 GJ**

Sauðárdalur dam

In total, 1 million m^3 of soil was used in the construction of Sauðárdalur dam. This amounts to 22,666 trips for the trucks, using 70,666 litres of oil fully loaded, and 40,000 driving empty back. This amounts to 110,666 litres of oil, or 4,249 GJ. Excavator work for this stage amounts to 4,166 hours, or 108,333 litres of oil. This results in 4,160 GJ for the excavator. 8,409 GJ were used by machinery handling soil in the construction of Sauðárdalur dam. These results are further listed in Table 3.21.

Table 3.21 - Distribution of energy consumption in soil handling for Sauðárdalur dam

Machinery used	**Amount of oil**
Trucks	110,666 litres
Excavators	108,333 litres
Total oil	218,999 litres
Gigajoules	**8,409 GJ**

Desjarár dam

In total, 2.5 million m^3 of soil was used in the construction of Desjarár dam; most of this material was retrieved from dams located in the lagoon area. This amounts to 66,667 trips for the trucks, using 176,666 litres of oil fully loaded, and 100,000 driving empty back. This amounts to 276,666 litres of oil, or 10,624 GJ. Excavator work for this stage amounts to 10,416 hours, or 270,833 litres of oil. This results in 10,400 GJ for the excavator. 21,024 GJ were used by machinery handling soil in the construction of Desjarár dam. These results are further listed in Table 3.22.

Table 3.22 - Distribution of energy consumption in soil handling for Desjarár dam

Machinery used	**Amount of oil**
Trucks	276,666 litres
Excavators	270,833 litres

Total oil	547,499 litres
Gigajoules	**21,024 GJ**

Sum of energy consumption in soil handling

It is evident that Fljótsdalslína 3 & 4, and all soil handling for the general Kárahnjúkar dam, amount to the biggest energy consumption in regards to soil handling. Road construction, Desjarárdalur dam and Sauðárdalur dam did not amount for such vast energy consumption as the other stages. Table 3.23 lists the relevant phases included in the calculations.

Table 3.23 - Distribution of energy consumption in soil handling at the preparation stages

Phase	**Energy (GJ)**
Fljótsdalsl. 3&4	65,410
Road constr.	20,895
Kárahnj. Dam	71,481
Sauðárdalur Dam	8,409
Desjarárdalur Dam	21,024
Total	**187,219**

The relative distribution can be seen in Figure 3.15. The total energy consumption at the soil handling stage amounts to 187,219 GJ.

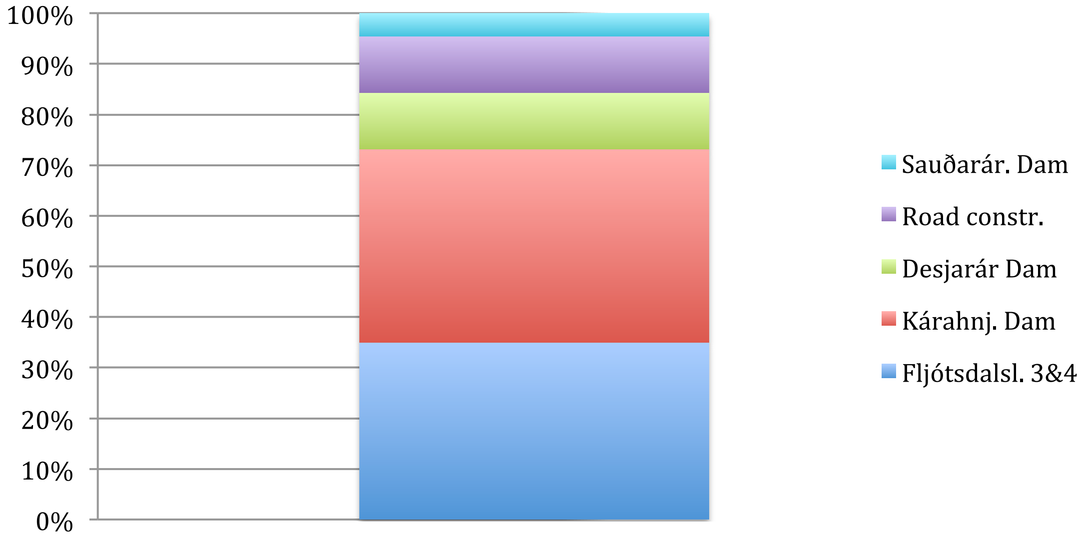

Figure 3.15 - Relative distribution of energy consumption in soil handling at Fljótsdalsstöð hydro power plant and associated constructions.

3.2.7 Maintenance

In the LCA on Fljótsdalsstöð hydro power plant, the concrete constructions are expected to be renewed by 50% after the first 100 years, therefore 0.5 % of the energy consumed in its production will be accounted for annually in maintenance (Efla, 2011). For concrete maintenance, 7,473 GJ are consumed annually. It is also mentioned in the LCA report about Fljótsdalsstöð that after 60 years, the engine and electrical appliances at the stationhouse have been replaced. This study will therefore 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 3,350 GJ per year, or 331,650 GJ for the first 100 years of the plants life since it is assumed that no maintenance will occur the first year of operation.

3.2.8 Transportation

Because of the good set of data acquired for Fljótsdalsstöð hydro power plant, the total oil consumption of transporting all relevant materials to Iceland had already been calculated. This totalled in 218,223 litres of oil for the three most relevant stages of the plant. These stages include preparation (13,230 litres), general construction (161,626 litres) and engines and electronics (43,367 litres). In total, transportation of materials to Iceland amounted to 8,379 GJ. This number is however included in the embodied energy within relevant phases and are not excluded from the calculations of the total energy.

3.2.9 Total input energy at Fljótsdalsstöð hydro power plant

When all phases have been calculated, the sum of them can be seen. The phases are: energy used in soil handling, Embodied energy, own usage and maintenance. For clarity these phases will be separated further. Soil handling at Fljótsdalslína power lines 3 & 4 (65,410 GJ), preparation roadwork (20,895 GJ), soil removed in dam construction (100,914 GJ), embodied energy for the preparation work (32,032 GJ), construction (4,607,665 GJ), engines and electrical (209,409) and Fljótsdalslína power lines 3 & 4 (278,404). Own usage is included (86,400 GJ per year) as well as electrical maintenance (3,350 GJ per year) and concrete maintenance (7,473 GJ). The distribution between different phases over the first 100-year lifetime of the plant can further be seen in Figure 3.16.

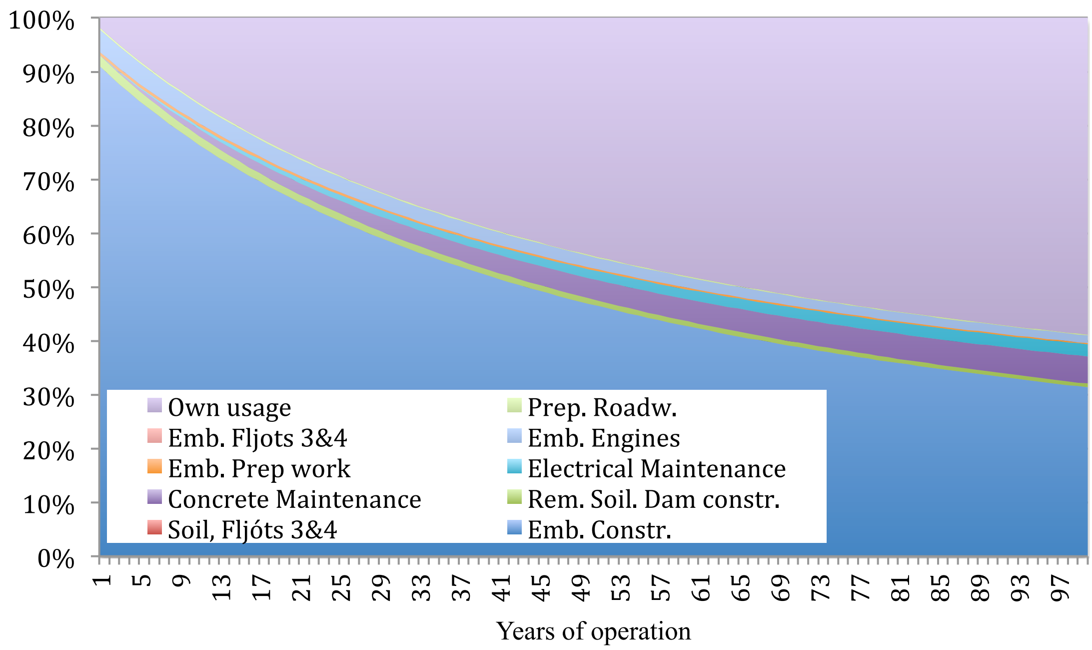

Figure 3.16 - Relative distribution between energy usages at Fljótsdalsstöð hydro plant for the first 100 years. X-axis shows years.

Figure 3.16 shows that the embodied energy within the construction materials is not the largest energy-consuming factor of the plant. Just like Nesjavellir geothermal power plant, energy consumption at site is the biggest in the form of own usage, even though it is only 0.5% per year of its production. The total energy consumed within the $EROI_{3,i}$ boundaries is 15,026,296 GJ over the first 100 years of operation.

3.2.10 EROI of Fljótsdalsstöð hydro power plant

In this section, the $EROI_{stnd}$, $EROI_{3,i}$, and $EROI_{ide}$ are calculated, the energy payback time and then conduct a sensitivity analysis to see the effects if certain factors are modified.

3.2.11 $EROI_{stnd}$

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 Fljótsdalsstöð hydro power plant, this will include the inputs mentioned in previous chapters, but will exclude the mechanisms for delivering the energy, namely Fljótsdalslína power lines 3 and 4. This calculation will also exclude all soil handling operations associated with the power lines.

The input is calculated to be 5,057,315 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 3.24.

Table 3.24 - Different scenarios for the $EROI_{stnd}$ calculations at Fljótsdalsstöð hydro power plant.

Year	**Output (GJ)**	**Input (GJ)**	**$EROI_{stnd}$**
1	16,560,000	5,057,315	3.27
20	331,200,000	6,904,569	47.9
40	662,400,000	8,849,047	74.8
60	993,600,000	10,793,525	92
80	1,324,800,000	12,738,003	104
100	1,656,000,000	14,682,481	112.7

This scenario shows that the $EROI_{stnd}$ is around 112 over the first 100 years of the plants lifetime of the plant. Figure 3.17 explains the development of the $EROI_{stnd}$.

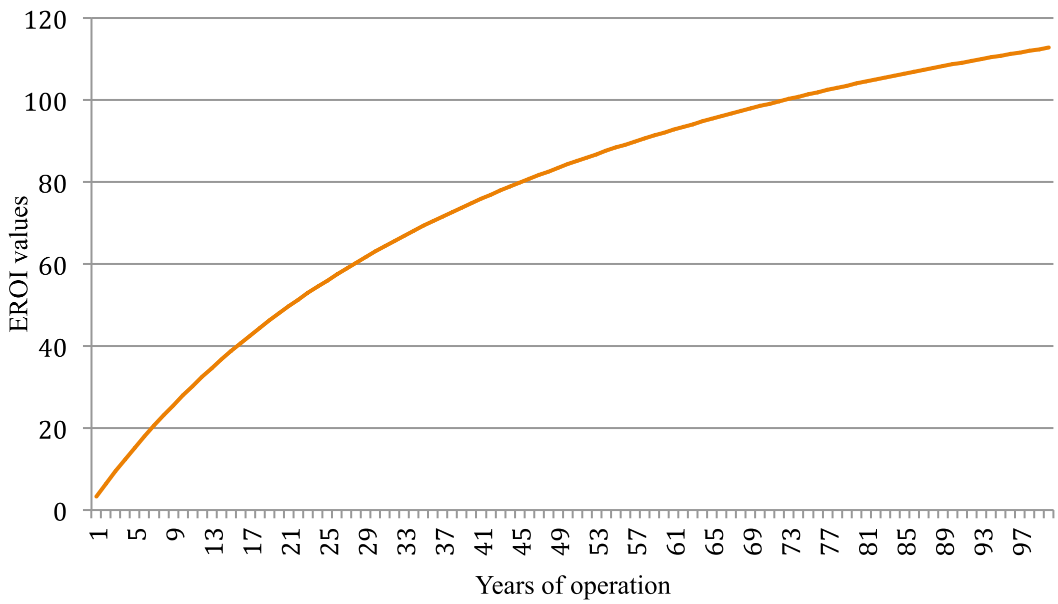

Figure 3.17 - Development of the $EROI_{stnd}$ at Fljótsdalsstöð hydro power plant over the first 100 years of the plants lifetime

3.2.12 $EROI_{3,i}$

As before, the $EROI_{3,i}$ includes the hardware to deliver the energy to the consumer, which in this case is an aluminium smelter. These calculations will therefore include the Nesjavallalína power line 3 & 4. Table 3.25 further shows the EROI development over the first 100 years of the plants lifetime.

Table 3.25 - Different scenarios for the $EROI_{3,i}$ calculations at Fljótsdalsstöð hydro power plant.

Year	Output (GJ)	Input (GJ)	EROI
1	16,560,000	5,401,130	3
20	331,200,000	7,248,383	45.6
40	662,400,000	9,192,861	72
60	993,600,000	11,137,339	89.2
80	1,324,800,000	13,081,817	101.2
100	1,656,000,000	15,026,296	110.3

It can be seen that over the first 100 years of the operational life of the plant, the $EROI_{3,i}$ is at 110.3 but is still rising. The lifetime of the plant is however not known, but it is assumed that it will at least operate for 100 years. Figure 3.18 shows the development of the $EROI_{3,i}$ for the hydro power plant.

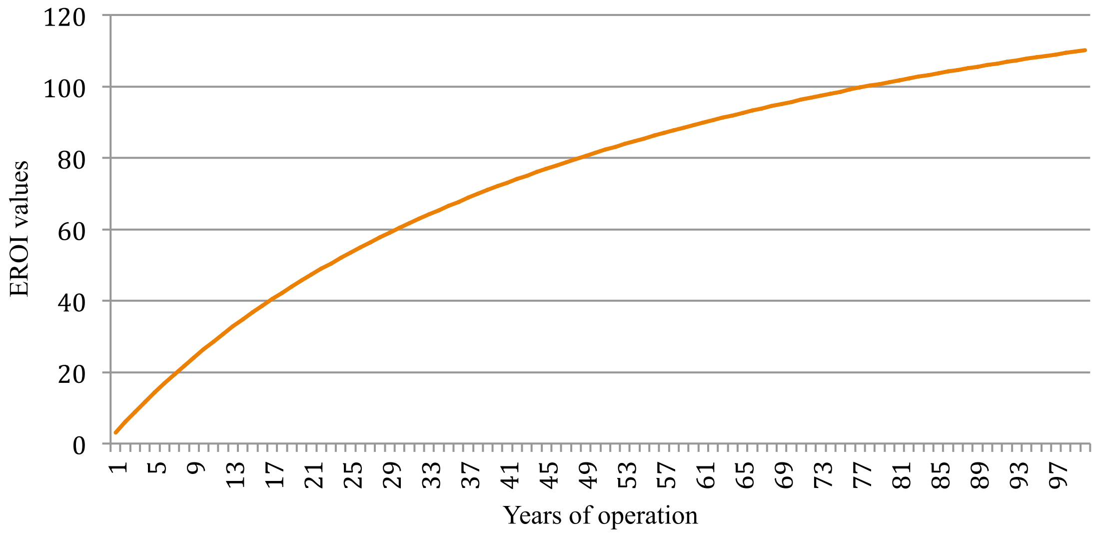

Figure 3.18 - Development of the $EROI_{3,i}$ over the first 100 years of the operational life of Fljótsdalsstöð hydro power plant. The x-axis shows years of operational time.

3.2.13 $EROI_{ide}$

With the knowledge of the total input required to construct, maintain and operate Fljótsdalsstöð hydro power plant and the associated constructions over its lifetime, it is possible to calculate the $EROI_{ide}$ as was described in equation 4. Different from Nesjavellir geothermal, the operational energy use at Fljótsdalsstöð hydro power plant is 0.5%, instead of a constant value. This means that since the input value in the $EROI_{ide}$ is greater, the own usage will increase as well. Table 3.26 shows the $EROI_{ide}$ for the same intervals as the EROI was calculated previously.

Table 3.26 - Different scenario calculations for the $EROI_{ide}$ at Fljótsdalsstöð hydro power plant.

Year	**Output (GJ)**	**Input (GJ)**	**$EROI_{ide}$**
1	26,730,000	5,440,824	4.91
20	534,600,000	8,042,283	66.4
40	1,069,200,000	10,780,661	99.1
60	1,603,800,000	13,519,039	118.6
80	2,138,400,000	16,257,417	131.5
100	2,673,000,000	18,995,796	140.7

The numbers provided in Table 3.26 show the EROI of the power plant if it was 100% efficient, omitting all losses, e.g. due to friction. Table 3.26 illustrates that the $EROI_{ide}$ increases rapidly the first decade, but then slows off evenly. It is however still rising quite rapidly after the first 100 years of the plants operation. The $EROI_{ide}$ is estimated to be at 140.7 after 100 years. This EROI represents the upper limits of the plant capacity. Figure 3.19 depicts the development of the $EROI_{ide}$ of the hydro power plant.

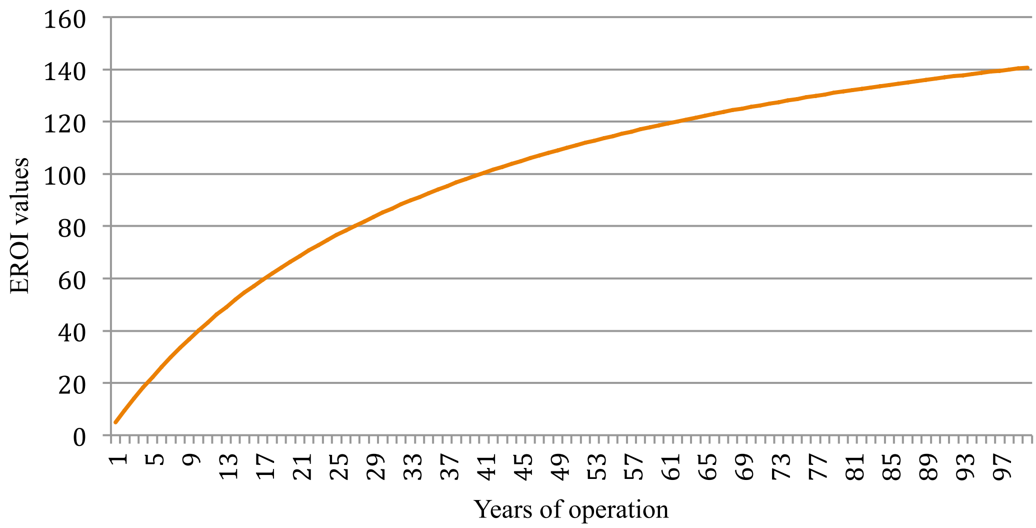

Figure 3.19 - EROI$_{ide}$ of Fljótsdalsstöð hydro power plant. The x-axis represents years and y-axis EROI values.

3.2.14 Energy payback time

As was done for the geothermal power plant, the energy payback time was calculated for the hydro power plant using the two methods. Method 1 shows that the EROI$_{ide}$ has the shortest payback time, or around 9 months. 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 3.20 depicts different energy payback times.

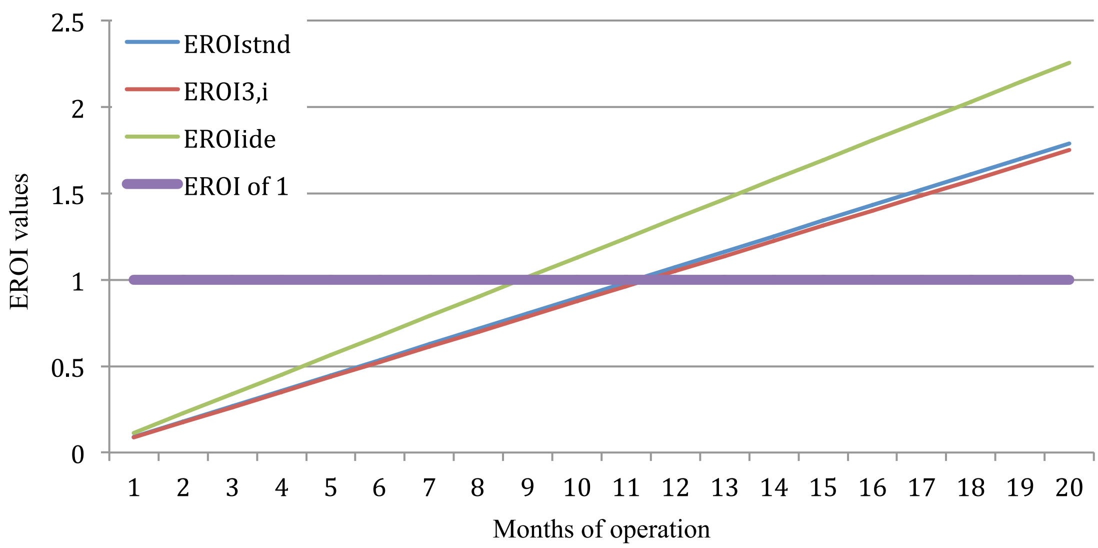

Figure 3.20 - Different energy payback times of the different EROI scenarios calculated using method 1 for Fljótsdalsstöð hydro power plant. The x-axis represents months and y-axis EROI values.

Using method 2, one can see that as was expected, the EROI$_{ide}$ was shown to have the fastest energy payback time, or approximately 11 weeks. The EROI$_{stnd}$ and EROI$_{3,i}$ were shown to have almost identical energy payback time, or around 17 – 18 weeks. Method 2 can further be seen in Figure 3.21.

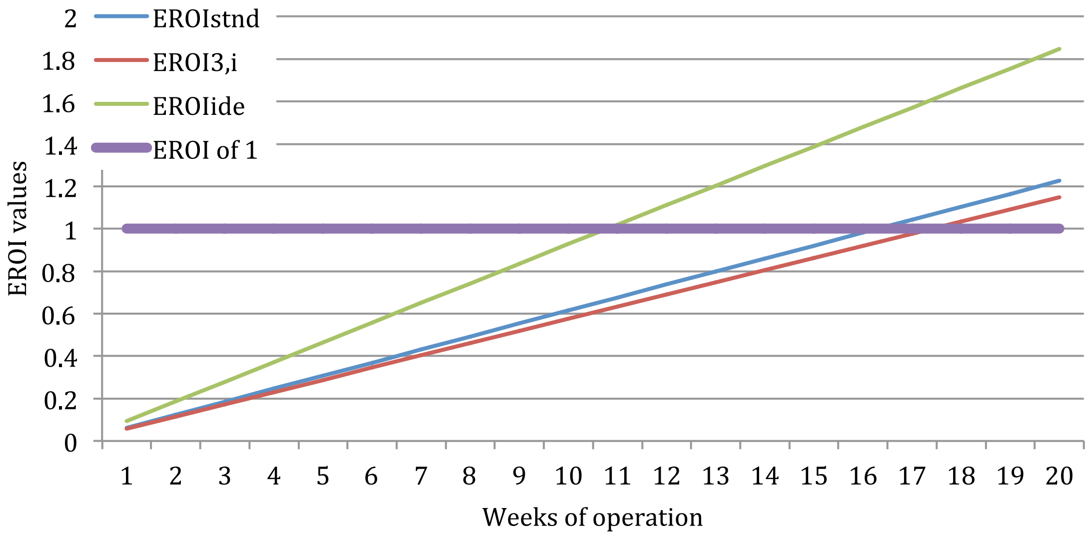

Figure 3.21 - Energy payback time using method 2 for Fljótsdalsstöð hydro power plant, where inputs are in logical order. X-axis shows weeks and y-axis EROI values.

3.2.15 Sensitivity analysis

To determine how much the variables affect the EROI of Fljótsdalsstöð hydro power plant, a sensitivity analysis was conducted. Since the own consumption of Fljótsdalsstöð hydro power plant is much less than of Nesjavallavirkjun geothermal plant, it is not realistic to assume an increase from 0.5% of own usage to 10%, this analysis will account for intervals of 0.5% increase up to a total of 5% of own usage, and maintenance increase from 1% per year, up to 5%. This is further illustrated in Table 3.27. It shows that even though the maintenance is increased by 5% of the original embodied energy within electrical appliances and concrete, the $EROI_{3,i}$ does not change significantly over the 100 year lifetime of the plant. It is however shown, that with a little increase in the operational usage of the plant, the EROI drops greatly. The scenario for the sensitivity analysis was the $EROI_{3,i}$.

Table 3.27 - Results from a sensitivity analysis of Fljótsdalsstöð hydro power plant. The x-axis in this table represents an proportional increase in maintenance, where the y-axis represents a proportion of own usage from the overall production.

	Increase in overall maintenance				
Own usage	1.0%	2%	3%	4%	5%
0.5%	*110.3*	110.1	109.7	109.2	108.5
1.0%	71.1	71.0	70.8	70.6	70.3
1.5%	52.5	52.4	52.3	52.2	52.0
2.0%	41.6	41.5	41.5	41.4	41.3
2.5%	34.4	34.4	34.3	34.3	34.2
3.0%	29.4	29.3	29.3	29.3	29.2
3.5%	25.6	25.6	25.6	25.5	25.5
4.0%	22.7	22.7	22.7	22.6	22.6
4.5%	20.4	20.4	20.4	20.3	20.3
5.0%	18.5	18.5	18.5	18.5	18.4

The EROI drops by 39 for the first 0.5% increase of own usage at the plant, where it reaches 1%. It is therefore vital that the information supplied by Landsvirkjun is accurate. If the plant consumed 5% of its own power, but the maintenance cost would stay the same, the EROI would drop to 18.4.

3.2.16 Summary of Fljótsdalsstöð hydro power plant

This section calculated three EROI scenarios and the energy payback time of the Fljótsdalsstöð power plant. It was found that the largest energy-consuming factor over 100 years was the plant itself, which however only consumed 0.5% of the energy it produced, followed by the embodied energy in construction materials and finally maintenance. The $EROI_{stnd}$ was found to be 112.7 over a 100-year lifetime of the plant. The $EROI_{3,i}$ was found to be slightly lower, or 110.3 since it included the energy needed to transfer the electricity to Alcoa's aluminium plant. The $EROI_{ide}$ was calculated to be 140.7 over the 100-year lifetime of the plant. Figure 3.22 further illustrates the differences between the EROI scenarios. Energy payback time was found to be approximately one year using method 1 (within $EROI_{stnd}$ and $EROI_{3,i}$ boundaries) and approximately 18 weeks using method two within the same boundaries.

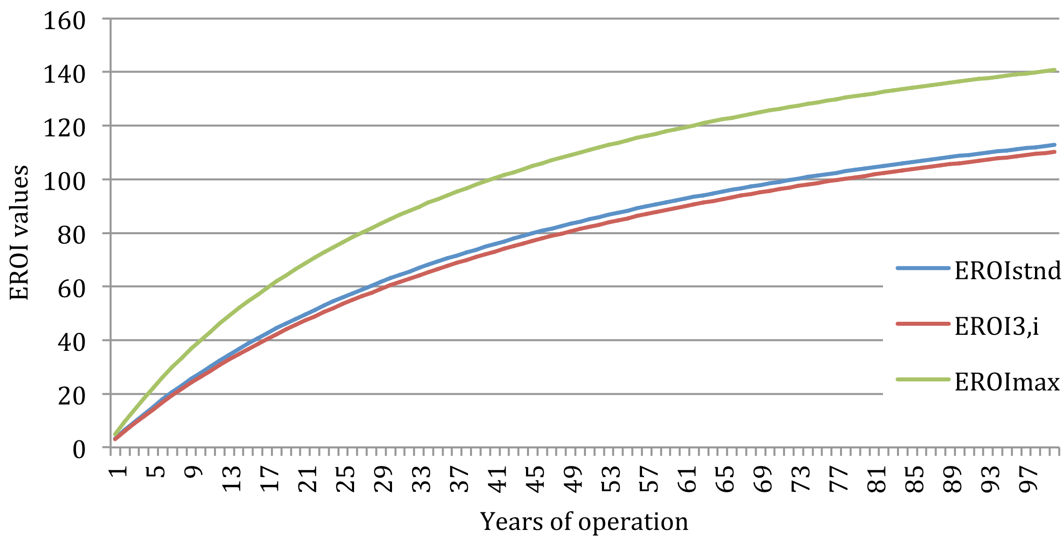

Figure 3.22 - Development of different EROI scenarios calculated. The x-axis indicates years and the y-axis EROI values. Fljótsdalsstöð hydro power plant

The energy payback time was calculated to be 0.93 years in the $EROI_{stnd}$ scenario and 0.95 in the $EROI_{3,i}$ scenario, which is approximately 1 year. The energy payback time was however only little more than half a year (0.59 years) for the $EROI_{ide}$ scenario. The sensitivity analysis however showed the importance of data accuracy, where it was shown that with only a little increase in own usage of the plant, the EROI drops significantly. The data accuracy was therefore checked and was confirmed to be correct.

3.3 Energy efficiency in embodied energy production

In producing various materials for the construction of the plants, energy was used in the production process. By expanding the boundaries slightly and account for the energy lost in the power production, one can see how much energy was used, excluding energy loss at the power plants producing power for the factories. This section will discuss the method used to calculate this scenario, as well as compare the results with previous calculations. The boundaries used in these calculations are shown with a blue line in Figure 2.3.

3.3.1 Method

Previous chapters included the embodied energy within various materials. However, the energy used in producing these parts are from various energy sources, such as coal and nuclear. Much energy was lost in the transformation to electricity when these parts were produced, and it should prove interesting to calculate the EROI when these losses are omitted. These calculations will therefore include the energy embodied in the resources used for the power production. For example: when coal is burned for electricity production, the efficiency is known to be at around 30-40% at the plant. Electricity from coal-fired power plants will therefore be divided by 0.4 to account for these losses. However, hydro power plants are known to be much more efficient or around 90%. Even though some of the machinery at the construction phase of the power plants uses oil directly without transforming it to electricity, the power has still to be transformed within the combustion engine with similar results as is observed in power plants (or worse). The efficiencies of different power plants and methods were gathered from the literature and are provided in Appendix 3. A problem however arises when the total energy used in the production of construction material is to be calculated. Their exact location of production is not known beforehand and the type of energy used in the production process is also not known. In this case it is assumed that all parts are produced within Europe and the average distribution between power sources is used in the calculations. The distribution is shown in Table 3.28 (Consumption of Energy, 2011). The blue line shown in Figure 2.3 shows the boundaries used in this method, where the amount of energy in the "EU energy source" is to be located since energy is lost in each stage after.

Table 3.28 - Relative distribution of energy sources in electricity production within Europe

Energy source	Relative of total energy production in EU
Hydro	9%
Nuclear	14%
Coal	15%
Natural gas	25%
Oil	37%

The total embodied energy is therefore divided between the energy sources shown in Table 3.28 and the output energy divided by its relevant efficiency factor shown in Appendix 3.

3.3.2 Results from system expansion

This section will show the results when boundaries have been expanded like mentioned, the EROI$_{stnd}$ scenario will be used in the calculations.

Nesjavellir geothermal power plant

At the Nesjavellir geothermal power plant, after dividing the embodied energy between different energy sources and subsequently calculating the energy used in the production of the energy used for producing the construction materials, including maintenance, the total energy went from 941,622 GJ to 2,263,153 GJ. Total consumption of own energy at the plant went from 15,137,280 to 16,819,200 GJ over the plants lifetime. The total output from the plant went from 529,804,800 GJ to 588,672,000 GJ after correction. Nesjavellir geothermal power plant has an EROI$_{stnd}$ of 30.8 when these factors are included.

Fljótsdalsstöð hydro power plant

After expanding the boundaries at Fljótsdalsstöð hydro power plant, the energy consumption goes from 6,782,398 GJ up to 16,301,240 GJ. Own consumption went from 8,640,000 GJ to 9,600,000. The total output over the first 100 years of the lifetime of the plant went from 1,656,000,000 GJ to 1,840,000,000 resulting in a recalculated EROI$_{stnd}$ of 71.

3.3.3 comparison

After including these parameters, it proves useful to compare the results with the original EROI$_{stnd}$ results. Figure 3.23 depicts the comparison between normal and the EROI$_{stnd}$ before losses due to inefficiency in power generation at the early stages of production.

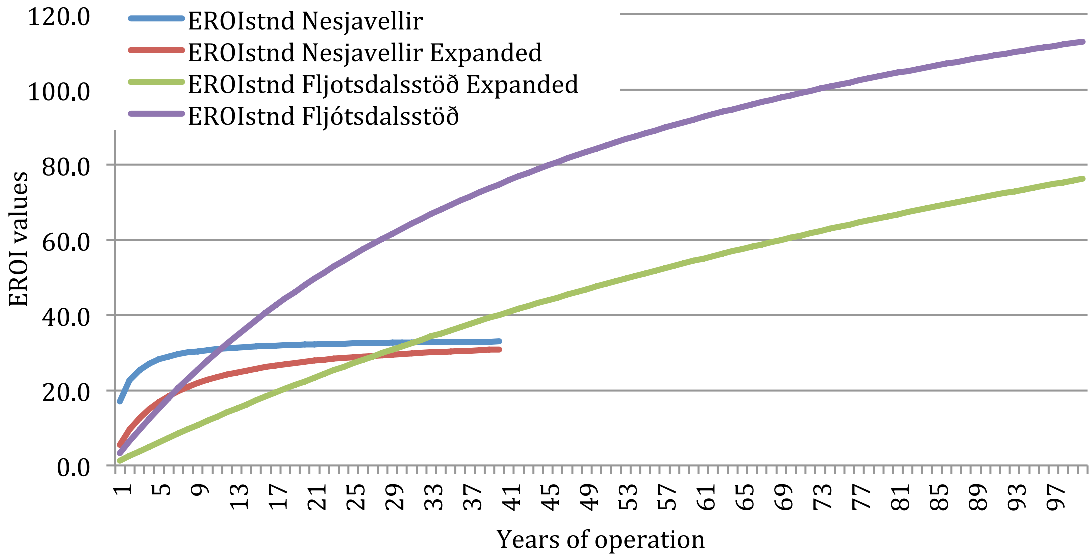

Figure 3.23 - Results from the calculations when inefficiency in power production is emitted. Y-axis shows EROI values, and X-axis shows years. Nesjavellir geothermal power plant and Fljótsdalsstöð hydro power plant

One can see that when boundaries are expanded slightly, the EROI$_{stnd}$ at Nesjavellir geothermal plant is relatively close to the previous results. The reason for this is that even though the plant is producing more energy, it is consuming a large quantity of its own production, which accounts for the biggest factor in its EROI. However, at Fljótsdalsstöð hydro power plant the $EROI_{stnd}$ drops substantially. The reason for this is the large amount of fossil fuels used in the production of all construction materials. Lower EROI is what was expected when these factors were included, as was mentioned previously, the larger the boundaries are, the lower the EROI becomes.

3.3.4 Summary of energy loss correction

This section calculated, using slightly different parameters than before, the $EROI_{stnd}$ of both plants studied. It was found that the EROI dropped slightly for Nesjavellir but immensely for Fljótsdalsstöð when energy lost due to inefficiency in electricity production was included.

3.4 General Comparison of Nesjavellir geothermal power plant and Fljótsdalsstöð hydro power plant

This chapter will compare the two power plants studied; the biggest parts will be compared, such as energy usage in soil handling, embodied energy in construction materials, own usage, energy in power deliverance and EROI comparisons. However, due to the large difference in size of the plants, a reference unit of 1 MWh will be used. This number is simply derived by dividing the given energy value with the total output of the plant over its lifetime, which in the case of Nesjavellir geothermal power plant is 40 years, while it is 100 years at Fljótsdalsstöð hydro power plant.

3.4.1 Embodied Energy

Since embodied energy was calculated for both the power plants, comparing them should be relatively straightforward; it is however not, since the size of the plants is quite different. As mentioned, a reference unit will therefore be used to compare them. When the energy used in construction of the plants is divided by the energy the given plant produces over its lifetime, great difference is detected. Figure 3.24 shows further that for every 1 MWh produced at Nesjavellir geothermal power plant, 0.42% of energy were consumed in the production of the construction materials, at Fljótsdalsstöð hydro power plant, the effectiveness was a little better, or 0.31% of every 1 MWh of output energy over the 100 years of the plants lifetime.

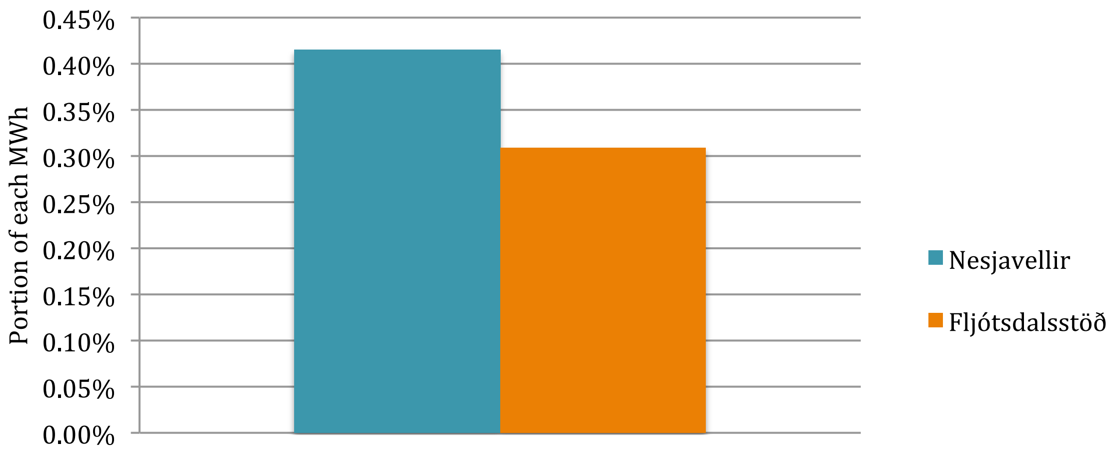

Figure 3.24 – Relative distribution of energy used in the production of construction materials at Nesjavellir geothermal power plant and Fljótsdalsstöð hydro power plant per 1 MWh of output energy.

This ratio would benefit Fljótsdalsstöð hydro power plant even greater if the plant operates for longer time than 100 years. As mentioned, this amounts to all energy used in the production of the construction materials divided by the energy produced by the plant over its lifetime. This shows that 34% more energy was used per 1 MWh in material production at Nesjavellir geothermal power plant.

3.4.2 Soil handling

At Fljótsdalsstöð hydro power plant, massive dams were built, this allows for an assumption that much more soil had be handled and removed than at Nesjavellir geothermal power plant. However, like before, Fljótsdalsstöð hydro power plant performs better when looking at the energy used in this phase, where it consumed 0.011% of every output MWh. At Nesjavellir geothermal power plant, 0.014% was consumed for every MWh output, which amounts to 27% more energy used by machinery at Nesjavellir for soil handling per MWh. The difference can further be seen in Figure 3.25.

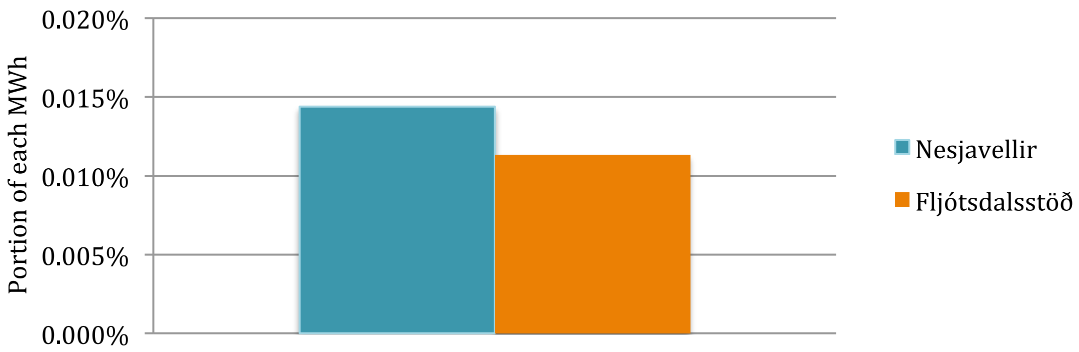

Figure 3.25 – Portion of energy used by Nesjavellir geothermal power plant and Fljótsdalsstöð hydro power plant in soil handling for every MWh of energy produced. Y-axis shows MWh.

3.4.3 Own usage

As has been shown, the own usage by the plants is quite large of the total consumption. At Nesjavellir, 12 MW are consumed for the 320 MW produced (120 MW of electricity and 300 MW of hot water). However, at Fljótsdalsstöð, the plant consumes 0.5% of the power produced.

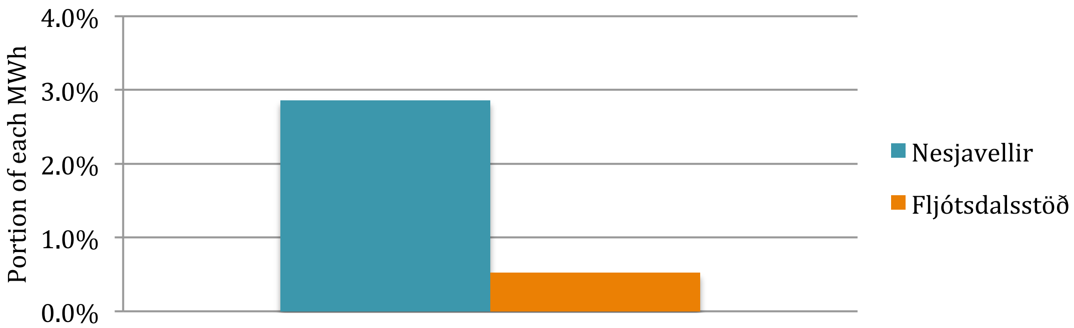

Figure 3.26 – Portion of energy consumed by the plants per 1 MWh of output energy at Nesjavellir geothermal power plant and Fljótsdalsstöð hydro power plant

At Nesjavellir, this amounts to 4,205,000 MWh over the 40-year lifetime of the plant. In total, 2.9% were used at Nesjavellir of every MWh produced. However, at Fljótsdalsstöð, this ratio was much lower, or 0.5%. This extravagant difference can be seen in Figure 3.26.

Relative to Fljótsdalsstöð hydro power plant, Nesjavellir geothermal power plant used almost 6 times more of its own energy for every 1 MWh of output energy. Additionally, Fljótsdalsstöð does not need to pump cold water towards its turbines for cooling, as is the case at Nesjavellir, which consumes a large proportion of the energy at site.

3.4.4 Maintenance

One of the big uncertainties around both plants is the maintenance. An approximation was given of a scenario of what might be likely. These numbers were derived from LCA reports analysing both plants. In the case of Nesjavellir geothermal power plant, 2% of original material usage was considered to be used for maintenance annually. At Fljótsdalsstöð hydro power plant 1% of the energy used in concrete production was accounted for concrete maintenance annually, and 1.6% of the energy used in the production of electrical appliances. To put the plants in perspective, energy used in maintenance per 1 MWh of output energy will be analysed. The difference is shown in Figure 6.4, where Fljótsdalsstöð uses 0.11% of every 1 MWh of output energy for maintenance, whereas Nesjavellir used 0.36 %. The difference between maintenance energy can be seen in Figure 3.27.

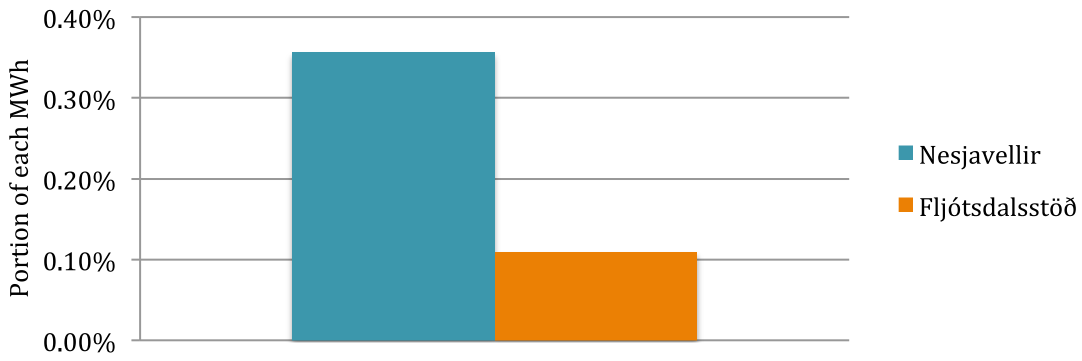

Figure 3.27 – Portion of energy used for maintenance per 1 MWh of output energy at Nesjavellir geothermal power plant and Fljótsdalsstöð hydro power plant

Over the lifetime of both plants, maintenance is a big portion of the energy use. However, time will only show the real amount of energy needed for maintenance, which hopefully will be thoroughly documented for further EROI analysis.

3.4.5 Transportation

As has been noted, much of the construction material had to be transported to Iceland for both plants. This study assumes that all materials are transported with ships overseas. The data for Fljótsdalsstöð hydro power plant was in this case more detailed, where oil usage had already been calculated. For Nesjavellir geothermal power plant the energy consumption of the ships had to be estimated, as well as the total amount of material needed to be shipped. However, results show, that the variability that this factor could bring on the final results is only minute. It was calculated that for Nesjavellir 220 tonnes of oil, amounting to 9,211 GJ were needed for transportation. For Fljótsdalsstöð, 218 tonnes were needed, amounting to 8,379 GJ for transportation. This shows that almost identical amount of energy was needed for both plants for transportation. Transportation was shown to have a minimal effect on the final EROI of the plants, this is only due to the small portion the energy associated with transport was of the total energy consumption of the plants.

3.4.6 EROI

When the EROIs are compared for the studied plants, the lifetime of the plants makes a great difference. It was shown that after the first 40 years of the operational lifetime of Fljótsdalsstöð hydro power plant, its $EROI_{3,i}$ was 69.84. The EROI had however not stopped increasing, like the EROI of Nesjavellir geothermal power plant, which was 32.4 over its 40 years of expected lifetime. $EROI_{3,i}$ at Fljótsdalsstöð was shown be 105 over the first 100 years of the plants operational lifetime. The EROI of Nesjavellir had however stopped increasing. After approximately 12 years, the $EROI_{3,i}$ of both plants was the same, around 30. The EROI of Fljótsdalsstöð would however continue to grown tremendously, whereas the EROI of Nesjavellir would by that time be levelling off. This can further be seen in Figure 7.5. The $EROI_{ide}$ of the plants would only collide after 27 years, with the EROI of approximately 79. Figure 3.28 shows the development of different EROIs for both plants, The reason for the EROIs of Nesjavellir to stop developing earlier than the ones of Fljótsdalsstöð is simply the expected lifetime of the plants. Also, one extra scenario was calculated for Nesjavellir, where hot water production was excluded. This calculation showed the tremendous effect the production of hot water has on the EROI of the plant, where this scenario had the lowest EROI of all scenarios calculated. Figure 3.28 also shows, that the difference between the $EROI_{3,i}$ and the $EROI_{ide}$ at Fljótsdalsstöð is much less than at Nesjavellir. This further underlines the difference in turbine utilization at the plants. The $EROI_{3,i}$ at Nesjavellir is proportionally further away from the ideal utilization of the energy source than Fljótsdalsstöð.

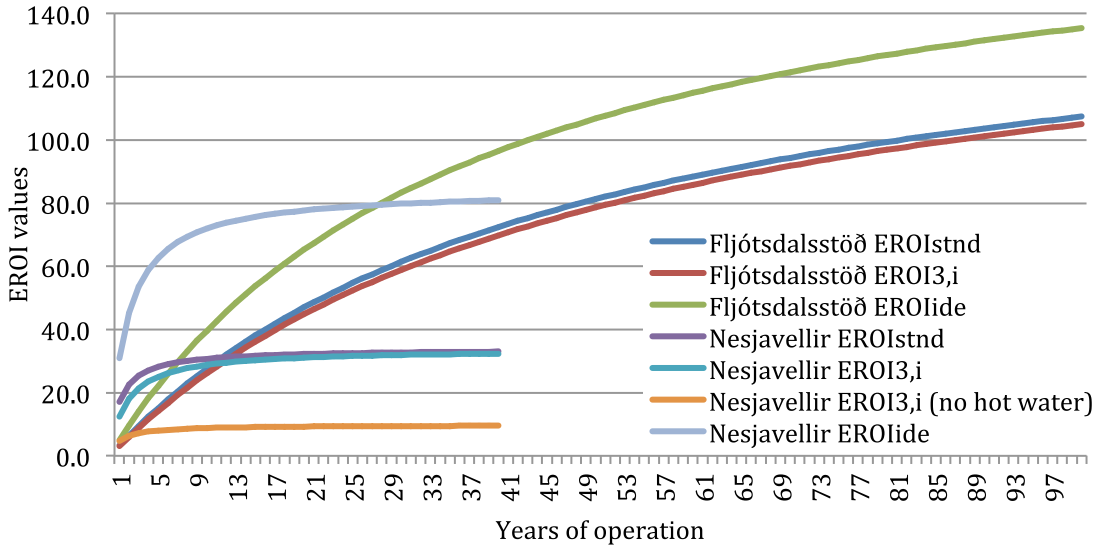

Figure 3.28 - Different EROIs calculated for Nesjavellir geothermal power plant and Fljótsdalsstöð hydro power plant. X-axis shows years, whereas y-axis shows EROI values.

This means that the possibilities for improvement at Nesjavellir geothermal power plant are much greater than at Fljótsdalsstöð hydro power plant. The potential energy at Fljótsdalsstöð hydro power plant is shown with the $EROI_{ide}$ to be much greater than at Nesjavellir geothermal power plant.

3.4.7 Energy Payback Time

When comparing the energy payback time (EPT), one can see that in both the $EROI_{stnd}$ and the $EROI_{3,i}$ scenarios, Fljótsdalsstöð hydro power plant performs better using method 1. However, in the $EROI_{ide}$ scenario, Nesjavellir geothermal power plant performs better. This might indicate, and further underlines that efficiency at Nesjavellir can be improved greatly. Efficiency can even improve to the extent that Nesjavellir geothermal power plant would pay its consumption energy quicker than Fljótsdalsstöð. The energy payback times using method 1 were however relatively close, with the exception of the $EROI_{3,i}$ scenario which excluded hot water production which resulted in an EPT more than 4 years. Other scenarios were shown to have the EPT around 1 year. Figure 3.29 shows the difference in energy payback time between different EROI scenarios. This means that after approximately 1 year, both plants would be producing surplus energy where all energy expenditures over the lifetime of the plant have been produced. However, when method 2 was calculated, which merely shows when the plants reach a break-even point in its production, not including future expenditures, Nesjavellir performed better in every scenario. This can easily be contributed to the relative difference in size of the plants. The results from method 2 can be viewed in Figure 3.30. It should however be noted that method 1 was measured in months, whereas method 2 in weeks.

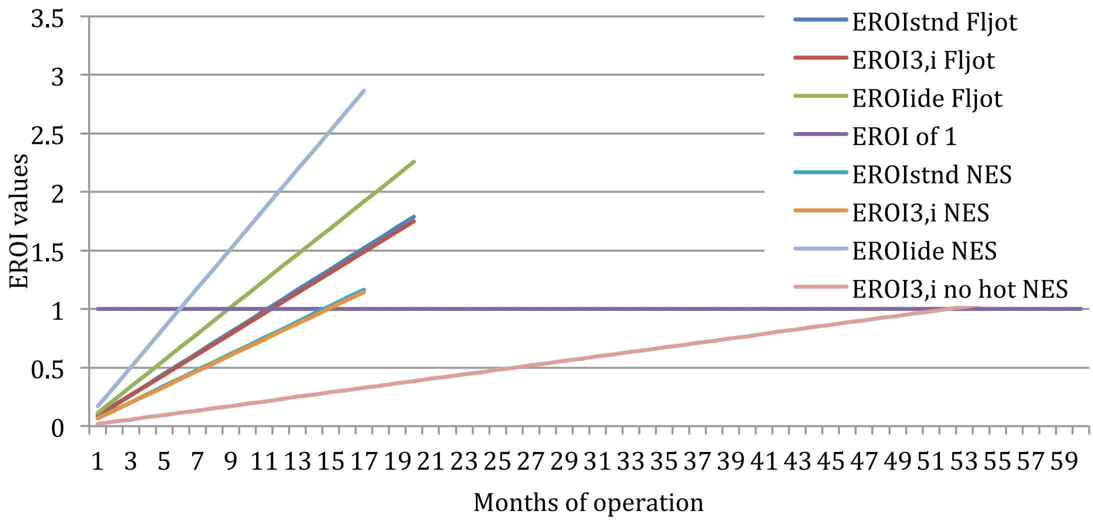

Figure 3.29 - Comparison between different energy payback times. X-axis shows months. Y-axis shows EROI values using method 1. NES: Nesjavellir geothermal power plant; Fljot: Fljótsdalsstöð hydro power plant

Interestingly when the energy consumption is put in correct time order, and the maintenance energy use and own consumption are not summed up, but rather listed in a sequence, Nesjavellir geothermal power plant outperforms Fljótsdalsstöð hydro power plant in all scenarios. The shortest EPT shown was the $EROI_{ide}$ at Nesjavellir, which is only around 1 week, the longest scenarios were the $EROI_{stnd}$ and $EROI_{3,i}$ at Fljótsdalsstöð which were approximately 17 weeks.

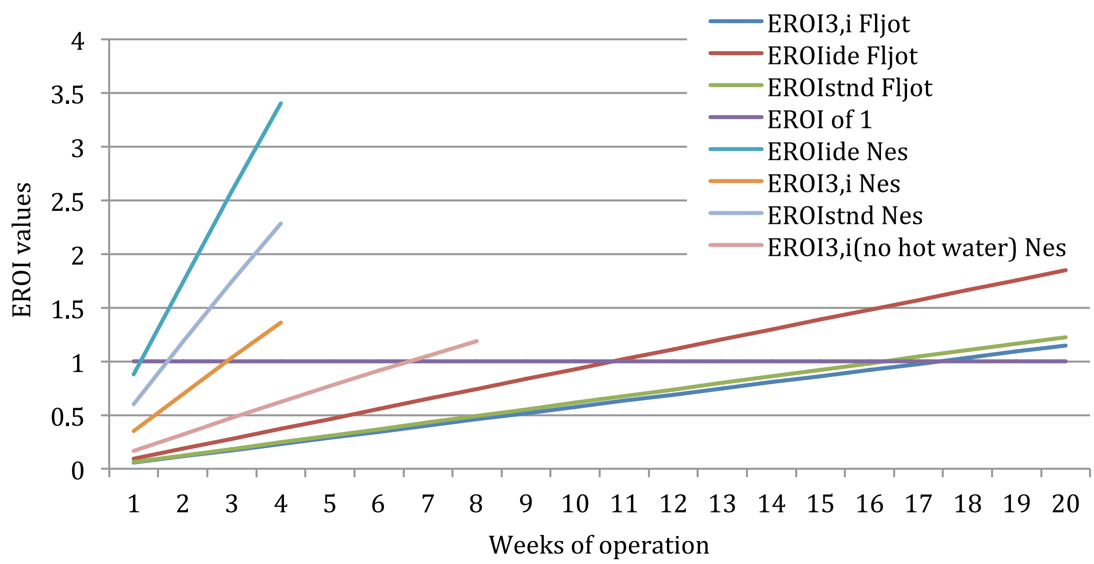

Figure 3.30 - Comparison between the two power plants looking at the energy payback time using method 2. X-axis shows weeks, y-axis shows EROI values. NES: Nesjavellir geothermal power plant ; Fljot: Fljótsdalsstöð hydro power plant

3.4.8 Chapter summary

This chapter showed the various EROI calculations from both power plants. It was shown that Fljótsdalsstöð hydro power plant resulted in a much better EROI, or on average almost threefold the EROI Nesjavellir geothermal power plant scored. It showed the effects loss of energy in energy production has on the EROI when the boundaries are extended slightly. With the boundaries expanded, the EROI of Fljótsdalsstöð dropped significantly, whereas the EROI at Nesjavellir geothermal power plant was relatively close to original results. This chapter compared various aspects of the production phase, such as maintenance and soil handling, where Fljótsdalsstöð hydro power plant outperformed Nesjavellir geothermal power plant in every stage. Fljótsdalsstöð hydro power plant was however shown to have a longer energy payback time in the $EROI_{ide}$ scenario. The causes of this will be further discussed in Chapter 4.

4 Discussion

4.1 Major findings

After studying Nesjavellir geothermal power plant, and Fljótsdalsstöð hydro power plant, it was shown that the hydro plant was much more efficient in terms of energy use. The hydro plant outperformed the geothermal plant in every phase calculated except in some cases of EPT. The massive difference shows that the hydro power plant is outperforming the geothermal plant more than threefold. It was shown that the geothermal plant would even perform worse if it would not produce hot water where the EROI would drop down to approximately 9. An EROI for a hydropower generation of >100 is in junction with the literature and confirms the extravagant EROI of hydroelectric production. EROI for geothermal power generation has hardly been studied. If only looking at electricity production, where Nesjavellir had the EROI of approximately 9, and Gilliland's study (1975) the EROI of 10-12, and Herendeen and Plant the EROI of 4, the conclusion can be made that efficiency in electricity production from geothermal power has hardly improved for almost 40 years. These studies do however use different methodologies, which might skew the results and therefore make them incomparable to this one. Further studies, following the standard methodology used in this study should however allow for future comparison.

A new concept was introduced to the literature, $EROI_{ide}$, which shows the maximum EROI possible at a given site. Room for improvement was found to be greater at the geothermal plant, as was shown in the $EROI_{ide}$ calculations.

4.2 Problems and weaknesses

For a study of this sort, it is essential to acquire a relatively good set of data on construction materials from the plant studied. Rough estimations can be done, but these would not allow for as detailed results as desired. However, for recently built power plants, this information should be available digitally for investigation. As for the power plants studied in this thesis, both of them had been studied in a life cycle assessment (LCA) and therefore all data on the construction material was available, retrieving them was the only hindrance. The EROI of Fljótsdalsstöð was shown to be highly interlinked with the own consumption of the plant, results might therefore change drastically if a slight difference is made in the own consumption. This problem was however addressed and Landsvirkjun was contacted to verify the stability of the own power consumption. Numbers (in the case of Fljótsdalsstöð, 0.5%) are therefore considered to be accurate and give a realistic view of the situation.

This study did not look at many of the factors that could easily be associated with the plants studied, these are for example environmental effects of the power plants, which differ between types of plants. Social matters, such as workers safety in the construction of the plants, wages and benefits associated with the location of the plants. General economic matters were also never considered, where the price of the energy delivered might differ. An example of this is the different price of electricity and hot water. All economic matters relating to markets were deliberately avoided. Criticism regarding the effects different boundaries can have on the final results, and the dependency on monetary data were successfully avoided in this study. A proposed standard was followed throughout the study, and no monetary data was used. Instead, real data was acquired directly from stakeholders, which allowed for a very precise analysis, except for the case of shipping at Nesjavellir. Shipping was however was shown to be almost irrelevant, even though the energy used in shipping doubled, it would not have reached 1% of the total energy consumption.

4.3 Lifetime expectations

At the geothermal plant, the expected lifetime of the plant was estimated to be around 40 years. This however does not need to be the case. If the resource is still present, delivering the same amount of energy and maintenance has been adequately done, the lifetime could be expected to be longer. However, when the calculations were conducted on the $EROI_{stnd}$ scenario, and the lifetime extended to 100 years, the EROI did not exceed 33.4. This demonstrates that the EROI is fully developed and shows relatively close to the final results after 40 years as was calculated in earlier scenarios. In the Nesjavellir LCA report, it was estimated that after 2002, one production hole would be drilled every four years and one re-injection hole every ten years. This was not included in this study, but after investigation, the EROI would not change noticeably if these factors were included. In the LCA report studying Nesjavellir, the lifetime was shown to have significant impact on the final results. It was however shown that extended lifetime did not have much impact on the EROI's.

4.4 $EROI_{ide}$

The above equations and boundaries can be useful when comparing energy resources. The problem however is, that the subject is looked at solely from the perspective of society, the government, or the human race as a whole. The question that always seems to be posed is "what is the best energy source for society" which is a valid question nonetheless. That question is however usually not of interest to the actual energy producers. A sense of practicality seems to be missing in the whole discussion of the viability of energy sources. The following questions seem to be missing:

1) For whom is the resource viable?
2) What is the possible EROI from that resource?

For question 1, if the answer is that the source is viable for society, but because of some other factors (some may relate to question 2) it is simply not practical for monetary profits, the project is obviously not viable. A high EROI resource might be developed, where high-grade petroleum is used in the process, which in the end will deliver cheap electricity. This will benefit society greatly but is not viable for the private sector. This might however be something that governments might want to engage in.

A special interest should however be given to question 2 since it can show the producer of a given energy what the possible EROI of that source could be if, for example, technology advances and the process becomes more efficient. If a resource delivers an EROI of 6, but has the potential of delivering an EROI of 20, the producer might want to develop the resource and focus (or support) on the development of the production technology. This is missing from the literature all together it seems. If producers are provided with the knowledge of the possible EROI before engaging in construction of a power plant, they might perhaps be more likely to engage in the improvement of the production technology, which will mean economic profit for the given firm. At the same time, if they possess the knowledge that immediately after construction of the plant, the EROI will be at its maximum and will only decline with time, the attitude might thus be different altogether towards the construction. The plant might still provide economic profit for its lifetime even though the EROI will decline (an example of this is the oil industry). But even though the EROI declines with time for non-renewable resources, the declining EROI can be slowed down or improved with superior technologies. Figure 4.1 shows how the area for improvement can be visualised.

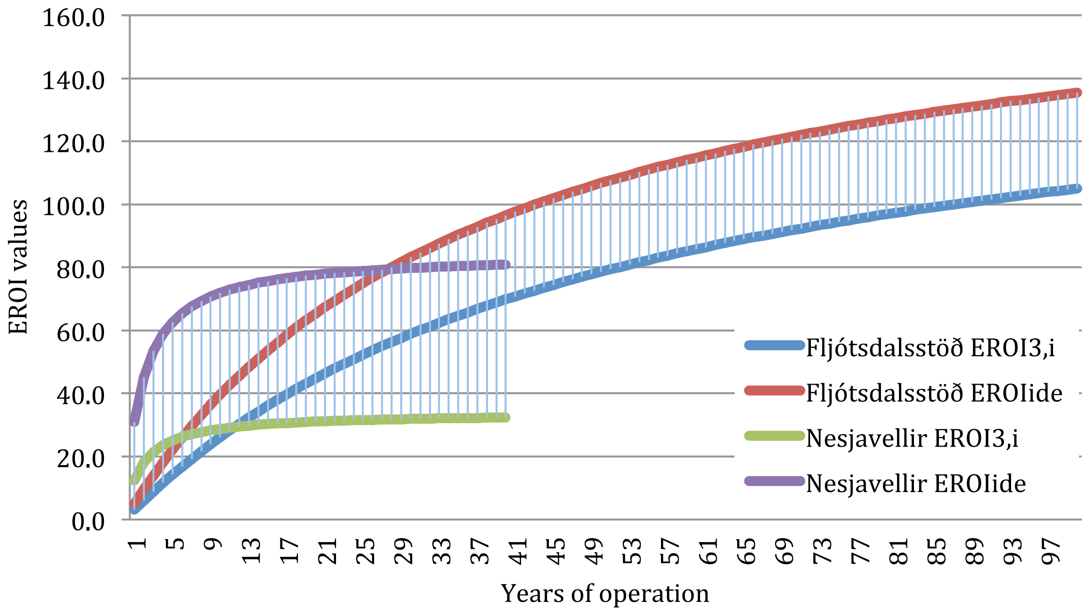

Figure 4.1 - Room for improvement at Nesjavellir geothermal power plant and Fljótsdalsstöð hydro power plant. X-axis shows years, Y-axis shows EROI values.

For example: a producer of geothermal energy has two sites to choose from, who both, say, deliver an EROI of 5. The only difference is that site 1 is cheaper than site 2. In business as usual, the producer will look at available energy in the area, economic cost of the plants etc. but normally would not have any knowledge about the $EROI_{ide}$. He would most likely purchase the cheaper site; it would cost less but still provide the same amount of energy. If the given producer would however be given the knowledge that site 2 had the potential of a much higher EROI, but technology will only harvest a given amount of energy (since engines always lose energy in form of heat etc.) it will provide the producer with a choice: be on the safe side and buy the cheap site, or take a risk and buy the more expensive site, wait and hope for technological advancements or even pursuit them himself for greater profits. However, theoretically the $EROI_{ide}$ for Nesjavellir might not even be as high as depicted in figure 4.1, further elaboration on that can be seen in appendix 8 where the exergy is rather calculated than the total enthalpy from the system.

4.5 Usefulness

An insight into the development of the availability of non-renewable resources such as oil can be seen with a series of EROI studies done throughout the years. Since oil has been thoroughly investigated throughout the years in terms of EROI, a decline in EROI can be seen. Therefore some assumptions can be made with regards to that particular resource, with regards to the effort it takes to retrieve the resource, and the development of technology. If the EROI of a renewable resource is shown to increase with time, either better resources are being utilized, or technology is getting more efficient with time. Up-to-date knowledge on the status of EROI's of different energy sources can give policy and decision makers a tool to base their decisions on. However, as has been noted, EROI should not be the only consideration when such decisions are made, due to its limitations. It does however relate to all major parameters of sustainability (economic, social and environmental) and can provide an insight to the efficiency of various energy sources. It has even been claimed that, "Energy Return on Investment is a powerful metric for weighing which energy systems are worth pursuing" (Kreith, 2012). A single number score, like the EROI provides, should however not be taken as the whole truth since there are, like mentioned, other factors to be included.

4.6 Comparison to other EROIs

The EROI of 33 when hot water is included at Nesjavellir proves to be relatively low compared to energy sources such as coal and hydro (with the EROI of approximately 80 and >100 respectively) (Cleveland. 2005, Gagnon et al. 2002). Nesjavellir however scores a better EROI than oil which has a declining EROI from approximately 100 in the 30's to approximately 11 in the mid 2000) (Cleveland. 2005, Cleveland. 1992, Guilford et al. 2011), and Nuclear of around 10 (Manfred. 2008, Kreith. 2012). If however hot water would not be produced at Nesjavellir, the EROI would be so low that it would score even less than oil and nuclear. This might be an indicator that geothermal power plants who do not produce other forms of energy (such as hot water for heating) have a relatively low EROI compared to most other energy sources. Stating that energy generation from oil power plants is preferable than geothermal because of the relatively low EROI should be avoided. Factors such as long term EROI development of the resource, environmental, social and economical are excluded from EROI's. It should therefore be stressed that EROI does not include many factors that are to be included in such decision-making. The EROI's studied at Fljótsdalsstöð hydro plant was found to be in conjunction with the literature, or greater than 100.

4.7 Future research

As was shown for both Nesjavellir geothermal plant and Kárahnjúkar hydro plant, maintenance played a large role in the overall consumption of energy. By improving the maintenance methods, the energy consumption might therefore be reduced greatly. In maintenance and turbine utilization is the greatest possibility for improvement since these factors consume the largest amount of energy. Maintenance methods should therefore studied and the effectiveness of different maintenance methods can therefore be shared between power plants to improve the overall EROI. As was shown with oil, a series of EROI studies can provide an insight into the viability of the resource. Series can also provide some insight into the future development of the EROI of a given source. A series of geothermal EROI's is non-existent today. Studying the EROI of other geothermal plants can also shed a light on the strengths some power plants have over others which can subsequently be shared. Further studies on the EROI of hydroelectric generation are also needed since previous studies show very different results from one another. The methodology presented by Murphy et al. (2011) should be used so these studies can be compared.

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Appendixes

Appendix 1

Table A.1 - Energy embodied in the major materials used in the construction of the power plants. The information is retrieved from the literature and various trusted websites.

Material	Embodied energy	Source
Aluminium	105.8 (GJ/t)	U.S. Energy Requirements for Aluminum Production: Historical Perspective, Theoretical Limits and Current Practices. (2007). U.S. Department of Energy.
Oil (general)	38.4 (GJ/t)	Envestra. (n.d.). Natural Gas. Retrieved 07.2, 2012, from http://www.natural-gas.com.au/about/references.htm
Steel	35.3 (GJ/t)	Hammond, G. P., & Jones, C. I. (2008). Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers - Energy, 161(2), 87-98.
Stainless steel	62 (GJ/t)	T.E. Norgate, S. Jahanshahi, & Rankin, W. J. (2004). Alternative Routes To Stainless Steel - A life Cycle Approach. Paper presented at the Tenth International Ferroalloys Congress, Cape Town, South Africa.
Steel for concrete	59 (GJ/t)	Embodied Energy Coefficients - Alphabetical. (n.d.). Retrieved 06.02.2012, from Victoria University of Wellington:
Steel (Recycled)	10.1 (GJ/t)	Embodied Energy Coefficients - Alphabetical. (n.d.). Retrieved 06.02.2012, from Victoria University of Wellington:
Cement	3.9 (GJ/t)	Cement Technology Roadmap 2009: Carbon emissions reductions up to 2050. (2009). International Energy Agency.
Concrete	2.07 (GJ/m3) 0.8 (MJ/Kg)	Leslie Struble, & Godfrey, J. (n.d.). How sustainable is concrete? Paper presented at the International Workshop on Sustainable Development and Concrete Technology.
Plexiglas	97.34 (GJ/m3)	Embodied Energy Coefficients - Alphabetical. (n.d.). Retrieved 06.02.2012, from Victoria University of Wellington:
Fiberglass	970 (GJ/m3)	Embodied Energy Coefficients - Alphabetical. (n.d.). Retrieved 06.02.2012, from Victoria University of Wellington:
Wool for insulation	14.6 (GJ/t)	Embodied Energy Coefficients - Alphabetical. (n.d.). Retrieved 06.02.2012, from Victoria University of Wellington:

Iron extrusion	251200 (GJ/m3)	Embodied Energy Coefficients - Alphabetical. (n.d.). Retrieved 06.02.2012, from Victoria University of Wellington:
Polyethylene (HDPE)	103	Embodied Energy Coefficients - Alphabetical. (n.d.). Retrieved 06.02.2012, from Victoria University of Wellington:
PVC	93.62 (GJ/t)	Embodied Energy Coefficients - Alphabetical. (n.d.). Retrieved 06.02.2012, from Victoria University of Wellington:
Copper (Cu)	70.6 (GJ/t)	Baird, G., Alcorn, A., & Haslam, P. (1997). The Energy Embodied in Building Materials - Updated New Zealand Coefficients and Their Significance. Transactions of the Institution of Professional Engineers New Zealand: Civil Engineering Section, 24(1), 46-54.
Iron Sheet	22 (GJ/t)	T.E. Norgate, S. Jahanshahi, & Rankin, W. J. (2004). Alternative Routes To Stainless Steel - A life Cycle Approach. Paper presented at the Tenth International Ferroalloys Congress, Cape Town, South Africa.

Appendix 2

Table A.2 - Results from the sensitivity analysis at Nesjavellir geothermal plant

	Maintenance									
Operation	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
90%	36.3	35.7	35.0	34.4	33.8	33.2	32.7	32.2	31.6	31.1
91%	35.9	35.3	34.7	34.1	33.5	32.9	32.4	31.9	31.4	30.9
92%	35.6	35.0	34.3	33.7	33.2	32.6	32.1	31.6	31.1	30.6
93%	35.2	34.6	34.0	33.4	32.9	32.3	31.8	31.3	30.8	30.3
94%	34.9	34.3	33.7	33.1	32.6	32.0	31.5	31.0	30.5	30.1
95%	34.5	33.9	33.4	32.8	32.3	31.7	31.2	30.7	30.3	29.8
96%	34.2	33.6	33.0	32.5	32.0	31.5	31.0	30.5	30.0	29.6
97%	33.9	33.3	32.7	32.2	31.7	31.2	30.7	30.2	29.8	29.3
98%	33.5	33.0	32.4	31.9	31.4	30.9	30.4	30.0	29.5	29.1
99%	33.2	32.7	32.1	31.6	31.1	30.6	30.2	29.7	29.3	28.8
100%	32.9	**32.4**	31.8	31.3	30.8	30.4	29.9	29.4	29.0	28.6
101%	32.6	32.1	31.6	31.1	30.6	30.1	29.6	29.2	28.8	28.4
102%	32.3	31.8	31.3	30.8	30.3	29.8	29.4	29.0	28.5	28.1
103%	32.0	31.5	31.0	30.5	30.0	29.6	29.2	28.7	28.3	27.9
104%	31.7	31.2	30.7	30.2	29.8	29.3	28.9	28.5	28.1	27.7
105%	31.4	30.9	30.5	30.0	29.5	29.1	28.7	28.3	27.9	27.5
106%	31.2	30.7	30.2	29.7	29.3	28.9	28.4	28.0	27.6	27.3
107%	30.9	30.4	29.9	29.5	29.0	28.6	28.2	27.8	27.4	27.0
108%	30.6	30.1	29.7	29.2	28.8	28.4	28.0	27.6	27.2	26.8
109%	30.3	29.9	29.4	29.0	28.6	28.2	27.8	27.4	27.0	26.6
110%	30.1	29.6	29.2	28.8	28.3	27.9	27.5	27.2	26.8	26.4

Appendix 3

Table A.3 - Efficiencies at various types of power plants

Power source	Efficiency in power generation	Reference
Hydro (Francis)	90%	Tester, J. W. (2005). *Sustainable energy: choosing among options*: MIT Press.
Crude oil	33%	Electric Generation Efficiency: Working Document of the NPC Global Oil & Gas Study. (2007).
Coal	44%	Electric Generation Efficiency: Working Document of the NPC Global Oil & Gas Study. (2007).
Nuclear	37%	Nuclear Reactors, Nuclear Power Plant, Nuclear Reactor Technology. Retrieved 12.06, 2012, from http://www.world-nuclear.org/info/inf32.html
Geothermal	12-18%	Malyshenko, S. P., & Schastlivtsev, A. I. (2010). Thermodynamic Eficiency of Geothermal Plants with Hydrogen Steam Superheating. Paper presented at the WHEC, May 16.-21. 2010, Essen Schriften des Forschungszentrums Jülich / Energy & Environment,.
Natural gas	54%	Electric Generation Efficiency: Working Document of the NPC Global Oil & Gas Study. (2007).

Appendix 4

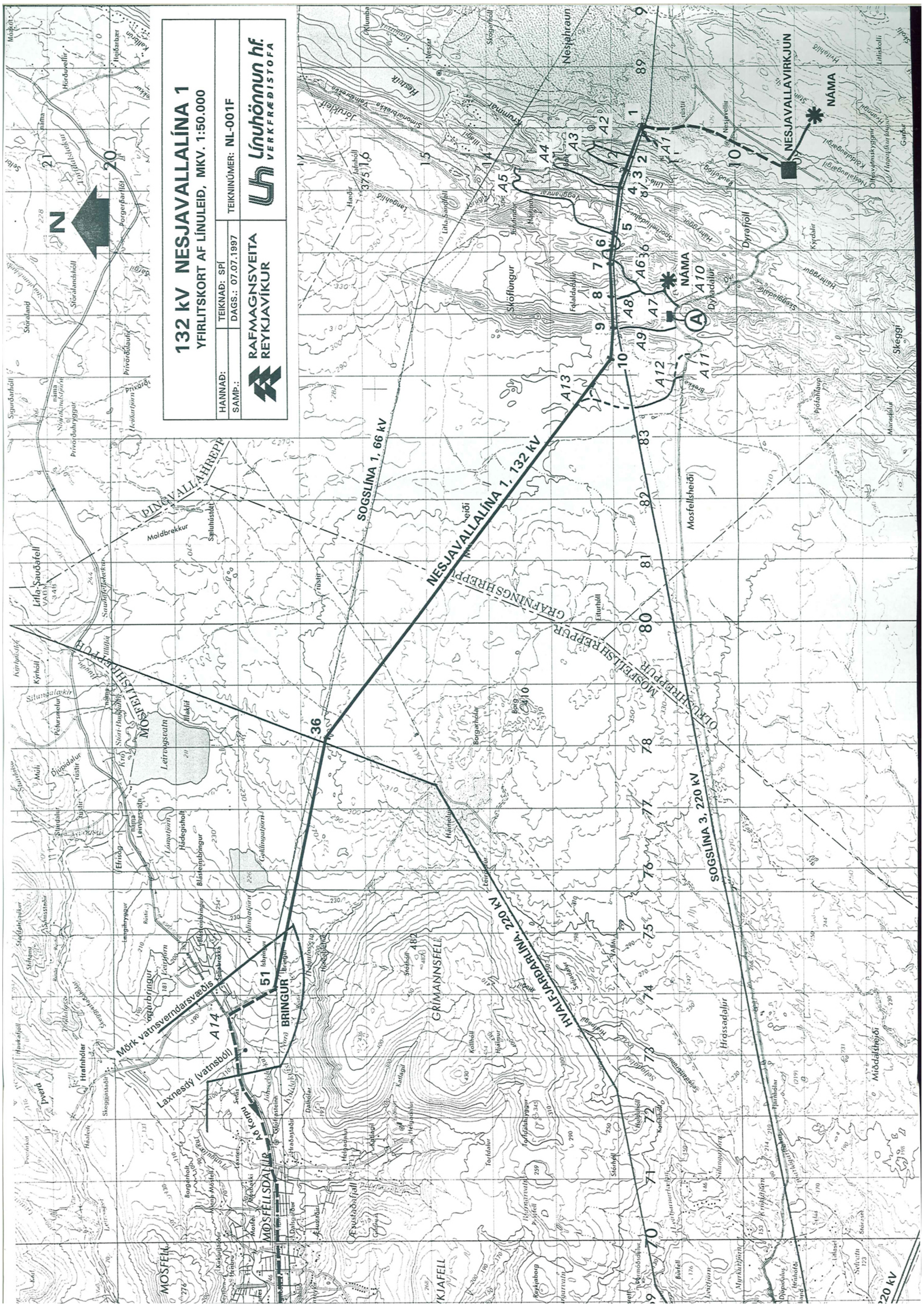

Figure A.1 - A map of Nesjavallalína power line 1 (Línuhönnun, 2002)

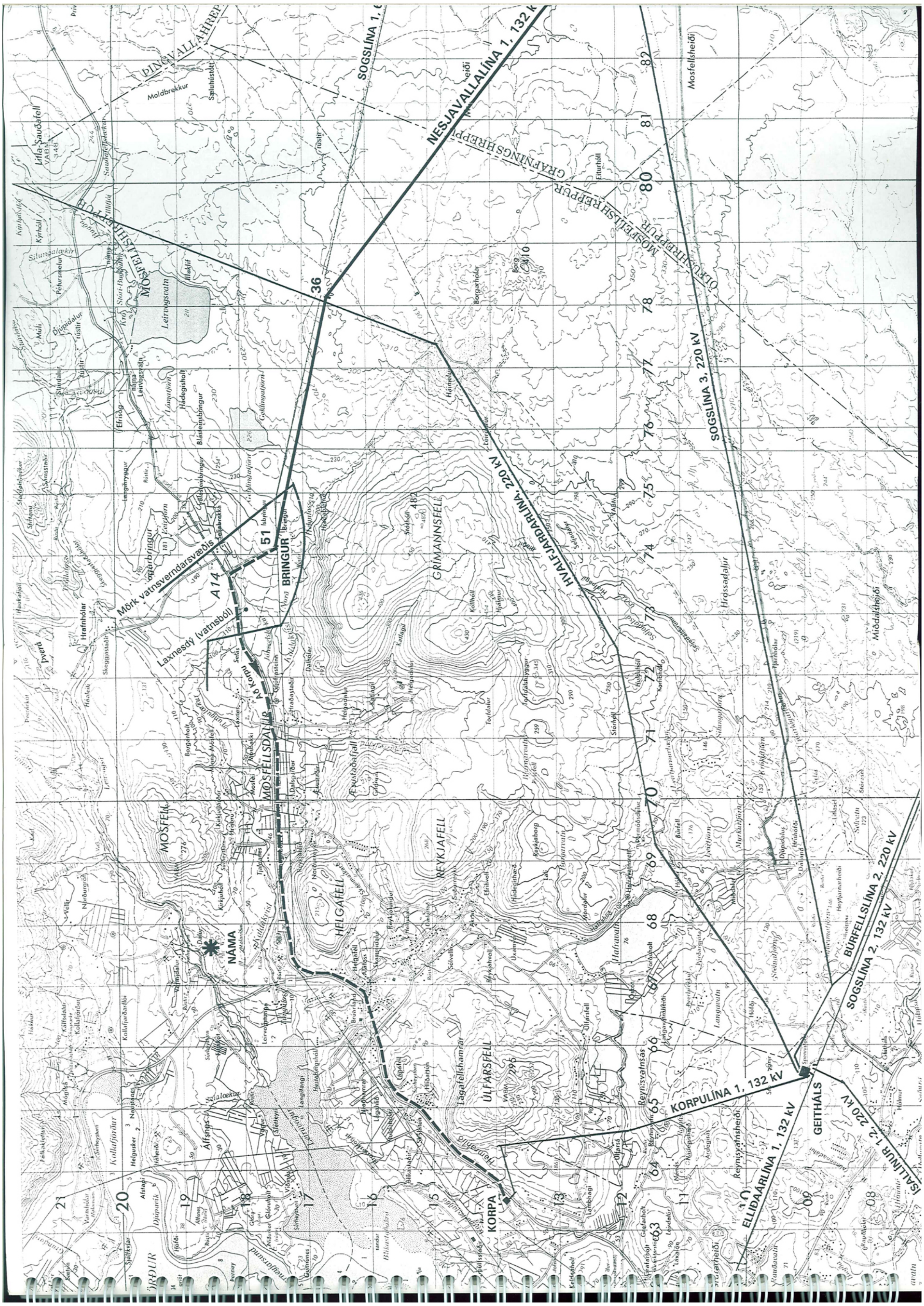

Figure A.2 - The second part of Nesjavallalína 1power line (Línuhönnun, 2002)

Appendix 5

Table A.4 - Steam table used for the ideal output calculations at Nesjavellir (ASU, n.d.)

1012 CHAPTER 12. SUPPLEMENTAL MATERIALS

SATURATED STEAM - TEMPERATURE TABLE (Continued)

T °C	P bar	Spec. vol. m^3=kg Sat. liq. v_f X1000	Spec. vol. m^3=kg Sat. vap. v_g	Int. Ener. kJ/kg Sat. liq. u_f	Int. Ener. kJ/kg Sat. vap. u_g	Enthalpy kJ/kg Sat. liq. h_f	Enthalpy kJ/kg Sat. vap. h_g	Entropy kJ=(kg°K) Sat. liq. s_f	Entropy kJ=(kg°K) Sat. vap. s_g
85	0.5783	1.033	2.828	355.8	2488	355.9	2652	1.134	7.544
90	0.7013	1.036	2.361	376.8	2494	376.9	2660	1.193	7.479
95	0.8455	1.039	1.982	397.9	2501	398.0	2668	1.250	7.416
100	1.013	1.044	1.673	418.9	2507	419.0	2676	1.307	7.355
110	1.433	1.052	1.21	461.1	2518	461.3	2691	1.418	7.239
120	1.985	1.060	0.892	503.5	2529	503.7	2706	1.528	7.130
130	2.701	1.069	0.669	546.0	2540	546.3	2720	1.634	7.027
140	3.613	1.080	0.509	588.7	2550	589.1	2734	1.739	6.930
150	4.758	1.091	0.393	631.7	2559	632.2	2746	1.842	6.838
160	6.178	1.102	0.307	674.9	2568	675.5	2758	1.943	6.750
170	7.916	1.114	0.243	718.3	2576	719.2	2769	2.042	6.666
180	10.02	1.127	0.194	762.1	2584	763.2	2778	2.140	6.586
190	12.54	1.141	0.157	806.2	2589	807.6	2786	2.236	6.508
200	15.54	1.156	0.127	850.6	2596	852.4	2793	2.331	6.432
210	19.06	1.172	0.104	895.5	2600	897.8	2798	2.425	6.358
220	23.18	1.190	0.086	940.8	2603	943.6	2802	2.518	6.286
230	27.95	1.209	0.072	986.7	2603	990.1	2804	2.610	6.215
240	33.44	1.229	0.06	1033	2603	1037.3	2804	2.702	6.144
250	39.73	1.251	0.05	1080	2603	1085.3	2802	2.793	6.073
260	46.88	1.275	0.042	1128	2600	1134.4	2797	2.884	6.002
270	54.98	1.302	0.036	1177	2592	1184.5	2790	2.975	5.930
280	64.11	1.332	0.03	1227	2587	1236.0	2780	3.067	5.857
290	74.36	1.365	0.026	1279	2573	1289.0	2766	3.159	5.782
300	85.81	1.403	0.022	1332	2560	1344.0	2749	3.253	5.704
320	112.7	1.499	0.015	1445	2531	1461.5	2700	3.448	5.536
340	145.9	1.638	0.011	1570	2462	1594.1	2622	3.659	5.336
360	186.5	1.893	0.007	1725	2351	1760.5	2481	3.915	5.053
374.14	220.9	3.155	0.003155	2030	2030	2099.3	2099	4.430	4.430

Table A.5 - steam table continued (ASU, n.d.)

SATURATED STEAM - PRESSURE TABLE

		Spec. vol. m^3=kg		Int. Ener. kJ/kg		Enthalpy kJ/kg		Entropy kJ=(kg^{o}K)	
P bar	T ^{o}C	Sat. liq. v_f X1000	Sat. vap. v_g	Sat. liq. u_f	Sat. vap. u_g	Sat. liq. h_f	Sat. vap. h_g	Sat. liq. s_f	Sat. vap. s_g
0.04	28.96	1.004	34.80	121.4	2415	121.4	2554	0.423	8.475
0.06	36.15	1.006	23.75	151.5	2425	151.5	2567	0.521	8.331
0.08	41.5	1.008	18.11	173.8	2432	173.8	2577	0.593	8.229
0.1	45.8	1.010	14.68	191.8	2438	191.8	2585	0.649	8.150
0.2	60.07	1.017	7.649	251.4	2457	251.4	2610	0.832	7.908
0.3	69.11	1.023	5.229	289.2	2468	289.2	2625	0.944	7.769
0.4	75.87	1.026	3.994	317.5	2477	317.6	2637	1.026	7.670
0.5	81.33	1.030	3.240	340.4	2484	340.5	2646	1.091	7.594
0.6	85.94	1.033	2.732	359.8	2490	359.9	2653	1.145	7.532
0.7	89.95	1.036	2.365	376.6	2494	376.7	2660	1.192	7.480
0.8	93.5	1.039	2.087	391.6	2499	391.7	2666	1.233	7.435
0.9	96.71	1.041	1.870	405.1	2503	405.1	2671	1.270	7.395
1	99.62	1.043	1.694	417.3	2506	417.4	2675	1.303	7.359
1.5	111.4	1.053	1.159	466.9	2520	467.1	2694	1.434	7.223
2	120.2	1.061	0.886	504.5	2530	504.7	2707	1.530	7.127
3	133.6	1.073	0.606	561.1	2544	561.5	2725	1.672	6.992
4	143.6	1.084	0.463	604.3	2554	604.8	2739	1.777	6.896
5	151.9	1.093	0.375	639.7	2561	640.2	2749	1.861	6.821
6	158.9	1.101	0.316	669.9	2567	670.6	2757	1.931	6.760
7	165.0	1.108	0.273	696.4	2573	697.2	2764	1.992	6.708
8	170.4	1.115	0.240	720.2	2577	721.1	2769	2.046	6.663
9	175.4	1.121	0.215	741.8	2580	742.8	2774	2.095	6.623
10	179.9	1.127	0.194	761.7	2584	762.8	2778	2.139	6.586
20	212.4	1.177	0.100	906.4	2600	908.8	2800	2.447	6.341
30	233.9	1.217	0.067	1005	2604	1008	2804	2.646	6.187
40	250.4	1.252	0.050	1082	2602	1087	2801	2.796	6.070
50	264.0	1.286	0.039	1148	2597	1154	2794	2.920	5.973
60	275.6	1.319	0.032	1205	2590	1213	2784	3.027	5.889
70	285.9	1.352	0.027	1258	2580	1267	2772	3.121	5.813
80	295.1	1.384	0.024	1306	2570	1317	2758	3.207	5.743
90	303.4	1.418	0.021	1350	2558	1363	2742	3.286	5.677
100	311.1	1.453	0.018	1393	2545	1408	2725	3.360	5.614
110	318.2	1.489	0.016	1434	2530	1450	2706	3.429	5.553
120	324.8	1.527	0.014	1473	2513	1491	2685	3.496	5.492
130	331.0	1.567	0.013	1511	2496	1532	2662	3.561	5.432
140	336.8	1.611	0.012	1549	2477	1571	2638	3.623	5.372
150	342.3	1.658	0.010	1586	2456	1611	2611	3.685	5.310
160	347.4	1.711	0.009	1623	2432	1650	2581	3.746	5.246
170	352.4	1.770	0.008	1660	2405	1690	2547	3.808	5.178
180	357.0	1.839	0.008	1699	2375	1732	2510	3.871	5.105
190	361.5	1.924	0.007	1740	2338	1776	2465	3.938	5.024
200	365.8	2.036	0.006	1786	2295	1826	2411	4.013	4.931
220.9	374.1	3.155	0.003	2030	2029	2099	2099	4.430	4.430

Appendix 6

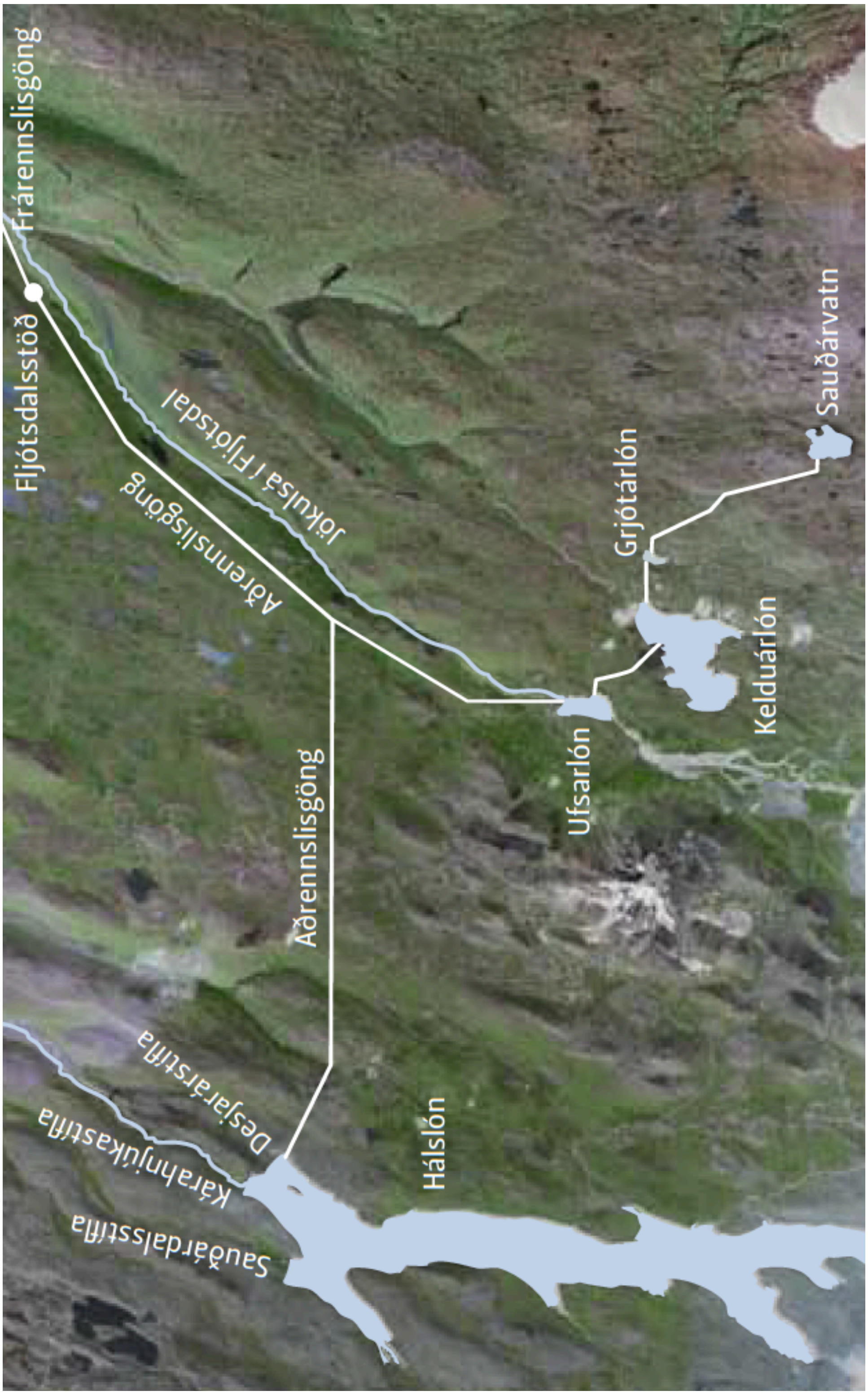

Figure A.3 - A map of Fljótsdalsstöð hydro power plant and relevant structures (Landsvirkjun, 2011)

Appendix 7

Figure A.4 shows the development of a theoretical system with regards to its energy payback time using method 2. When the dotted line crosses the solid line and reaches an EROI of 1, the energy payback time is reached.

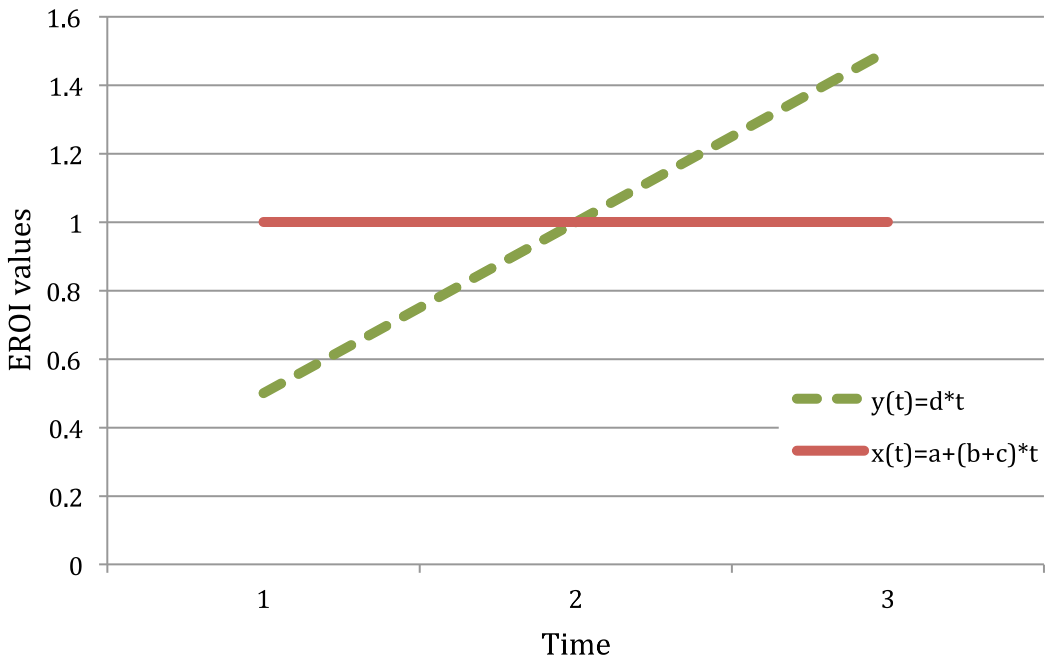

Figure A.4 shows when a theoretical energy producing system reaches its energy payback time

Appendix 8

The ideal output from Nesjavellir as described in chapter 3 can in one way be described as has been done, but that method might perhaps not shed the light on the amount of energy that is available for energy production. Even though the flow from the holes involves a certain amount of energy, some of it cannot be used. Calculating the maximum available energy might therefore be a better metric to show the ideal output, for exergy calculations the following equation was used:

$$e = h - h_0 - T_0(s - s_0) \tag{11}$$

Where h is the enthalpy (kJ/kg), s is the enthropy (kJ/kg), T is ambient temperature in Kelvin and 0 is sink conditions. In these calculations, it is estimated that the ambient temperature is 283.2 K (10°celcius). It is also estimated that the exergy is reached in electricity production and that hot water production is done in the same quantity as is currently done (300 MW). These results do merely indicate that when more accurate calculations are done on the ideal output from geothermal power plants, the actual levels are lower than if all energy is harvested, since it is simply not possible to harvest all the energy. Results show that the EROIide drops from approximately 80 down to 52 as can be seen in figure A.5.

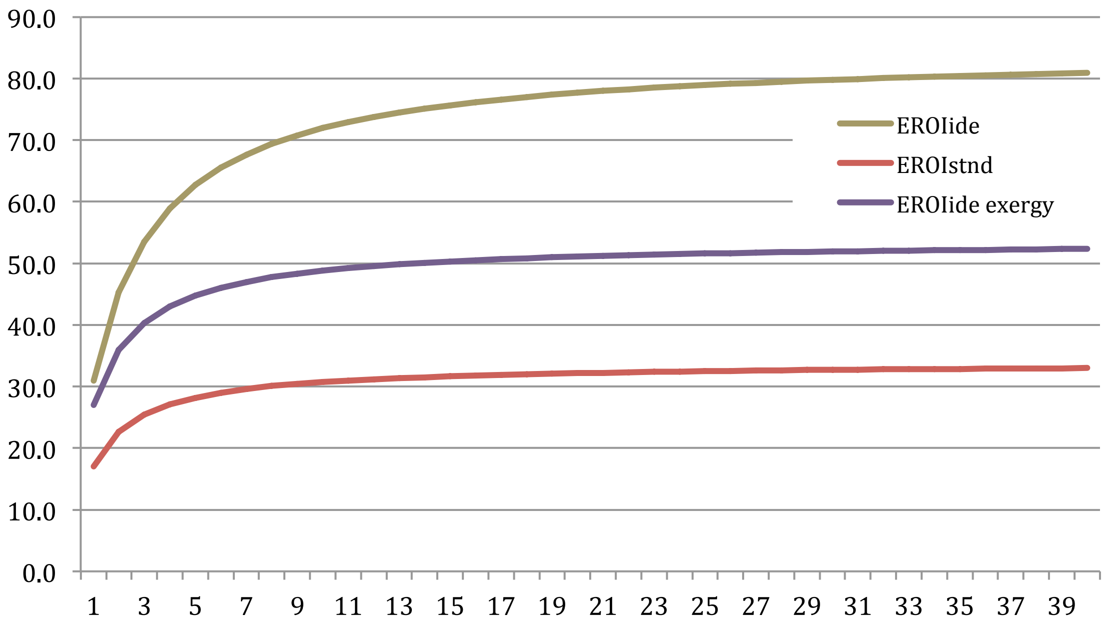

Figure A.5 shows the EROI values if the exergy is calculated rather than total enthalpy as an ideal output from the geothermal power plant.

However, to retrieve more accurate results on the ideal output from the geothermal power plant, a more in depth study needs to be done. The results shown in figure A.5 do merely provide a rough indication of what the exergy values might provide. It is however shown without a doubt that the values would decrease substantially from the total enthalpy values.