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EFFICIENCY IN GEOTHERMAL UTILIZATION PROCESSES

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ABSTRACT

Improvements in energy efficiency have been advocated by many acclaimed world bodies. One of the targets of UN Sustainable Development Goal 7 is to double the global rate of improvements in energy efficiency by 2030. In this paper, efficiency in geothermal utilization processes is examined – in electricity generation and direct utilization. An overview is given of these two main types of processes and how geothermal fluid is suitable for different purposes at different temperatures. Carnot efficiency, exergy and the work potential of geothermal fluid are addressed. First and second law efficiencies of geothermal power plants are reported – many obtained from the literature, but some values estimated by the author. Comparisons are made between different types of geothermal processes (steam cycles and binary cycles) and between geothermal power plants on one hand and fossil fuel fired and nuclear power plants on the other. While geothermal power plants do not compare well to the other types of thermal power plants on first law basis, they compare well on second law basis and in particular outperform fossil fuel fired power plants on carbon emissions parity basis. Different forms of efficiency equations (simple, functional and conditional) are presented on the basis of primary energy (first law efficiencies) and exergy (second law efficiencies) for both types of processes (electricity generation and direct use). The equations are used to calculate efficiencies for five Icelandic power plants. Efficiencies are dynamic metrics that, through effort, can improve with time. Improvements in energy efficiency benefit the environment and have the potential to conserve resources compared to a business-as-usual scenario.

1. INTRODUCTION

Efficiency is a term generally used to indicate some measure of how well resources are used. One can make efficient use of material resources, energy resources, funds, time, space etc. – thereby minimizing waste.

In the past years, improvements in energy efficiency have been gaining ever greater attention as a way to conserve resources and avoid detrimental environmental effects of energy utilization, including keeping global warming in check through curtailed greenhouse gas emissions associated with the use of fossil energy. Improvements in energy efficiency can also bring about economic and societal benefits.

One of the targets of the United Nations Sustainable Development Goals is to double the global rate of improvement in energy efficiency by 2030. In line with this, the World Energy Council notes that *energy efficiency continues to improve all over the world but despite the significant advances, much more can and should be done to improve the efficiency of energy production and use* (WEC, 2016). The International Energy Agency claims that *an entire 70% of the world's energy use takes place outside of any efficiency performance requirements* (OECD/IEA, 2016). It is therefore clear that much can be done, and in particular in developing countries and emerging economies.

Along the same lines, the Intergovernmental Panel on Climate Change (IPCC) acknowledges the following (Bruckner et al., 2014):

The TPES [Total Primary Energy Supply] *is not only a function of end users' demand for higher-quality energy carriers, but also the relatively low average global efficiency of energy conversion, transmission, and distribution processes (only 37% efficiency for fossil fueled power and just 83% for fossil fuel district heat generation). However, low efficiencies and large own energy use of the energy sector result in high indirect multiplication effects of energy savings from end users.*

They further state that energy efficiency improvements can lead to reductions in greenhouse gas emissions.

It can therefore be stated with confidence that:

1. The conversion of primary energy to other energy forms and the delivery to end-users is unnecessarily inefficient on the global scale;
2. There is considerable room for improvement;
3. Improvements can be achieved for both electricity generation processes and direct heat use – as well as other types of energy use (e.g. transportation); and
4. These improvements will benefit the environment, e.g. as climate change mitigation efforts.

This paper looks at efficiency in geothermal electricity generation processes and direct utilization processes, which are often combined.

Section 2 is a short overview of the two main types of processes and how geothermal fluid can be used for different purposes at different temperatures. Section 3 offers a look at some theoretical aspects and idealized cases that warrant consideration and set the stage for further discussion. Carnot efficiency, exergy and the work potential of geothermal fluid are addressed. Section 4 looks to real world cases of geothermal power plants, as well as other types of thermal power plants. First and second law efficiencies are reported – many obtained from the literature, but others calculated by the author based on available data for Icelandic geothermal power plants (Appendix I). Section 5 introduces efficiency forms and equations that can be applied to electricity generation processes and direct utilization processes in isolation or together. These equations are used to calculate efficiencies for five Icelandic geothermal power plants (as demonstrated in Appendix II) based on available information. Section 6 looks at efficiencies as dynamic metrics that can improve with time. Section 7 turns the sights to the relationship between efficiency and the environment and Section 8 is devoted to a summary and some concluding remarks. Section 9 presents some recommendations.

The paper is written with both general readers and experts in mind.

2. GEOTHERMAL ELECTRICITY GENERATION AND DIRECT UTILIZATION PROCESSES

In most countries, the primary objective of utilizing geothermal resources is electricity generation. However, direct uses are also of significant economic, environmental and social importance in many countries.

2.1 Geothermal electricity generation

Tried and tested conversion processes that are also used in other thermally based electricity generation (e.g. fossil fuel fired and nuclear power plants) have been adopted for geothermal. The setup can vary in multiple ways. Steam units can be simple back-pressure units ejecting steam to the atmosphere or condensing units operating at sub-atmospheric backpressure. The inlet steam can be a product of a dry steam field or a separation process, including flashing of brine in one or more stages. The geothermal fluid can also be used to heat up a secondary fluid that drives a turbine, as is done in binary power plants. In some geothermal power plants, these processes can be found in different combinations. The combination of the properties of the geothermal fluid itself, the local environment and technological/ economic factors lead to differences in efficiencies between power plants.

The details of geothermal power plant cycles have been described by various authors.

The electricity generated from geothermal resources is transmitted, distributed and consumed as any other electricity. It can be transmitted over long distances with some losses.

2.2 Direct uses

Geothermal resources have been used directly since antiquity (Haraldsson and Lloret Cordero, 2014; Kępińska, 2003). Lund and Boyd (2015) categorize these uses as space heating, greenhouse heating, aquaculture pond heating, agricultural drying, industrial uses, bathing and swimming, cooling / snow melting and other – and other systems of categorization exist with slight variations. Additionally, they mention geothermal heat pumps. As the term implies, direct uses revolve around using the heat directly in one way or another.

Making direct use of geothermal resources is probably more obvious in countries with cool climates than those with more temperate or tropical climates. In Iceland (~65°N) for example, the primary drive for utilizing geothermal resources in the 20th century was direct utilization (e.g. space heating, bathing and swimming, greenhouse farming, industrial activities etc.) (Haraldsson and Ketilsson, 2010a). Experimentation with the first small backpressure turbine for electricity generation (3 MW_e) did not start until 1969 when well over 40% of Icelandic homes were already heated with geothermal, mostly through district heating systems. However, geothermal resources have also been explored and used for various direct purposes in countries closer to the equator, e.g. for agricultural drying in Guatemala, Indonesia and Kenya (Merida, 2000; Sukaryadi and Dictus, 2014; Kinyanjui, 2013). These are of course but a few examples.

The geothermal fluid is often used directly, but the heat is also often transferred to secondary fluids through heat exchangers, e.g. when the chemical properties of the geothermal fluid make it unsuitable for distribution and use. Although the carrier has changed, this is still considered direct use as the energy retains its form as heat. The fluid is often used near its origin, but transmission and distribution through piping networks is also common. However, due to heat's eternal tendency to dissipate, there are limits to how far it can be transported and losses are inevitable. The longest district heating transmission pipeline in the world runs from the Deildartunga hot spring in Iceland to the town of Akranes (Georgsson, 2010). Over its 62 km length, the geothermal water cools by 19°C under design conditions, from 96°C at the Deildartunga inlet to 77°C at the Akranes storage tank (Ragnarsson and Hrólfsson, 1998).

Once the energy is delivered, it is up to the consumer to use it efficiently.

2.3 Combined uses

Different uses require different enthalpies / temperatures. Due to reasons covered in subsequent sections, high enthalpy fluids are best suited for electricity generation, while direct uses mostly require lower enthalpies. If fluids have a sufficiently high enthalpy, the primary drive for utilization tends to be electricity generation. But society has various needs for heat. Fluid discharged from geothermal power plants can thus be used for direct use applications, and fluids that have low- to medium-enthalpy to start with can be used directly for direct utilization processes without being used for electricity generation. The most efficient use of geothermal fluids tends to be where the fluid is passed from one type of utilization process to another in a cascade fashion. The possibilities for cascaded use are captured well in the Líndal diagram, first presented by Baldur Líndal in 1973 (Figure 1).

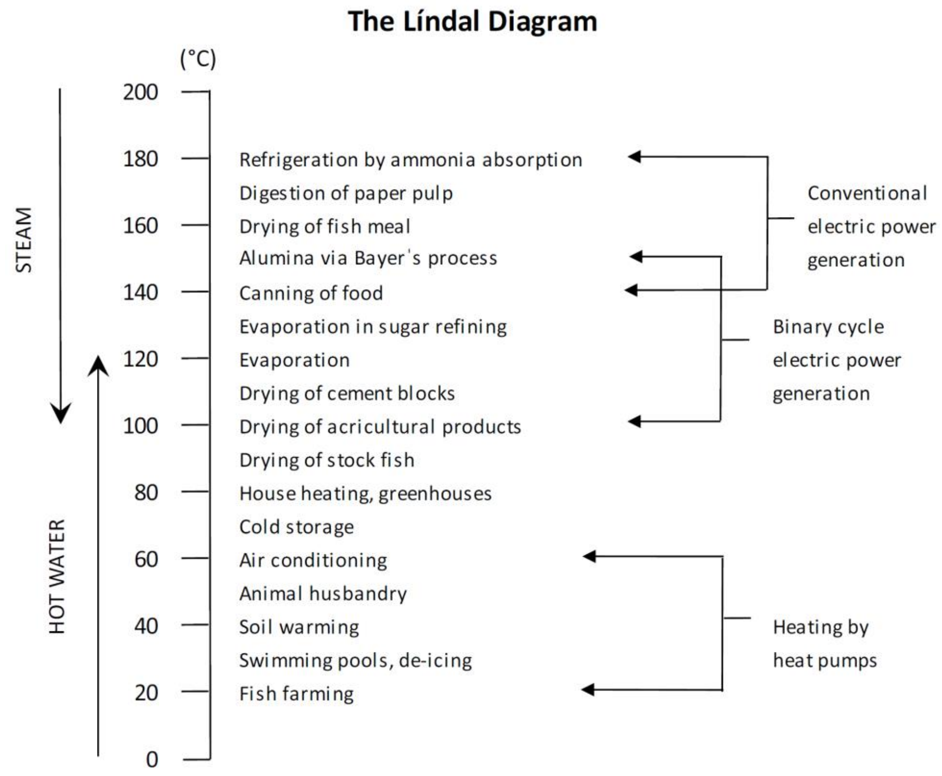

FIGURE 1: The Líndal diagram (Sveinbjörnsson, 2016)

It is up to designers, owners and operators of utilization processes to use the fluid in as efficient a way as possible, and society can also present requirements regarding the use of common resources, the handling of discharge fluids, allowable environmental impacts etc., through laws and regulations. Utilization processes can be designed with the aim of maximizing efficient use of the fluid within the constraints set by technology, economics, societal and environmental considerations.

In order to achieve efficient use of fluids, the primary developers of a geothermal resource (e.g. those with a utilization license who have the drive and means to initiate use; public, private or public-private partnerships) can take heed of economic, market and societal opportunities and needs to make the most of the resource. The implementation of an ideal setup of utilization processes may require a central entity with high stakes in utilization that liaises with other (partial) stakeholders and organizes parallel and serial uses of the resource streams. Such entities can be governments, municipalities, energy companies, partnership clusters and others. An example of multi-use development is found in the Resource Park at Reykjanes in Iceland where geothermal fluid is used for electricity generation, district heating, baths and spas, production of health and cosmetic products, fish farming, food processing, horticulture, and methanol production.

After energy extraction at the surface, geothermal fluid can be returned to the reservoir from which it was withdrawn. Reinjection can provide pressure support to the reservoir and any remaining energy may potentially make it back to the surface to contribute to utilization processes – whether it be for the benefit of the same or later generations.

2.4 Quantification of the efficiency of geothermal utilization

Making the most of geothermal fluids requires considerable theoretical and technical knowledge and know-how. At the heart of geothermal utilization is thermodynamics, and its laws both dictate limits and provide a direction on the rational setup of utilization processes. Some of these limits are explored in subsequent sections in order to bring to light the boundaries of the possible, which those who concern themselves with geothermal resources need to be aware of. Efficiencies of real world power plants are presented, as are efficiency equations applicable to geothermal utilization processes, whether it be electricity generation or direct utilization processes in isolation, or combined processes.

3. THE IDEAL WORLD – BOUNDARIES OF THE POSSIBLE

3.1 Carnot efficiency and exergy

Sadi Carnot poposed his ideal thermodynamic cycle in 1824, which served to reveal Nature's upper limit on the efficiency of thermal engines designed to perform work by passing heat between two heat reservoirs at different (constant) temperatures. The Carnot efficiency is:

$$\eta_{Carnot} = 1 - \frac{T_C}{T_H} \tag{1}$$

where T_C = Temperature of the colder reservoir (K); and
T_H = Temperature of the hotter reservoir (K).

(It may be noted that in the border cases, the efficiency approaches 1 as T_C approaches absolute zero or/and T_H goes to infinity.)

This indicates that only a part of the primary (heat) energy of a thermal fluid can be used to do useful work, whereas the rest must be discarded. The concept of exergy has thus been coined to keep tabs on the maximum work output that could theoretically be obtained from a substance at specified thermodynamic conditions relative to its surroundings (DiPippo, 2008).

Exergy analysis can be applied to more complex thermal processes than the Carnot process, which operates over a fixed temperature interval between two infinite heat reservoirs. One can introduce a "Carnot engine" which can operate between variable input temperature T_H and a fixed environmental temperature T_{env} (Bödvarsson and Eggers, 1972). The machine converts infinitesimal units of heat energy to work by passing them from the initial temperature (which continually decreases as a result) to the final reservoir at environmental temperature. The fraction of the heat energy that does not get converted to work (termed anergy) is discarded to the environment. Through each successive step, the fluid passes to an infinitesimally lower energy state until the machine is stopped or the fluid comes to thermodynamic equilibrium with the environment. In this way, the machine can produce maximum possible work output. This maximum work output is captured by the concept of exergy.

Exergy is a relative concept as it must always be referenced to a particular base state, such as annual average ambient temperature and pressure. Geothermal fluid at identical thermodynamic conditions at the wellhead in Djibouti and Iceland, for example, will therefore most likely not have the same specific exergy (exergy per mass unit) if referenced to prevalent conditions in the surrounding environment. In spite of this "fluidity" of the concept, it can be very useful for analyzing the efficiency of thermal processes as will be further discussed.

The exergy of a thermal fluid, disregarding any influences beside the thermal state (e.g. initial velocity, gravity or chemical potential), is expressed as:

$$e = h - h_{env} - T_{env}(s - s_{env}) \tag{2}$$

where e = Specific exergy referenced to the environmental state (kJ/kg);
h = Specific enthalpy at the initial state (kJ/kg);
h_{env} = Specific enthalpy at the environmental state (kJ/kg);
T_{env} = Temperature of the environmental state (K);
s = Specific entropy at the initial state (kJ/(kg K); and
s_{env} = Specific entropy of the environmental state.

The environmental state can also be referred to as the reference, base, or zero state depending on preferences – or other terminologies can be used. In line with common practice in the literature, the term "specific" will not be kept throughout the text, with inference left to the reader.

Equation 2 can be divided into two components where:

$$q = h - h_{env} \tag{3}$$

and

$$a = T_{env}(s - s_{env}) \tag{4}$$

where q = Specific primary energy, thermal energy, heat (kJ/kg); and
a = Specific anergy (kJ/kg).

The thermal energy (primary energy) can therefore be looked upon as having the potential for being divided into two components:

$$q = e + a \tag{5}$$

Bödvarsson and Eggers (1972) derive Equation 2 assuming constant pressure, while DiPippo (2004) derives it as a general equation. The equation is therefore considered valid for passing fluid between any two (reasonable) thermodynamic states, and it is left to the machine to choose the path through the space of thermodynamic variables. In effect, Equation 2 can be used to place an upper limit on the potential of a geothermal fluid at a particular initial state (e.g. at the wellhead or a separator) to do work, including generating electricity.

Figure 2 shows a plot of enthalpy (primary energy) vs. exergy for saturated steam (red) and saturated liquid water (blue) as the pressure (assumed to be at the wellhead) varies from 25 bar to atmospheric pressure (1 atm; 1.01325 bar (all pressure values in the paper indicate absolute pressure)). While the steam (vapor) enthalpy changes relatively little as the pressure drops (2802 kJ/kg to 2676 kJ/kg, difference of 126 kJ/kg), the exergy content drops much more steeply (and nearly linearly from 1001 kJ/kg to 558 kJ/kg, a difference of 443 kJ/kg), with a ratio of close to 1:3.5. For the water phase, this is reversed, with enthalpy dropping more steeply than exergy with pressure (962 kJ/kg to 419 kJ/kg, a difference of 543 kJ/kg vs. 228 kJ/kg to 44 kJ/kg, a difference of 184 kJ/kg), with a ratio of close to 3:1. The upper grey (dotted) line denotes different steam and water mixtures at 25 bar, with the steam fraction x varying from 0 to 1. The lower grey line denotes the different mixtures at 1 atm. Two phase flow with a wellhead pressure at or below 25 bar will therefore have enthalpy and exergy coordinates within the area enclosed by these boundaries at the wellhead.

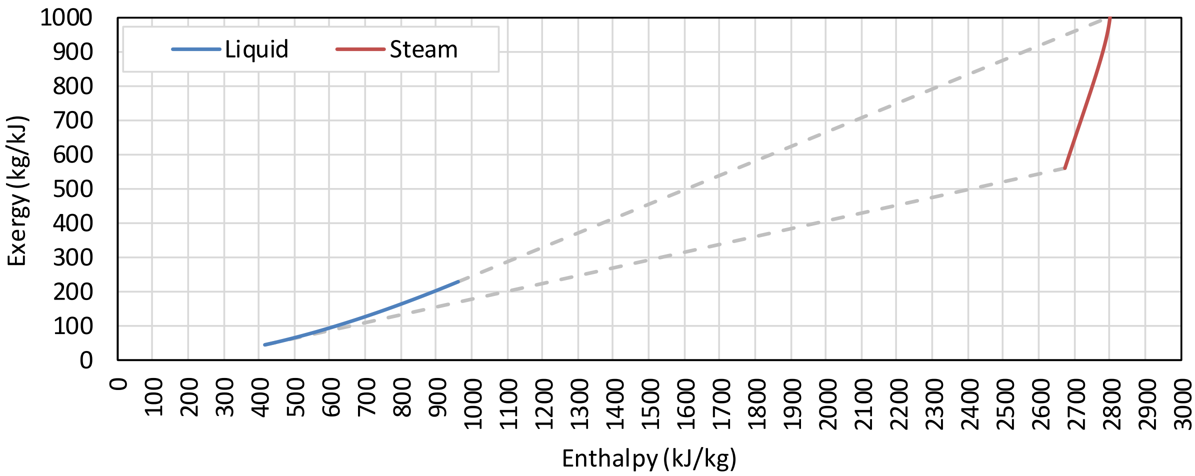

FIGURE 2: Wellhead enthalpy and exergy as functions of wellhead pressure (not shown), which is varied from 25 bar to 1 atm. Blue denotes saturated liquid and red denotes saturated steam over the indicated pressure range. The upper and lower grey dotted lines indicate (h, e) for different steam fractions as varied from 0 to 1 at 25 bar and 1 atm respectively.

Figure 3 shows exergy as a fraction of enthalpy as wellhead pressure is varied from 25 bar to 1 atm. The meaning of the plot lines is identical to that in Figure 2. The exergy ratio, or work potential of the fluid, increases with increasing enthalpy and pressure.

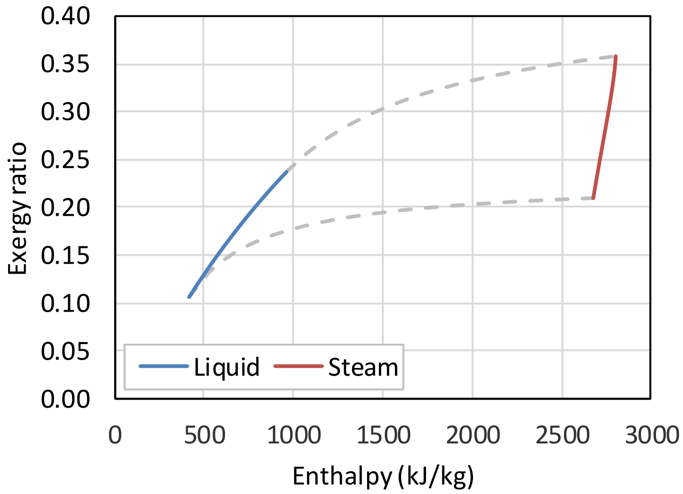

FIGURE 3: Exergy as a fraction of enthalpy as wellhead pressure is varied from 25 bar to 1 atm. Refer to Figure 2 for the meaning of plot lines.

Figure 4 shows enthalpy and exergy as functions of wellhead pressure and temperature. The drop in these quantities is nearly linear with respect to temperature. Enthalpies and exergies of fluids with steam fraction between 0 and 1 will plot between the solid and dotted lines, respectively.

3.2 Electricity or direct use?

As mentioned previously, there are two main categories of geothermal utilization: a) Electricity generation; and b) Direct utilization. The former involves extracting work (exergy) from the fluid, while the latter involves using the fluid for heating applications.

In general, energy in the form of work is worth more than energy in the form of heat. For the case of geothermal power plants, electricity can be looked upon as extracted exergy with the potential to do work, as noted by Valdimarsson (2014). The idea that a unit of “pure” exergy is worth more than a unit of energy intended for heating purposes is well reflected in comparing the price of electricity in Reykjavík, Iceland to the price of heating. Energy bills issued by a prominent Icelandic energy group in August 2016, for both electricity and hot water indicate that the price of electricity is roughly 10 times higher than that of hot water per energy unit, assuming that the hot water is delivered at 80°C and cooled to 30°C, taxes included.

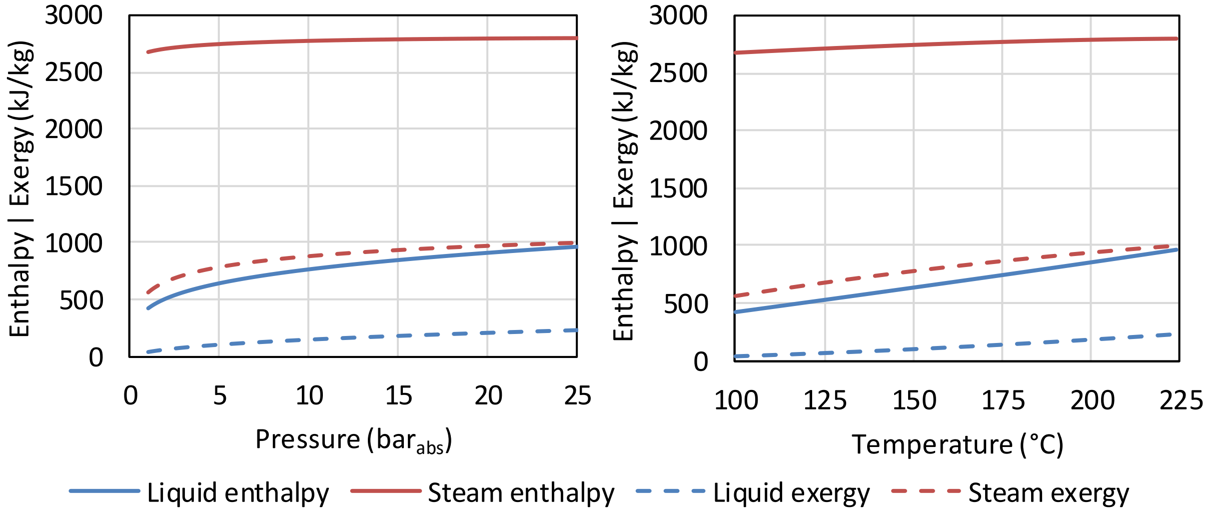

FIGURE 4: Enthalpy and exergy for saturated steam and liquid as functions of wellhead pressure (left) and temperature (right). The enthalpy of two-phase flow at the given wellhead pressure range (25 bar to 1 atm) will range between the solid lines depending on steam fraction, whereas exergy will range between the dotted lines.

Bloomster and Fassbender (1980) proposed that the price of a geothermal fluid should indeed reflect its exergy rather than its enthalpy. However, they also noted that other factors contribute to pricing as well. DiPippo (1987) and others have explored similar ideas. Although such notions will not be addressed further here, they lend further weight to recognizing the importance of the concept of exergy in the analysis of geothermal utilization projects.

Society has a need for both electricity and heat, and while it is true that local climate can affect demand for the latter, the former is always more difficult and costly to produce.

From this, it follows that a reasonable goal in geothermal utilization is to:

1. Maximize the extraction of exergy to do work (generate electricity). In the real world this goal is of course constrained by technology, economics and other factors.
2. Use any heat that remains efficiently.

From Figures 2-4, and the preceding discussion, one can observe that it makes most sense to extract exergy at the highest enthalpy levels, whereas heating applications are more appropriate at lower enthalpy levels. This is of course also conveyed effectively in the Líndal diagram (Figure 1).

3.3 How much electricity and how much heat?

From the preceding discussion, the question arises where the appropriate division may be between electricity generation on one hand and direct utilization on the other. In an ideal world endowed with Carnot machines it will make sense to divide between the two energy forms simply according to the needs of society. If thermal energy is required over specific temperature intervals, the fluid can be passed between direct utilization processes and electricity generation processes at will. Probably the thermal energy needs will be considered first, with the fluid directed to Carnot machines at temperatures (thermodynamic states) not needed for direct utilization. But here it is assumed that the ideal world mimics the real one in the sense that if electricity generation is to take place at all, it will start at the highest thermodynamic state(s) (at wellhead conditions) and if the fluid is needed for direct utilization, the designers will choose a point m (a set of thermodynamic variables that suffice to determine the thermodynamic state) where the fluid is discharged from the Carnot machine to the direct utilization process(es). The Carnot machine can be a wellhead unit, or a machine with multiple inlets that can receive fluid streams at different thermodynamic states and extract maximum work from the exergy of the individual streams to point m or until a common thermodynamic state is reached, at which point the fluid can be mixed and handled as one stream until point m is reached. No mixing of fluid is allowed unless thermodynamic states are identical.

So let us imagine the Carnot machine accepting geothermal fluid at specific *steady* inlet conditions, extracting exergy by performing work and discarding anergy to the stable environment. The machine can be set to eject the fluid stream at a specific thermodynamic state below the inlet state (point m) in order to use the fluid for direct utilization processes. The fluid is used to the fullest potential for either performing work (electricity generation) or for heating purposes.

Let us now define the following ratios (which may possibly exist under different names elsewhere in the literature).

Work potential ratio (analogous to first law efficiency in real machines – see Equation 12 and coverage in Section 4.2):

$$\omega_1 = \frac{\dot{E}_{in} - \dot{E}_m}{\dot{Q}_{in}} = \frac{e_{in} - e_m}{q_{in}} \tag{6}$$

where, in accordance with Equation 3,

$$q_{in} = h_{in} - h_{env}$$

with $\dot{E}_{in}$ = Exergy flow (exergetic power) at the Carnot machine inlet (e.g. MW);
$\dot{E}_m$ = Exergy flow at the Carnot machine outlet;
$\dot{Q}_{in}$ = Primary energy flow, thermal energy flow, thermal power at the Carnot machine inlet (e.g. MW);
e_{in} = Specific exergy of the fluid stream at the inlet of the Carnot machine (e.g. kJ/kg);
e_m = Specific exergy of the fluid stream at the outlet of the Carnot machine.
q_{in} = Specific primary (thermal) energy (e.g. kJ/kg) at the Carnot machine inlet;
h_{in} = Enthalpy of the fluid at the Carnot machine inlet; and
h_{env} = Enthalpy of the fluid at environmental conditions (reference state).

The two expressions of Equation 6 are equivalent as there is only a single steady fluid stream, with mass flow cancelling out of the latter expression.

In a similar way, the work utilization ratio (analogous to second law efficiency in real machines – see Equation 13 and coverage in Section 4.2) is defined in a similar way:

$$\omega_2 = \frac{\dot{E}_{in} - \dot{E}_m}{\dot{E}_{in}} = \frac{e_{in} - e_m}{e_{in}} \tag{7}$$

where $\dot{E}_{in}$ = Exergy flow (exergetic power) at the Carnot machine inlet (e.g. MW);
$\dot{E}_m$ = Exergy flow at the Carnot machine outlet;
e_{in} = Specific exergy of the fluid stream at the inlet of the Carnot machine (e.g. kJ/kg);
e_m = Specific exergy of the fluid stream at the outlet of the Carnot machine.

Heating ratio:

$$\tau = \frac{q_m}{q_{in}} = \frac{h_m - h_{env}}{h_{in} - h_{env}} \tag{8}$$

where h_m = Enthalpy of the fluid at the outlet of the Carnot machine.

Primary energy utilization ratio:

$$\pi = \frac{(e_{in} - e_m) + q_m}{q_{in}} = \omega_1 + \tau \tag{9}$$

Anergy disposal ratio:

$$\alpha = \frac{(q_{in} - q_m) - (e_{in} - e_m)}{q_{in}} \tag{10}$$

One can also observe that:

$$\pi + \alpha = 1 = \omega_1 + \tau + \alpha \tag{11}$$

In order to visualize the relationships between these ratios as point m is varied from the machine inlet conditions to the environmental state, an (arbitrary) example is presented.

Example:

A Carnot machine accepts saturated geothermal liquid (pure water, x = 0) at 25.34 bar. The pressure is constant through the machine, with the anergy discarded to the environment at 15°C (and 25.34 bar (this could be a planet with a thick atmosphere)). The energy content of the fluid exiting the machine is used for direct use heating applications. Depending on the machine outlet conditions (point m), the ratios introduced above vary as shown in Figure 5.

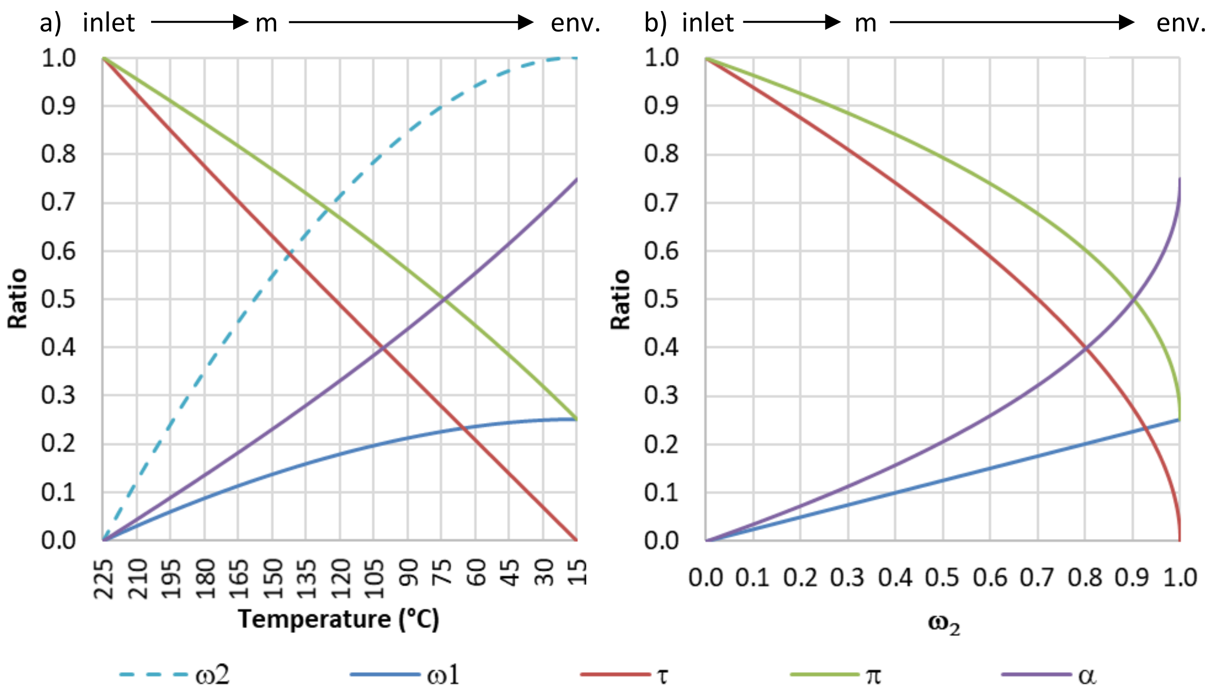

FIGURE 5: The different ratios as defined in Equations 6-11 when point m travels between the initial condition and the environmental state for the particular case described in the example (P = 25.34 bar): a) The ratios shown varying with temperature; b) The variation of ratios with ω_1

Figure 5a shows how the work utilization ratio (ω_2) goes from 0 to 1 as the temperature drops from 224.7°C at the set pressure to the environmental temperature of 15.0°C. When ω_2 reaches 1, the Carnot machine has converted all of the available fluid exergy to work (electricity). One can observe how the other ratios change in correspondence, but the border cases are of greatest interest.

Border case 1: T = 224.7 °C and $\omega_2 = 0$.

All of the fluid is passed right through the Carnot machine without any extraction of exergy as work. In effect, all of the available thermal / primary energy of the fluid is used for heating applications.

- As no work is being done: $\omega_1 = 0$.
- As all of the primary energy is used for heating, there is no disposal of anergy to the environment: $\alpha = 0$.
- The heating ratio is: $\tau = 1$.
- And the same is true for the primary energy utilization ratio: $\pi = 1$.

Border case 2: T = 15.0°C and $\omega_2 = 1$.

The Carnot machine extracts all of the exergy as work.

- A quarter of the primary energy is turned to work: $\omega_1 = 0.25$.
- The primary energy utilization ratio is equal to the work utilization: $\pi = 0.25$.
- All of the rest of the primary energy is disposed of as anergy to the environment: $\alpha = 0.75$.
- As all of the anergy is disposed of to the environment at the environmental temperature, there is no potential for direct use heating applications: $\tau = 0$.

Although this is an arbitrary example, it serves the purpose of drawing out some interesting points that may not be obvious at first glance. In particular, attention is drawn to the fact that even if the Carnot machine extracts all of the exergy as work, and that work being only a fraction of the initial thermal energy content of the fluid (primary energy), the remaining energy cannot be used for heating as it is released to the environment at the environmental temperature. The other extreme is more obvious, i.e. if all of the energy content is used for heating, there will be no production of work. This observation holds generally true.

In an ideal world that needs heating, it is therefore not feasible to extract all of the exergy as work. Fortunately perhaps, this is not an issue in the real world.

4. ELECTRICITY GENERATION IN THE REAL WORLD

4.1 Electricity generation through thermal processes

Real world processes that convert heat to work (Section 2.1) differ from the ideal processes presented in previous sections in some fundamental ways, e.g.

- They are irreversible: friction and dissipation processes abound.
- They take place in a limited number of steps compared to the infinite number of steps in the Carnot machine.

Due to exergy destruction and losses, the performance of real world utilization processes will always be less than ideal. How close they come to the ideal depends on various factors, such as technical possibilities, economic considerations, and societal requirements, and is evaluated through the concept of efficiency.

4.2 First and second law efficiencies

The first law of thermodynamics revolves around the conservation of energy (without regard for the quality of the energy), whereas the second law indicates that the quality of energy has a tendency to be degraded through processing. The thermal / primary energy content of a fluid is an overall energy measure that fits to the former, while exergy is a measure of the quality of the fluid and fits to the latter.

The first law efficiency is thus a measure of how well energy is used for a particular purpose without regard for its quality (i.e. without regard for the fundamental limits imposed by Nature on energy conversion). The first law efficiency is also commonly referred to as thermal efficiency and these two terms will be used interchangeably through the text. For a geothermal power plant, thermal efficiency of electricity generation can be expressed as:

$$\eta_{1,el} = \frac{\dot{W}}{\dot{Q}_{in}} = \frac{\dot{\zeta}_{net}}{\dot{Q}_{in}} \tag{12}$$

where $\eta_{1,el}$ = First law efficiency of electricity generation;
$\dot{W}$ = Rate of work (power); and
$\dot{\zeta}_{net}$ = Net electrical power.

And other variables as before, noting that $\dot{Q}_{in}$ is referenced to a particular thermodynamic state, such as prevailing environmental conditions. The dot denotes that the quantities are in a state of flux, which is assumed to be steady for the cases presented herein. The thermal efficiency is analogous to the work potential ratio (ω_1) for ideal machines (Equation 6).

The second law efficiency is a measure of how well exergy is used. It is also referred to as exergetic efficiency and the two terms will be used interchangeably throughout the text. For a geothermal power plant it can be expressed as:

$$\eta_{2,el} = \frac{\dot{W}}{\dot{E}_{in}} = \frac{\dot{\zeta}_{net}}{\dot{E}_{in}} \tag{13}$$

This expression is analogous to the work utilization ratio (ω_2) for ideal machines (Equation 7).

In order to determine these efficiencies one will need to carry out energy and exergy analyses of the relevant processes. In the case of geothermal utilization, it can be considered fitting to measure / calculate energy and exergy at the *wellheads*.

Committed exergy analysis of thermal fluids requires more information than energy analysis, as an extra thermodynamic variable is needed to determine exergy content (in addition to the environmental state). While knowing enthalpy and mass flow through a separator connected to production wells may produce a good approximation of the total primary energy produced by the wells (since one only needs to consider energy conservation), there can be some destruction of exergy from a wellhead to a separator. To obtain proper exergetic efficiency for a geothermal power plant, one therefore needs to know the thermodynamic state at each wellhead, e.g. enthalpy and pressure or enthalpy and temperature. This information is often more difficult to come by than enthalpy and mass flow through a separator.

As a first look, if one assumes enthalpy of 1500-2000 kJ/kg, one would expect the exergetic efficiency of the electricity generation of geothermal power plants to be roughly 3-5 times higher than the thermal efficiency referring to Figure 3. Consequently, the ratio of thermal efficiency to exergetic efficiency would be expected to be in the range of 0.20-0.33. This ratio will be explored further in subsequent sections.

4.3 First and second law efficiencies of geothermal power plants

Moon and Zarrouk (2012) conducted a worldwide review of the first law efficiency of geothermal power plants, based on data from 94 plants, using net electricity generation, mass flow from wells and the fluid reservoir enthalpy (reference temperature of 0°C). They found that the average thermal efficiency was close to 12%, with the highest at 21% (vapor dominated system) and the lowest at 1% (low temperature binary power plant). This average efficiency compares well with the 12.0% average "electricity utilization ratio" reported by Haraldsson and Ketilsson (2010b) for Icelandic power plants in 2008. That ratio is calculated as:

$$\psi = \frac{Annual\ net\ electricity\ generation\ within\ a\ geothermal\ field}{Annual\ primary\ energy\ produced\ by\ that\ geothermal\ field} \tag{14}$$

where primary energy produced by a geothermal field is that of the fluid flowing from wells within the field (not taking into account energy that may flow from natural manifestations within the field) and is in this case referenced to 15°C and 1 bar.

Equation 14 may also be expressed for N wells as:

$$\psi = \frac{\int_0^{year} \dot{\zeta}_{net}(t)\, dt}{\int_0^{year} \sum_{i=1}^{N} \dot{Q}(t)_{wellhead,i}\, dt}$$

The ratio may be compared to thermal efficiency, with the following in mind:

1. Using net generation leads to a *lower* ratio than if gross generation is used. Internal use in Icelandic power plants can be roughly evaluated as 5% of gross output.
2. The ratio considers all primary energy produced over the course of a year from a particular geothermal field, including the energy that is transferred directly to the environment during well testing or for other reasons and energy that may be used directly for purposes other than electricity generation. This leads to a higher denominator than is used in approaches that only consider the direct primary energy input to electricity generation processes, and thereby a *lower* ratio.
3. As the primary energy of the fluid is referenced to 15°C and 1 bar (i.e. h_{env} = 63 kJ/kg in Equation 3), the denominator is somewhat lower than used in approaches based on the "total" enthalpy of the fluid (h_{env} = 0 kJ/kg) or the reference state that is mainly used for calculations in this paper (i.e. 5°C and 1 atm; h_{env} = 21 kJ/kg). This leads to a *higher* calculated ratio.

The electricity utilization ratios for Icelandic geothermal power plants based on data from 2008 are shown in Table 1. The values range from 1.7% to 15.3%.

As first and second law efficiencies of Icelandic geothermal power plants are not readily available, a back-of-the-envelope analysis was carried out on the basis of process diagrams and other available information found in the published literature (Appendix I) – taken to be indicative of real performance. Estimates were made for five out of six power plants operating in 2016, with the Svartsengi power plant left out due to insufficient data. The estimates are valid for different years, depending on the availability of information. The results are shown in Table 2.

When viewing Table 2, it should be kept in mind that the design of the utilization processes can be quite different between power plants, contributing to differences in efficiencies. Thus, Hellisheidi has a bottoming plant and Krafla utilizes two stage turbines, while Bjarnarflag utilizes a 3 MW back-pressure turbine.

TABLE 1: Installed capacity, electricity generation, and electricity utilization ratios (ψ) for Icelandic geothermal power plants in 2008

Power plant	**Installed capacity[1] (MW$_e$)**	**Electricity generation[1] (GWh)**	**Electricity utilization ratio (ψ)[2] (%)**
Krafla	60	487.4	11.4
Bjarnarflag	3.2	15.9	1.7
Nesjavellir	120	975.5	15.3
Hellisheidi	213.4[3]	1,127.2	12.1
Svartsengi	76.4	566.4	10.6
Reykjanes	100	864.4	11.9
Total / Average	575[4]	4,036.9	12.0

1: Orkustofnun, 2016; 2: Haraldsson and Ketilsson, 2010b; 3: The capacity was 123 MW for most of the year. 45 MW was installed in September and another 45 MW in November (Hallgrímsdóttir et al., 2012).; 4: Note that the Húsavík Kalina plant (2 MW) is not included in the list, as it was not operational in 2008. It is, however, counted within the total installed capacity of 575 MW.

TABLE 2: Estimated first and second law efficiencies of electricity generation processes of Icelandic geothermal power plants assuming 5% internal electricity consumption and 5% destruction of exergy from wellhead to separator (see Appendix I). The reference state is (5°C, 1 atm), except for Reykjanes power plant, where it is (8.5°C, 1 atm).

Power plant	**Installed capacity (MW$_e$)**	**η_1 (%)**	**η_2 (%)**	**η_1/η_2 (-)**
Krafla	60	11-12	37	0.31
Bjarnarflag	3	2.5	8	0.31
Nesjavellir	120	13	38	0.34
Hellisheidi	303	14-15	44-46	0.32-0.33
Reykjanes	100	11	35	0.32

The ratio of first law efficiency to second law efficiency reported in Table 2 is the ratio of exergy to primary energy at the inlet conditions:

$$\frac{\eta_{1,el}}{\eta_{2,el}} = \frac{\frac{\dot{\zeta}}{\dot{Q}_{in}}}{\frac{\dot{\zeta}}{\dot{E}_{in}}} = \frac{\dot{E}_{in}}{\dot{Q}_{in}} \tag{15}$$

For the Icelandic geothermal power plants, this ratio is very close to being 1/3 overall (see also Figure 3).

The electricity utilization ratio reported in Table 1 (ψ) can be compared to the first law efficiency estimates shown in Table 2, although it should be kept in mind that the Hellisheidi power plant had not reached full size in 2008 (Hallgrímsdóttir et al., 2012) (see further in Appendix I).

Efficiencies of various steam cycle power plants, as reported in the literature, are shown in Table 3. The ratio of exergy to primary energy is lower than for the Icelandic geothermal power plants, with a 0.27 average (weighted by power plant size).

DiPippo (2004) has reported efficiencies for some binary power plants as shown in Table 4.

TABLE 3: Efficiencies of various geothermal steam cycle power plants. Various information that is relevant for efficiency considerations (e.g. thermodynamic conditions at inlet(s) and number of stages) is not included.

Power plant	**Size[1] (MW_e)**	**η_1 (%)**	**η_2 (%)**	**η_1/η_2 (-)**	**Reference state**	**Source**
Cerro Prieto I	180 (net)	12.6	47.5	0.27	25°C, 101.3 kPa	Self et al., 2015
Germencik	39.7 (net)	6.9[2]	29.6[2]	0.23	15°C, 101.325 kPa	Unverdi and Cerci, 2013
Kizildere	11.4 (net)	5.0[3]	20.8	0.24	15°C, 101.325 kPa	Cerci, 2003
Olkaria I	45 (inst.)	15	42	0.36	20°C, 0.86 bar	Kwambai, 2010
Takigami	25 (net)	6.7	28.8	0.23	15°C, atm. pressure	Jalilinasrabady et al., 2010

1: Information on capacity varies. Some authors report installed (nominal) capacity while others report net capacity. Either figure will give an idea of the "size" of the power plant (this is not an exact science).; 2: Calculated by the author from information presented in Unverdi and Cerci (2013); 3: Calculated by the author from information presented in Cerci (2003).

TABLE 4: First and second law efficiencies of various geothermal binary power plants based on cases reported by DiPippo (2004)

Power plant	**Size (MW_e)**	**η_1 (%)**	**η_2 (%)**	**η_1/η_2 (-)**	**T_{in}[8] (°C)**	**T_{env}[10] (°C)**
Otake pilot plant[1]	1	10.3[6]	53.9[6]	0.19	130[9]	18
Nigorikawa pilot plant[2]	1	3.7[6]	21.6[6]	0.17	140	13
Heber SIGC[3]	6.9 (net)	8.6[6]	43.7[6]	0.20	165	15
Húsavík[4]	1.7 (net)	3.8[6]	22.5[6]	0.17	124	5
Brady[5]	2.9-4.3 (net)	1.8-2.3[6]	16.4-18.0[6]	0.11-0.13	107.8-108.7	16.8-30.1

1: Utilized an 18-stage flash evaporator, recuperator and isobutene as working fluid, receiving both steam and brine. Dismantled after testing.; 2: Simple binary cycle with two stage condenser and Refrigerant-114 as working fluid. Dismantled after testing.; 3: Dual-level units, wet cooling towers.; 4: Kalina cycle utilizing 82% ammonia and 18% water, river cooling.; 5: Simple binary bottoming cycle with air cooled condensers (and large diurnal variation in env. temperature).; 6: Calculated based on data provided by DiPippo (2004) in accordance with Equations 12 and 13. Slight differences may be present in calculated exergy values as compared to DiPippo due to different pressures and calculation platforms being used.; 8: Inlet temperature; 9: Brine and steam, whereas the rest of the plants receive brine only; 10: Reference temperature.

Various other authors have reported on efficiencies of individual geothermal binary power plants as shown in Table 5.

TABLE 5: Efficiencies of various binary geothermal power plants

Power plant	**Size (MW_e)**	**η_1 (%)**	**η_2 (%)**	**η_2/η_1 (-)**	**T_{in}[1] (°C)**	**Reference state**	**Source**
A power plant	27 (net)	4.4	21.1	0.21	160	3°C, 84 kPa	Kanoglu and Bolatturk, 2008
Dora II	9.5 (net)	6.1[2]	30.0[2]	0.20	169	17.1°C, 101.3 kPa	Ganjehsarabi et al., 2012
Las Pailas	39[3] (net)	8.6[4]	37.2[4]	0.23	160	25°C, 0.093 MPa	DiPippo and Moya, 2013
Stillwater	12.4 (net)	5.8	29.1	0.20	163	12.8°C, 0.84 kPa	Kanoglu, 2002
Tuzla	5.2[5] (net)	9.5[6]	45.2[6]	0.21	175	25.4°C, 101 kPa	Coskun et al., 2011

1: Inlet temperature (rough).; 2: Calculated based on data provided by the authors. CO_2 inlet stream ignored.; 3: Based on calculated value by the author.; 4: Calculated based on data provided by the authors.; 5: Calculated by the authors.; 6: Annual average. The reported ranges are η_1 = 6-12% and η_2 = 35-49%, with η_1/η_2 = 0.17-0.24.

Looking at this sample of geothermal power plants (whether representative or not), the following observations can be made:

- All of the binary power plants have a thermal efficiency below 10%, except the experimental Otake pilot plant, at 10.3%. The range is 2.1%-10.3%, with a weighted average at 6.7% (assuming mid-efficiency for Brady). The exergetic efficiencies generally exceed 20% with a range of 17.2%-53.9% and a weighted average of 31.5%. The ratio of average exergy to average primary energy at the inlet is 0.21.
- Many of the steam "cycle" power plants have higher thermal efficiencies than the binary power plants, although two have lower thermal efficiencies than the average of the binaries, Bjarnarflag at an estimated 2.5% efficiency and Kizildere at 5.0%, while Takigami is at the average of 6.7%. The range is 2.5%-15%, with a weighted (some net and some gross) average of 12.6%. This is close to twice the average for the binary power plants. The range of exergetic efficiencies for the steam cycles is 8%-47.5%, with a weighted average of 41.0%, which is about 10% points above the average of the binaries. The ratio of average exergy to average primary energy at inlet is 0.31, well above that of the binary power plants, indicating higher enthalpy fluids being used.
- Looking at the exergy to primary energy ratios, they hover close to 0.20 for the binary power plants and close to 0.30 for the steam cycles. However, the Icelandic power plants have higher ratios than the other steam power plants, with an average of 0.33 (13.2% thermal efficiency and 40.7% exergetic efficiency) compared to an average of 0.27 (11.4% thermal efficiency and 41.8% exergetic efficiency) for the other steam power plants sampled. This points to a somewhat higher work potential of the fluids available in Iceland compared to the other cases.

The first law efficiency of geothermal power plants is quite low compared to other types of thermal power plants as shown in Figure 6 presented by Moon and Zarrouk (2012). This has on occasion been looked at with a critical eye by proponents of efficient energy resources management. However, for such comparisons it is more appropriate to use second law efficiencies as discussed in the subsequent sections.

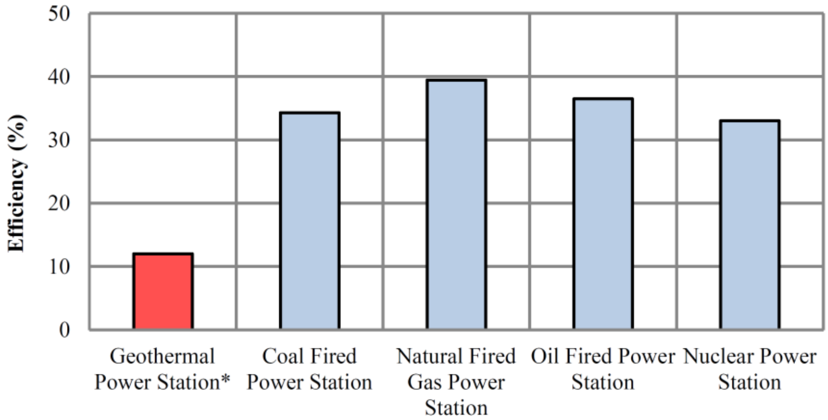

FIGURE 6: First law efficiency of geothermal power plants compared to that of other types of thermal power plants (Moon and Zarrouk, 2012)

4.4 First and second law efficiencies of fossil fuel fired power plants

In a report titled *Energy efficiency indicators for public electricity production from fossil fuels*, the International Energy Agency reported on efficiencies of public electricity-only and combined heat and power (CHP) fossil fuel power plants in 35 countries over the period 2001-2005. The efficiency was calculated on an annual basis as:

$$E = \frac{P + H \cdot s}{I} \tag{16}$$

where P = Gross electricity production from public electricity plants and public CHP plants;
H = Useful heat output from public CHP plants;
s = Correction factor between heat and electricity (see discussion below); and
I = Fuel input for public electricity plants and public CHP plants (NCV).

The agency has determined that heat extraction in CHP plants decreases the efficiency of electricity production. The term H·s in Equation 16 is thus introduced in an attempt to compare with the efficiency potential of an electricity-only generation process. A value of s = 0.175 is used. The impact of varying s to 0.150 or 0.200 is within 0.5% for 28 countries out of 35. Energy input (I) is based on net calorific value (NCV; lower heating value), but the reference conditions are not stated. The differences in net and gross values for solid fuels are typically about 5-6% of the gross value (OECD/IEA, 2005). Energy outputs (P and H), on the other hand, are based on gross production. Efficiency values on net energy output per gross energy input basis, referenced to 5°C and 1 atm, may thus call for 10-15% reduction in the values reported in Table 6.

TABLE 6: Average efficiencies of public electricity-only and CHP fossil fuel power plants over the period 2001-2005 as reported by the International Energy Agency (Taylor et al., 2008)

	Coal	**Natural gas**	**Oil**
Average in OECD countries	37%	45%	37%
Average in non-OECD countries	32%	35%	36%
Range OECD countries	36-43%		
Range all countries	27-43%	31-55%	23-43%
Improvement in OECD countries over the period 1990-2005	~0.5%	~8%	Slight incr.
Improvement in non-OECD countries over the period 1990-2005	~2%	~2%	Slight incr.

These values align well with the IPCC estimate of 37% efficiency for fossil fueled power as mentioned in Section 1 (Bruckner et al., 2014).

While the statistics presented in Table 6 are based on a large dataset, thermal and exergetic efficiencies have also been presented in the literature for various specific power plants as shown for coal-fired power plants in Table 7. The thermal efficiency values compare well with those presented by IEA in Table 6.

TABLE 7: Some reported first and second law efficiencies of coal-fired power plants

Power plant	**Country**	**Size (MW)**	**η_1 (%)**	**η_2 (%)**	**η_1/η_2 (-)**	**Reference state**	**Source**
Nanticoke	Canada	1368 (net)	37	36	1.0	15°C, 1 atm	Rosen, 2001
Yatagan	Turkey	630 MW (inst.)	37.0	32.0	1.2	25°C, 1.013 bar	Erdem et al., 2009
Seyitomer	Turkey	600 MW (inst.)	38.0	31.5	1.2	25°C, 1.013 bar	Ibid.
Can	Turkey	320 MW (inst.)	42.1	37.9	1.1	25°C, 1.013 bar	Ibid.
Catalagzi	Turkey	300 MW (inst.)	37.9	35.2	1.1	25°C, 1.013 bar	Ibid.
Kangal	Turkey	457 MW (inst.)	37.2	28.6	1.3	25°C, 1.013 bar	Ibid.
Afsin Elbistan	Turkey	1440 MW (inst.)	42.6	32.5	1.3	25°C, 1.013 bar	Ibid.
Orhaneli	Turkey	210 MW (inst.)	37.6	35.5	1.1	25°C, 1.013 bar	Ibid.
Soma	Turkey	990 MW (inst.)	36.1	32.4	1.1	25°C, 1.013 bar	Ibid.
Tuncbilek	Turkey	429 MW (inst.)	38.4	33.1	1.2	25°C, 1.013 bar	Ibid.

The average weighted thermal efficiency of the power plants in Table 7 is 38.6% and the average exergetic efficiency is 33.3%, with an average exergy to primary energy ratio of 1.2.

Rosen (2001) points out that the specific chemical exergy of coal is slightly greater than its specific base enthalpy, which is quite different from the geothermal case where the exergy is only a fraction of the primary energy. The chemical composition of coal can vary significantly, strongly influencing the values of chemical exergy. Bilgen and Kaygusuz (2008) estimate the specific chemical exergies of Turkish tertiary coal. Their results (referenced to T = 25°C and P = 0.1 MPa) show exergies slightly exceeding the higher heating values of dry and ash free coals, which is consistent with the ratio of exergetic efficiency to primary energy being larger than unity in Table 7. Indeed, Bilgen and Kaygusuz (2008) point out that the use of the higher heating value of a fuel to approximate the fuel chemical exergy is frequently observed in the literature. The exergetic efficiency of coal-fired power plants is therefore not to be expected to exceed the thermal efficiency as is the case for geothermal power plants.

The author lacks information to make a similar comparison for liquid fuel and natural gas fired power plants. However, it is worth mentioning that manufacturers of gas turbines eye thermal efficiencies as high as 60% for combined cycle power plants. A 62% efficiency has been reported for a combined cycle power plant in Bouchain in France (Keller, 2016). Such high thermal efficiency is obtained by high turbine inlet temperature (Equation 1) and reuse of exhaust heat (combined cycle, additional steps).

4.5 First and second law efficiencies of nuclear power plants

Dunbar et al. (1995) state that nuclear power plants generally operate at a thermal efficiency of about 30-35%. Rosen (2001), Dunbar et al. (1995), and Durmayaz and Yavuz (2001) also state efficiencies for specific modelled existing or proposed nuclear power plants as shown in Table 8.

TABLE 8: Some reported first and second law efficiencies of nuclear power plants

Power plant[1]	Country	Size (MW)	η_1 (%)	η_2 (%)	η_1/η_2 (-)	Reference state	Source
Pickering	Canada	1763 MW (net)	30	30	1.0	15°C, 1 atm	Rosen, 2001
LaSalle	US	1140 MW (net)	34.4	34.4	1.0	15.6°C, 0.02 bar	Dunbar et al., 1995
-	Turkey / China	1500 MW (net)	36.5	36.5	1.0	20.6°C, 1 bar	Durmayaz and Yavuz, 2001

1: Pickering and LaSalle are operating power plants, while the last one was proposed.

The same authors note that for nuclear power plants, the available thermal energy and exergy are considered equal, which leads to equal thermal and exergy efficiencies. The underlying assumption is that the temperature at which heat can be produced by fissioning uranium is very high (Rosen, 2001) (Equation 1 close to unity). However, due to the violent, irreversible fission process and heat transport through large temperature gradients from the fission reaction sites within the fuel rods to the lower temperature water coolant flowing through the reactor, the majority of the plant irreversibility takes place within the reactor (Dunbar et al., 1995). Rosen (2001) notes that if the fission heat is taken to be available at the temperature at which it is actually produced (at the thermal neutron flux-weighted average temperature of about 880°C), the exergy is about 75% of the energy. From that viewpoint, the exergetic efficiency of the power plants reported on in Table 8 would increase to roughly 40-50%.

4.6 Comparison of electricity generation of thermal power plants

Although the thermal efficiency of electricity generation of geothermal power plants is significantly lower than the thermal efficiency of fossil fuel fired and nuclear power plants, the geothermal plants compare well on second law basis. The weighted average exergetic efficiency of the steam cycle geothermal power plants for which data were presented was estimated as 41.0% and that of geothermal binary power plants was calculated as 31.5%. The average exergetic efficiency of coal fired power plants was calculated as 33.3%, falling in between the two types of geothermal power plants. The three nuclear power plants for which data were found (one proposed) had a second law efficiency in the range of 30-36.5%. The data used in the paper therefore suggest that geothermal electricity generation compares well with coal fired and nuclear power plants on an exergy basis. Indeed, geothermal steam cycle power plants seem to lead the pack.

This conclusion is of course made assuming that the data presented are representative for the different types of power plants. In the case of geothermal steam cycle power plants, the back-of-the-envelope analysis of this paper weighs heavily. Other data are obtained from the literature after performing what the author considers reasonable search in scientific journals. However, it is likely that some additional information is available unbeknownst to the author. The case is similar for the coal fired and nuclear power plants, but the author was not able to find similar research for liquid fuel or gas fired power plants. Hopefully more extensive data will become available. Also, the different use of reference states, net or gross calorific values, low or high heating values, gross or net electricity production etc. make the comparison quite rough. Efficiency calculations and especially efficiency comparisons are rarely an exact science. Nevertheless, the results are considered of some value and in particular it appears clear that the efficiency of geothermal electricity generation compares well with coal fired and nuclear electricity generation on the second law basis.

4.7 Taking carbon into account

Taking heed of Sustainable Development Goal 13 (Take urgent action to combat climate change and its impacts (Georgsson and Haraldsson, 2016)), the case can be made that carbon emissions of power plants should be taken into account when comparing one plant to another. This can be done through economics, by assigning an economic value to CO_2 equivalents as has been done in Clean Development Mechanism trading in past years (Haraldsson, 2012). Another approach is to look at the effects of capturing and sequestering carbon to put power plants on an equal emissions footing. As such processes require energy input, they lower the net efficiency of a carbon based power plant. Hanak et al. (2014) presented a study using a model of a supercritical coal-fired power plant (with a net base thermal efficiency of 39.1%) fitted with a post-combustion capture system with a capture level of 90%. The reported energy penalty was estimated to cause a 25% fall in the power output (and thereby the efficiency). They further reported a summary of previous studies revealing that the net thermal efficiency of coal-fired power plants is reduced by 10% points when fitted with post-combustion capture systems.

Bertani and Thain (2002) reported that the weighted average CO_2 emission intensity for geothermal power plants was 122 g/kWh based on 85% of the world geothermal power plant capacity at the time. They also gave some typical CO_2 emission intensities for fossil fueled power plants (Table 9). By comparison, Bloomfield et al. (2003) reported that the weighted average CO_2 emissions intensity for geothermal power plants in the United States was 91 g/kWh. This value includes binary power plants and represents 14% of the surveyed capacity. The weighted average emission intensity for Icelandic geothermal power plants was 50 g/kWh in 2009, when installed geothermal capacity was 575 MWe (Baldvinsson et al., 2010). These weighted average CO_2 intensities are summarized in Table 9 along with estimates for fossil fueled power plants. Bertani and Thain estimate the latter based on the assumed efficiencies of the conversion processes, as well as the energy and carbon content of the fuels, while Bloomfield et al. state that their calculations are based on data from the US Energy Information Administration.

TABLE 9: Weighted average CO_2 emission intensities for different sets of geothermal power plants and estimates for fossil fueled power plants

	Geothermal (g/kWh)	**Natural gas (g/kWh)**	**Oil (g/kWh)**	**Coal (g/kWh)**
Bertani and Thain (2002)	122 (World)	315	760	915
Bloomfield et al. (2003)	91 (USA)	599	893	950
Baldvinsson et al. (2010)	50 (Iceland)			

Assuming emission intensity of 915-950 g/kWh for coal fired power plants, a capture level of 90% would get the intensity down to 92-95 g/kWh, which is comparable to geothermal power plants. Comparing the exergetic efficiencies of geothermal and coal fired power plants on emission parity basis therefore indicates an advantage of geothermal power plants over the former.

5. EFFICIENCIES OF COMBINED ELECTRICITY GENERATION AND DIRECT UTILIZATION

The coverage of real world power plants in Section 4 has been restricted to electricity generation, without much regard for heat use, except for the IEA efficiency formula (Equation 16) which incorporates a correction factor associated with heat output. Even though heat is generally considered a lower quality energy form than work or electricity, it is needed (at different temperatures) to meet various demands in human society. Direct applications include space heating in cooler climates, cooling in warmer climates, bathing, swimming, therapeutic, and recreational applications, various agricultural and farming applications, industrial applications and more. Considerations of the efficiency of energy usage should therefore take heat into account.

While second law efficiency is the straightforward efficiency to look at in the case of electricity generation, it is not as straightforward when it comes to the utilization of heat, even though exergy is used through heating applications. It is, after all, energy in the form of heat that is being sought rather than the work potential of the fluid.

Some efficiency definitions that attempt to address both electricity generation and direct utilization are presented in this section, followed by a few examples of their application.

5.1 A revisit to the Carnot machine

In the ideal world, the Carnot machine presented in Section 3 accepts a fluid stream with exergy $\dot{E}_{in}$. The fluid is used for electricity generation and/or heating applications as efficiently as possible, in accordance with the particular utilization needs and decisions of the designers / society. The Carnot machine therefore generates the needed electricity at the highest exergy levels until the target production capacity is reached and then discharges the fluid to the heating application process(es) at exergy level $\dot{E}_m$.

In the real world, an electricity generation process (with any setup of cycles, turbines, number of steps etc.) accepts a fluid stream with exergy $\dot{E}_{in}$ and generates the same amount of electricity as the ideal process. The fluid is then discharged to the heating utilization process(es) at a lower exergy level than is the case in ideal process, $\dot{E}_{m^*}$. The points m and m* denote an appropriate set of thermodynamic variables at the outlet point(s) of the electricity generation process that suffice to determine the exergy content of the fluid. Necessarily, $\dot{E}_{m^*} \leq \dot{E}_m$ and $\dot{E}_{m^*} \rightarrow \dot{E}_m$ with improvements in the efficiency of the real world process.

This is shown graphically in Figure 7. For simplicity, a single fluid stream is assumed, entering the black box of electricity utilization at point 1, being discharged to heating applications at points m or m*, with the environmental state denoted by point 2.

Let us now relate the electricity production to the exergy given up in the electricity generation process. Such an approach is well documented in the literature. The corresponding efficiency has been referred to as functional exergetic efficiency by DiPippo (2008) and has been used by other authors under that or different terms. This term will be adopted here. The functional exergetic efficiency of the real world electricity generation is in this case defined as:

$$\eta_{2f,el} = \frac{\dot{\zeta}}{\dot{E}_{in} - \dot{E}_{m^*}} = \frac{\dot{E}_{in} - \dot{E}_m}{\dot{E}_{in} - \dot{E}_{m^*}} \quad (17)$$

where $\eta_{2f,el}$ = Second law functional efficiency of electricity generation;
$\dot{E}_m$ = Exergy at the outlet of an ideal electricity generation process; and
$\dot{E}_{m^*}$ = Exergy at the outlet of a real electricity generation process.

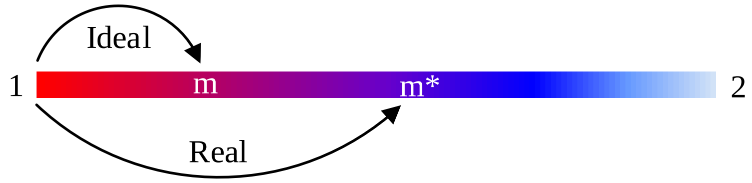

FIGURE 7: Two processes generating the same amount electricity. One in the ideal world and one in the real world. Points 1 and 2 denote the inflow and environmental states, respectively.

For the ideal process, the exergy left for direct use applications is $\dot{E}_m$ while the maximum available exergy in the real process is $\dot{E}_{m^*}$. In determining the efficiency of the direct utilization process, one can take the view to measure the utilization not against the actual exergy delivered to the process, but rather against the exergy that would be available from the ideal electricity generation process.

The second law efficiency of direct utilization, dependent / conditional on the electricity generation, can in this case be presented as:

$$\eta_{2fc,DU} = \frac{\dot{E}_{DU}}{\dot{E}_m} = \frac{\dot{E}_{DU}}{\dot{E}_{in} - \dot{\zeta}} \leq \frac{\dot{E}_{DU}}{\dot{E}_{m^*}} \quad (18)$$

where $\eta_{2fc,DU}$ = Second law conditional efficiency of direct utilization; and
$\dot{E}_{DU}$ = Exergy expended through a direct utilization process.

As this efficiency is influenced and restricted by the exergetic efficiency of electricity generation, it can only approach unity when the latter does ($\dot{E}_{m^*} \rightarrow \dot{E}_m$).

These two metrics should be presented together and are not to be combined.

5.2 An overview of commonly used efficiencies: simple and functional

Probably the most common approach to examining efficiency is simply associating useful output from a particular process with the input, without regard for any outputs beside the one being sought. This form has already been introduced in Equations 12 and 13 and is repeated below for review and context with other forms that follow. For lack of a better term, this form will henceforth be referred to as simple efficiency and will be marked by the subscript s. Note that it is not specifically denoted whether electrical power output is net or gross.

First law simple efficiency of electricity generation:

$$\eta_{1s,el} = \frac{\dot{\zeta}}{\dot{Q}_{in}} \quad (19)$$

First law simple efficiency of direct utilization:

$$\eta_{1s,DU} = \frac{\dot{Q}_{DU}}{\dot{Q}_{in}} \tag{20}$$

where $\dot{Q}_{DU}$ = Primary energy used in a direct utilization process.

If efficiency of CHP processes is to be captured in a single metric, the widely used form of overall efficiencies can be used.

Overall (combined) first law simple efficiency:

$$\eta_{1s,overall} = \frac{\dot{\zeta} + \dot{Q}_{DU}}{\dot{Q}_{in}} = \eta_{1s,el} + \eta_{1s,DU} \tag{21}$$

Second law simple efficiency of electricity generation:

$$\eta_{2s,el} = \frac{\dot{\zeta}}{\dot{E}_{in}} \tag{22}$$

Second law simple efficiency of direct utilization:

$$\eta_{s2,DU} = \frac{\dot{E}_{DU}}{\dot{E}_{in}} \tag{23}$$

where $\dot{E}_{DU}$ = Exergy expended in a direct utilization process.

Overall (combined) second law simple efficiency:

$$\eta_{2s,overall} = \frac{\dot{\zeta} + \dot{E}_{DU}}{\dot{E}_{in}} = \eta_{2s,el} + \eta_{2s,DU} \tag{24}$$

One issue to keep in mind when combining electricity generation and direct utilization efficiency metrics in an overall metric, as in Equations 21 and 24, is that exergy is the more appropriate measure in the case of electricity generation, whereas primary energy is the more appropriate measure in the case of direct utilization. The usefulness of the overall metric can therefore be questioned.

Functional efficiencies, based on energy / exergy are marked by the subscript f as before. Functional efficiency as used in subsequent equations refers to net energy / exergy delivered to a type of process, with reinjection treated as disposal to the environment (although reinjection is considered and incorporated in Section 5.5). There are only two types of processes: electricity generation and direct utilization. The input to the latter is deducted from the total input to the former to delineate a base for the efficiency calculation of the former, but no deduction is made for the latter even if the direct applications do not make full use of the energy / exergy. The functional efficiency of the electricity generation process thus refers to the energy / exergy *given up* in the process, whereas the term refers simply to the energy / exergy delivered to direct utilization process(es), without regard for any potentially useful output that may be discharged from the process(es).

First law functional efficiency of electricity generation:

$$\eta_{1f,el} = \frac{\dot{\zeta}}{\dot{Q}_{in} - \dot{Q}_{m^*}} \tag{25}$$

First law functional efficiency of direct utilization:

$$\eta_{1f,DU} = \frac{\dot{Q}_{DU}}{\dot{Q}_{m^*}} \tag{26}$$

Second law functional efficiency of electricity generation:

$$\eta_{2f,el} = \frac{\dot{\zeta}}{\dot{E}_{in} - \dot{E}_{m^*}} \tag{27}$$

Second law functional efficiency of direct utilization:

$$\eta_{2f,DU} = \frac{\dot{E}_{DU}}{\dot{E}_{m^*}} \tag{28}$$

5.3 Overall functional efficiencies

Note that the overall efficiencies given in Equations 21 and 24 can also be expressed in terms of the functional efficiencies as:

$$\begin{aligned}\eta_{1s,overall} &= \frac{\dot{\zeta} + \dot{Q}_{DU}}{\dot{Q}_{in}} = \frac{\dot{\zeta}}{\dot{Q}_{in}} + \frac{\dot{Q}_{DU}}{\dot{Q}_{in}} = \left(\frac{\dot{Q}_{in} - \dot{Q}_{m^*}}{\dot{Q}_{in}}\right)\left(\frac{\dot{\zeta}}{\dot{Q}_{in} - \dot{Q}_{m^*}}\right) + \left(\frac{\dot{Q}_{m^*}}{\dot{Q}_{in}}\right)\left(\frac{\dot{Q}_{DU}}{\dot{Q}_{m^*}}\right) \\ &= \left(\frac{\dot{Q}_{in} - \dot{Q}_{m^*}}{\dot{Q}_{in}}\right)\eta_{1f,el} + \left(\frac{\dot{Q}_{m^*}}{\dot{Q}_{in}}\right)\eta_{1f,DU}\end{aligned} \tag{29}$$

The corresponding form for exergetic efficiency is:

$$\eta_{2s,overall} = \left(\frac{\dot{E}_{in} - \dot{E}_{m^*}}{\dot{E}_{in}}\right)\eta_{2f,el} + \left(\frac{\dot{E}_{m^*}}{\dot{E}_{in}}\right)\eta_{2f,DU} \tag{30}$$

The appropriate form for overall functional efficiencies is therefore as follows.

First law overall functional efficiency:

$$\eta_{1f,overall} = \left(\frac{\dot{Q}_{in} - \dot{Q}_{m^*}}{\dot{Q}_{in}}\right)\eta_{1f,el} + \left(\frac{\dot{Q}_{m^*}}{\dot{Q}_{in}}\right)\eta_{1f,DU} \tag{31}$$

Second law overall functional efficiency:

$$\eta_{2f,overall} = \left(\frac{\dot{E}_{in} - \dot{E}_{m^*}}{\dot{E}_{in}}\right)\eta_{2f,el} + \left(\frac{\dot{E}_{m^*}}{\dot{E}_{in}}\right)\eta_{2f,DU} \tag{32}$$

Simple and functional overall efficiencies are one and the same, although the weights on component efficiencies are different.

While the overall efficiencies are the same, the simple component efficiencies are useful when one is interested in looking at the absolute contributions made by the electricity generation processes on one hand and direct utilization processes on the other. The functional component efficiencies are of value when looking at the two types of processes in isolation and the proportional contributions of each to the overall efficiency.

5.4 Conditional efficiencies

Let us now consider the following: Geothermal fluid is used for electricity generation and/or direct utilization. Some of the primary energy / exergy may be reinjected into the reservoir from whence it came and some will be discarded to the environment (atmosphere, surface water or shallow groundwater bodies) where the heat dissipates and cannot be used for practical purposes. In the cases where there is both electricity generation and direct use, the CHP plants may supply district heating systems with energy (as is done in several power plants in Iceland) or supply industrial activities at site (industrial parks).

In the case where geothermal fluid is used for electricity generation only and the remaining energy / exergy is discarded to the environment, it is straightforward to use the simple efficiencies as presented in Equations 19 and 24 as indicators of how well the energy / exergy is used (i.e. on the basis of the total primary energy / exergy supplied to the processes).

In the case where geothermal fluid is first used for electricity generation and then directed to direct utilization processes that make good use of the fluid, it may be more reasonable to use the functional efficiencies as metrics for the processes (Equations 25-28 and 31-32).

If only a part of the fluid from the electricity generation process is conveyed to direct utilization processes, while the rest is discarded to the environment, it would seem appropriate that the efficiency lie in between the former two cases, i.e. the simple and functional efficiencies.

In other words, the calculated efficiency of the electricity generation process should depend on how the discharge fluid is used. Conversely, the efficiency of direct utilization should take into account how the fluid has been used for electricity generation. One should be coupled, or conditioned, to the other.

The first law conditional efficiency of electricity generation (marked by the subscript c), given direct utilization, can thus be defined as:

$$\eta_{1c,el} = \frac{\dot{\zeta}}{\dot{Q}_{in} - \dot{Q}_{DU}} \tag{33}$$

First law conditional efficiency of direct utilization:

$$\eta_{1c,DU} = \frac{\dot{Q}_{DU}}{\dot{Q}_{in} - \dot{\zeta}} \tag{34}$$

Second law conditional efficiency of electricity generation:

$$\eta_{2c,el} = \frac{\dot{\zeta}}{\dot{E}_{in} - \dot{E}_{DU}} \tag{35}$$

Second law conditional efficiency of direct utilization:

$$\eta_{2c,DU} = \frac{\dot{E}_{DU}}{\dot{E}_{in} - \dot{\zeta}} \tag{36}$$

Taking inspiration from the overall functional efficiency as presented in the previous section, the overall conditional efficiencies follow.

Overall first law conditional efficiency:

$$\eta_{1c,overall} = \left(\frac{\dot{Q}_{in} - \dot{Q}_{m^*}}{\dot{Q}_{in}}\right)\eta_{1c,el} + \left(\frac{\dot{Q}_{m^*}}{\dot{Q}_{in}}\right)\eta_{1c,DU} \tag{37}$$

Overall second law conditional efficiency:

$$\eta_{2c,overall} = \left(\frac{\dot{E}_{in} - \dot{E}_{m^*}}{\dot{E}_{in}}\right)\eta_{2c,el} + \left(\frac{\dot{E}_{m^*}}{\dot{E}_{in}}\right)\eta_{2c,DU} \tag{38}$$

Conditional efficiencies are particularly appropriate when reporting the individual efficiencies of electricity generation and direct utilization processes together, as coupled metrics. The overall conditional efficiency is probably less useful, however, than simple / functional overall efficiency.

5.5 Efficiency and reinjection

Reinjection into, or at the peripheral capture zone of, geothermal reservoirs has various positive effects, e.g. reduction of environmental impacts due to discharge at or near the surface (Haraldsson, 2011), possible reduction of subsidence, pressure support to the reservoir and return of energy / exergy that may eventually make it to the surface again to be used in utilization processes. Negative side effects of reinjection may include micro-seismicity. If some energy / exergy makes it into the reservoir again due to reinjection, possibly to make another pass through utilization processes on the surface at a later time, it appears reasonable to deduct the reinjected energy / exergy from the process input energy / exergy and thus measure process performance against the net energy / exergy extracted from the reservoir (as measured at wellheads). Thus, the positive effects of injection would be captured to some degree by efficiency metrics.

Yet, there are some reservations that can be made regarding such an approach. First, the assumption is that the fluid is injected into the original reservoir, or at least its capture zone, for its energy / exergy content to be deductible – allowing for reasonable probability that the fluid will eventually take a second round through the utilization processes. The reservoir hydrology must therefore be known to a sufficient degree to ascertain that this is indeed the case. Second, if the fluid is injected into an environment of higher exergy state (higher temperature fluid), some exergy is bound to be destroyed through dilution. The same holds true if the fluid is injected into an environment of lower exergy state. However, the approach is supported by considering that in the absence of reinjection, the pressure difference between an open reservoir and its surroundings may lead to relatively cool fluid inflow from the sides, which may lead to a quicker depletion of the resource. Perhaps the deduction of reinjected exergy should take into account the original exergy state of the reservoir, or its capture zone, at the point of injection. From the exergy perspective, it seems ideal to inject the fluid to points where the exergy content of the reservoir fluid is the same as that of the exergy of the injected fluid in order to avoid destruction of exergy.

It is also worth noting in this context that Gíslason et al. (2005) report no increase in production capacity from reinjection to the Nesjavellir geothermal reservoir, as evaluated from numerical models, which draws into question the legitimacy of including reinjection in the efficiency equations.

With these reservations in mind, the simple, functional and conditional efficiencies can be stated on the basis of net energy / exergy extraction from a geothermal reservoir as follows in subsequent sections. Energy / exergy of injection fluid streams is calculated at the utilization process boundary, i.e. at the injection well head(s) in the case of gravity flow and just before the pump(s) in the case of forced flow.

5.5.1 Simple efficiencies based on net input

First law simple efficiency of electricity generation based on net input:

$$\eta_{1s,el,NI} = \frac{\dot{\zeta}}{\dot{Q}_{in} - \dot{Q}_r} \tag{39}$$

where $\dot{Q}_r$ = Primary energy reinjected into the geothermal reservoir.

First law simple efficiency of direct utilization based on net input:

$$\eta_{1s,DU,NI} = \frac{\dot{Q}_{DU}}{\dot{Q}_{in} - \dot{Q}_r} \tag{40}$$

Overall first law simple efficiency based on net input:

$$\eta_{1s,overall,NI} = \frac{\dot{\zeta} + \dot{Q}_{DU}}{\dot{Q}_{in} - \dot{Q}_r} = \eta_{1s,el,NI} + \eta_{1s,DU,NI} \tag{41}$$

Second law simple efficiency of electricity generation based on net input:

$$\eta_{2s,el,NI} = \frac{\dot{\zeta}}{\dot{E}_{in} - \dot{E}_r} \tag{42}$$

where $\dot{E}_r$ = Exergy reinjected into the geothermal reservoir.

Second law simple efficiency of direct utilization based on net input:

$$\eta_{s2,DU,NI} = \frac{\dot{E}_{DU}}{\dot{E}_{in} - \dot{E}_r} \tag{43}$$

Overall second law simple efficiency based on net input:

$$\eta_{2s,overall,NI} = \frac{\dot{\zeta} + \dot{E}_{DU}}{\dot{E}_{in} - \dot{E}_r} = \eta_{2s,el,NI} + \eta_{2s,DU,NI} \tag{44}$$

5.5.2 Functional efficiencies based on net input

When considering the functional efficiencies based on net input, the reinjection term must be split appropriately between the processes.

We have:

$$\dot{Q}_r = \dot{Q}_{r,el} + \dot{Q}_{r,DU} \tag{45}$$

where $\dot{Q}_{r,el}$ = Primary energy reinjected after the electricity generation process (and before the direct utilization process); and
$\dot{Q}_{r,DU}$ = Primary energy reinjected after the direct utilization process.

If water is conveyed outside of the geothermal field for direct utilization, it is unlikely that the fluid will be reinjected into the reservoir, but not unheard of, e.g. the example of Laugaland in Northern Iceland (Flóvenz et al., 2010).

The first law functional efficiency of electricity generation based on net input becomes:

$$\eta_{1f,el,NI} = \frac{\dot{\zeta}}{(\dot{Q}_{in} - \dot{Q}_{r,el}) - \dot{Q}_{m^*}} \tag{46}$$

First law functional efficiency of direct utilization based on net input:

$$\eta_{1f,DU,NI} = \frac{\dot{Q}_{DU}}{\dot{Q}_{m^*} - \dot{Q}_{r,DU}} \tag{47}$$

We have:

$$\dot{E}_r = \dot{E}_{r,el} + \dot{E}_{r,DU} \tag{48}$$

where $\dot{E}_{r,el}$ = Exergy reinjected after the electricity generation process;
$\dot{E}_{r,DU}$ = Exergy reinjected after the direct utilization process.

Second law functional efficiency of electricity generation based on net input:

$$\eta_{2f,el,NI} = \frac{\dot{\zeta}}{(\dot{E}_{in} - \dot{E}_{r,el}) - \dot{E}_{m^*}} \tag{49}$$

Second law functional efficiency of direct utilization based on net input:

$$\eta_{2f,DU,NI} = \frac{\dot{E}_{DU}}{\dot{E}_{m^*} - \dot{E}_{r,DU}} \tag{50}$$

The overall first law functional efficiency based on net input:

$$\eta_{1f,overall,NI} = \left(\frac{\dot{Q}_{in} - \dot{Q}_{r,el} - \dot{Q}_{m^*}}{\dot{Q}_{in} - \dot{Q}_r}\right)\eta_{1f,el,NI} + \left(\frac{\dot{Q}_{m^*} - \dot{Q}_{r,DU}}{\dot{Q}_{in} - \dot{Q}_r}\right)\eta_{1f,DU,NI} \tag{51}$$

Note that the combination of weights leads to unity, as it should.

The form for the second law functional efficiency based in net input is identical:

$$\eta_{2f,overall,NI} = \left(\frac{\dot{E}_{in} - \dot{E}_{r,el} - \dot{E}_{m^*}}{\dot{E}_{in} - \dot{E}_r}\right)\eta_{2f,el,NI} + \left(\frac{\dot{E}_{m^*} - \dot{E}_{r,DU}}{\dot{E}_{in} - \dot{E}_r}\right)\eta_{2f,DU,NI} \tag{52}$$

5.5.3 Conditional efficiencies based on net input

First law conditional efficiency of electricity generation based on net input:

$$\eta_{1c,el,NI} = \frac{\dot{\zeta}}{(\dot{Q}_{in} - \dot{Q}_r) - \dot{Q}_{DU}} \tag{53}$$

First law conditional efficiency of direct utilization based on net input:

$$\eta_{1c,DU,NI} = \frac{\dot{Q}_{DU}}{(\dot{Q}_{in} - \dot{Q}_r) - \dot{\zeta}} \tag{54}$$

Second law functional efficiency of electricity generation based on net input:

$$\eta_{2c,el,NI} = \frac{\dot{\zeta}}{(\dot{E}_{in} - \dot{E}_r) - \dot{E}_{DU}} \tag{55}$$

Second law conditional efficiency of direct utilization based on net input:

$$\eta_{2c,DU,NI} = \frac{\dot{E}_{DU}}{(\dot{E}_{in} - \dot{E}_r) - \dot{\zeta}} \tag{56}$$

First law overall conditional efficiency based on net input:

$$\eta_{1c,overall,NI} = \left(\frac{\dot{Q}_{in} - \dot{Q}_{r,el} - \dot{Q}_{m^*}}{\dot{Q}_{in} - \dot{Q}_r}\right)\eta_{1c,el,NI} + \left(\frac{\dot{Q}_{m^*} - \dot{Q}_{r,DU}}{\dot{Q}_{in} - \dot{Q}_r}\right)\eta_{1c,DU,NI} \tag{57}$$

Second law overall conditional efficiency based on net input:

$$\eta_{2c,overall,NI} = \left(\frac{\dot{E}_{in} - \dot{E}_{r,el} - \dot{E}_{m^*}}{\dot{E}_{in} - \dot{E}_r}\right)\eta_{2c,el,NI} + \left(\frac{\dot{E}_{m^*} - \dot{E}_{r,DU}}{\dot{E}_{in} - \dot{E}_r}\right)\eta_{2c,DU,NI} \tag{58}$$

5.6 A further examination of, and comparison between, efficiencies

The three types of efficiencies warrant some further examination. Let us first introduce some general notation.

Let α = 1 or 2, referring to the first or second law;
β = el or DU, referring to electricity generation or direct utilization; and
X_α = Q or E, referring to primary energy (α = 1) or exergy (α = 2). The subscript α precedes other subscripts introduced before.

In subsequent sections, the efficiency equations are used with the reinjection terms, with statements being valid also for the case where reinjection is regarded as discharge to the environment ($X_{\alpha,r}$ = 0).

5.6.1 Overall efficiencies within the limits of unity

Let us ensure that the three types of overall efficiencies are within the limits of unity.

In general notation, the simple overall efficiency is denoted as:

$$\eta_{\alpha s,overall,NI} = \frac{\dot{\zeta} + \dot{X}_{\alpha,DU}}{\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r}} \tag{59}$$

As the output from the processes cannot exceed the input, $\dot{\zeta} + \dot{X}_{\alpha,DU} \leq \dot{X}_{\alpha,in} - \dot{X}_{\alpha,r}$ and consequently $\eta_{\alpha s,overall,NI} \leq 1$.

Functional overall efficiency:

$$\eta_{\alpha f,overall,NI} = \left(\frac{\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r,el} - \dot{X}_{\alpha,m^*}}{\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r}}\right)\left(\frac{\dot{\zeta}}{(\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r,el}) - \dot{X}_{\alpha,m^*}}\right) + \left(\frac{\dot{X}_{\alpha,m^*} - \dot{X}_{\alpha,r,DU}}{\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r}}\right)\left(\frac{\dot{X}_{\alpha,DU}}{\dot{X}_{\alpha,m^*} - \dot{X}_{\alpha,r,DU}}\right) \tag{60}$$

One will observe that since $\dot{\zeta} + \dot{X}_{\alpha,r} + \dot{X}_{\alpha,m^*} \leq \dot{X}_{\alpha,in}$ (and consequently $\dot{\zeta} \leq \dot{X}_{\alpha,in} - \dot{X}_{\alpha,r} - \dot{X}_{\alpha,m^*} \leq \dot{X}_{\alpha,in} - \dot{X}_{\alpha,r,el} - \dot{X}_{\alpha,m^*}$ and $\dot{X}_{\alpha,DU} \leq \dot{X}_{\alpha,m^*} - \dot{X}_{\alpha,r} \leq \dot{X}_{\alpha,m^*} - \dot{X}_{\alpha,r,DU}$), and the combined weights being equal to 1, the overall efficiency will be less than or equal to 1, $\eta_{\alpha f,overall,NI} \leq 1$. This can also be simply observed by equivalence to $\eta_{\alpha s,overall,NI}$.

Conditional overall efficiency:

$$\eta_{\alpha c,overall,NI} = \left(\frac{\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r,el} - \dot{X}_{\alpha,m^*}}{\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r}}\right)\left(\frac{\dot{\zeta}}{\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r} - \dot{X}_{\alpha,DU}}\right) + \left(\frac{\dot{X}_{\alpha,m^*} - \dot{X}_{\alpha,r,DU}}{\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r}}\right)\left(\frac{\dot{X}_{\alpha,DU}}{\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r} - \dot{\zeta}}\right) \tag{61}$$

The argument is similar as for the functional efficiency: $\eta_{\alpha c,overall,NI} \leq 1$.

In the second law case, when electricity generation approaches the theoreticals limits ($\dot{\zeta} \to (\dot{E}_{in} - \dot{E}_{m^*})$) and the exergy of the direct utilization fluid is fully used ($\dot{E}_{DU} \to \dot{E}_{m^*}$) (and consequently $\dot{E}_r \to 0$), the overall efficiencies will approach 1. On the other hand, the first law efficiencies cannot approach unity unless all of the fluid is directed to direct utilization processes, as unusable anergy would inevitably be released to the environment if electricity generation were to approach its theoretical limits (see coverage in Section 3.3; also captured in Figure 5).

5.6.2 Relative positioning of the different types of efficiencies

Let us now examine the positioning of the three types of efficiencies in relation to one another.

The general forms for the three types of efficiencies for electricity generation processes only are:

Simple efficiency of electricity generation:

$$\eta_{\alpha s,el,NI} = \frac{\dot{\zeta}}{\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r}} \tag{62}$$

Functional efficiency of electricity generation:

$$\eta_{\alpha f,el,NI} = \frac{\dot{\zeta}}{(\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r,el}) - \dot{X}_{\alpha,m^*}} \tag{63}$$

Conditional efficiency of electricity generation:

$$\eta_{\alpha c,el,NI} = \frac{\dot{\zeta}}{(\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r}) - \dot{X}_{\alpha,DU}} \tag{64}$$

Looking at the denominators, it is evident that $\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r} \geq \dot{X}_{\alpha,in} - \dot{X}_{\alpha,r} - \dot{X}_{\alpha,DU}$, i.e. $denominator\ s \geq denominator\ c$.

Looking at the denominator of the functional efficiency and referring to Equations 45 and 48, one will also note that $\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r,el} - \dot{X}_{\alpha,m^*} = \dot{X}_{\alpha,in} - (\dot{X}_{\alpha,r} - \dot{X}_{\alpha,r,DU}) - \dot{X}_{\alpha,m^*} = \dot{X}_{\alpha,in} - \dot{X}_{\alpha,r} - (\dot{X}_{\alpha,m^*} - \dot{X}_{\alpha,r,DU})$. Further observing that $\dot{X}_{\alpha,m^*} - \dot{X}_{\alpha,r,DU} \geq \dot{X}_{\alpha,DU}$ leads to the conclusion that $denominator\ c \geq denominator\ f$.

With all values being positive (or zero), the following must then hold true:

$$\eta_{\alpha s,el,NI} \leq \eta_{\alpha c,el,NI} \leq \eta_{\alpha f,el,NI} \tag{65}$$

Looking at direct utilization processes, the general forms are:

Simple efficiency of direct utilization:

$$\eta_{\alpha s,DU,NI} = \frac{\dot{X}_{\alpha,DU}}{\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r}} \tag{66}$$

Functional efficiency of direct utilization:

$$\eta_{\alpha f,DU,NI} = \frac{\dot{X}_{\alpha,DU}}{\dot{X}_{\alpha,m^*} - \dot{X}_{\alpha,r,DU}} \tag{67}$$

Conditional efficiency of direct utilization:

$$\eta_{\alpha c,DU,NI} = \frac{\dot{X}_{\alpha,DU}}{\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r} - \dot{\zeta}} \tag{68}$$

It is evident that $denominator\ s \geq denomitator\ c$.

Looking at the denominator of the functional efficiency one gets $denominator\ f = \dot{X}_{\alpha,m^*} - \dot{X}_{\alpha,r,DU} = \dot{X}_{\alpha,m^*} - \dot{X}_{\alpha,r} + \dot{X}_{\alpha,r,el}$. Noting that $\dot{X}_{\alpha,m^*} \leq \dot{X}_{\alpha,in} - \dot{\zeta} - \dot{X}_{\alpha,r,el}$ one gets $denominator\ f \leq (\dot{X}_{\alpha,in} - \dot{\zeta} - \dot{X}_{\alpha,r,el}) - \dot{X}_{\alpha,r} + \dot{X}_{\alpha,r,el} = \dot{X}_{\alpha,in} - \dot{X}_{\alpha,r} - \dot{\zeta} = denominator\ c$.

Therefore:

$$\eta_{\alpha s,DU,NI} \leq \eta_{\alpha c,DU,NI} \leq \eta_{\alpha f,DU,NI} \tag{69}$$

And for any particular combination of α and β:

$$\eta_{\propto s,\beta} \leq \eta_{\alpha c,\beta} \leq \eta_{\alpha f,\beta}$$

For a given setup of processes, the weights of the functional and conditional overall efficiencies (Equations 60 and 61) will be identical for the electricity generation process on one hand and the direct utilization process on the other.

Acknowledging that:

$$C_1 \cdot \eta_{\alpha c,el} \leq C_1 \cdot \eta_{\alpha f,el} \qquad \text{and} \qquad C_2 \cdot \eta_{\alpha c,DU} \leq C_2 \cdot \eta_{\alpha f,DU}$$

where C_1 and C_2 are positive constants, with $C_1 + C_2 = 1$, the following must also be valid:

$$C_1 \cdot \eta_{\alpha c,el} + C_2 \cdot \eta_{\alpha c,DU} \leq C_1 \cdot \eta_{\alpha f,el} + C_2 \cdot \eta_{\alpha f,DU}$$

Referring to the equivalence of simple and functional overall efficiencies (Equations 59 and 60), the following relationship holds between the overall efficiencies:

$$\eta_{\alpha c,overall,NI} \leq \eta_{\alpha f,overall,NI} = \eta_{\alpha s,overall,NI} \tag{70}$$

So while the individual simple efficiencies are *lower than* or equal to the individual conditional efficiencies, the overall simple efficiencies are *higher than* or equal to the overall conditional efficiencies.

5.6.3 Border cases

In the case where the fluid is used for electricity generation only and there is no direct utilization, the direct utilization efficiencies will be irrelevant (see next section). With reference to Equations 59-61 and 62-64, and acknowledging that $\dot{X}_{\alpha,m^*} = \dot{X}_{\alpha,DU} = \dot{X}_{\alpha,r,DU} = 0$ and $\dot{X}_{\alpha,r,el} = \dot{X}_{\alpha,r}$, one will note that all three types of efficiencies are identical, i.e.

$$\eta_{\alpha s,el,NI} = \eta_{\alpha c,el,NI} = \eta_{\alpha f,el,NI} = \eta_{\alpha,overall,NI} = \frac{\dot{\zeta}}{\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r}}$$

Going back to the border cases presented in connection with Figure 5 (Section 3.3), this scenario corresponds to the second case, where the Carnot machine is used to do work only. As the real world case approaches the ideal case, $\eta_{2,el} \rightarrow \omega_2 = 1$ and $\eta_{1,el} \rightarrow \omega_1 < 1$, as $\alpha > 0$.

When there is no electricity generation and all of the fluid is used for direct applications, the electricity generation efficiencies will be irrelevant. One will note that in this case $\dot{X}_{\alpha,m^*} = \dot{X}_{\alpha,in}$; $\dot{X}_{\alpha,r,DU} = \dot{X}_{\alpha,r}$ and $\dot{\zeta} = \dot{X}_{\alpha,r,el} = 0$, and all three types of efficiencies are identical:

$$\eta_{\alpha s,DU,NI} = \eta_{\alpha c,DU,NI} = \eta_{\alpha f,DU,NI} = \eta_{\alpha,overall,NI} = \frac{\dot{X}_{\alpha,DU}}{\dot{X}_{\alpha,in} - \dot{X}_{\alpha,r}}$$

This scenario corresponds to the first case presented in connection with Figure 5, where all of the fluid is used for direct utilization without losses. As the real world case approaches that of the ideal case, $\eta_{\alpha,DU} \rightarrow 1$, as $\pi = \tau = 1$, and $\alpha = 0$.

5.6.4 Efficiency calculations for non-existent processes

If there is either no electricity generation process or no direct utilization process it should be understood that the efficiencies for the non-existent process are irrelevant. If calculation of those efficiencies is nevertheless carried out, it will mostly render zeros, with the exception of cases where the denominator is zero.

5.7 Energy and exergy accounting

The preceding equations assume steady conditions and are therefore simplifications. Also, the discussion so far has mostly assumed a single fluid stream, in and out, which is far from the reality of most utilization processes.

It is, however, fairly straightforward in theory to use the equations for time-varying conditions and/or multiple fluid streams, if sufficient data are available. In that case, it should be possible to make estimates for instantaneous conditions, or calculate average efficiencies over a specific period, e.g. a year. Yet, it must be acknowledged that accurate energy and exergy accounting in real world scenarios can be quite complex and tedious.

Ambient temperature and pressure change with the seasons and weather and so does the primary energy and exergy content of the fluid if these conditions dictate the reference state. Furthermore, flow and thermodynamic properties of geothermal fluids may change with time at the wellhead, leading to additional time dependent changes in energy and exergy content of the fluid. In addition, there are usually multiple streams at play, whose contributions (which may vary over time) must be combined. For example, instantaneous exergy flow from N wells into a utilization process control volume can be evaluated at the wellheads as:

$$\frac{dE_{in}}{dt} = \sum_{i=1}^{N} \dot{E}(t)_{wellhead,i} \tag{71}$$

and the annual generation of exergy can then be calculated as:

$$E_{in,annualtotal} = \int_0^{year} \sum_{i=1}^{N} \dot{E}(t)_{wellhead,i}\, dt = \sum_{i=1}^{N} \int_0^{year} \dot{E}(t)_{wellhead,i} dt \tag{72}$$

Other exergy flow streams and electricity generation can be summed up in a similar way over the specific period of interest and inserted into the efficiency equations in place of steady exergy flows. Similar holds true for energy.

The accounting of exergy in direct utilization processes (e.g. as may be supplied by district heating networks) can be quite complex. The evaluation of $\dot{E}_{DU}$ requires careful accounting of temperature (and possibly other thermodynamic variables) as the fluid makes its way through the different utilization processes, taking note of losses along the way. The utilization itself can be simple or complex, with the fluid directed to various utilization processes that may be parallel and/or serial (cascade use).

As noted in Appendix II (Section 2), direct utilization exergetic efficiency is sensitive to the temperature interval over which the exergy is extracted. Thus, while almost the same primary energy would be extracted over any 40°C interval within [80, 0]°C, the extracted exergy decreases as the starting temperature is lowered. For example, cooling water from 80°C to 40°C at 1 atm will yield Δh = ~167.4 kJ/kg and Δe = ~27.5 kJ/kg, while cooling from 50°C to 10°C will yield Δh = ~167.3 kJ/kg and Δe = ~13.6 kJ/kg. The exergy extraction in direct utilization processes is thus sensitive to temperature (and pressure) losses from the delivery points to transmission pipelines (m*), to the end user. The same is true of losses between different direct utilization processes. In other words, extracting energy / exergy from water over, say, the intervals [80, 40]°C, [50, 10]°C, and [80, 60]°C + [30, 10]°C (at constant pressure, greater than saturation pressure) will result in roughly the same total primary energy, while the total exergy will differ and this will affect the thermal and exergetic efficiencies differently.

5.8 Application examples

Equations 19-58 as presented in the preceding sections are used to calculate process weights and efficiencies for 5 different Icelandic geothermal power plants, under 4 different scenarios in Appendix II, using information available to the author – mostly from the published literature.

The 5 power plants are Krafla (electricity generation only), Bjarnarflag (CHP), Nesjavellir (CHP), Hellisheidi (CHP), and Reykjanes (electricity generation only). The Svartsengi CHP plant is not included due to lack of information.

The 4 scenarios are:

i) Gross input and gross generation, assuming no exergy destruction from wellhead to separator(s);
ii) Net input (taking reinjection into account) and gross generation, assuming no exergy destruction from wellheads to separator(s);
iii) Gross input and net generation (assuming 5% internal use of produced electricity), assuming 5% exergy destruction from wellheads to separators(s); and
iv) Net input and net generation, assuming 5% exergy destruction from wellheads to separator(s).

The outcomes are presented in tables in Appendix II. Tables 10-14 are a subset of those, showing the outcomes for the 5 power plants under Scenario iii as presented above.

TABLE 10: Simple, conditional and functional efficiencies for Krafla geothermal power plant under Scenario iii. Based on information obtained from Landsvirkjun (2016a) and Hauksson (2015).

	$W_{1,el}$[1] (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	11.6	1	0	11.6	1	37.2	1	0	37.2
Conditional	1	11.6	0	0	11.6	1	37.2	0	0	37.2
Functional	1	11.6	0	-[2]	-	1	37.2	0	-	-

1: Weight; 2: Division by zero. It should be understood that the direct use (DU) efficiencies are irrelevant when none of the fluid is directed towards direct use applications.

TABLE 11: Simple, conditional and functional efficiencies for Bjarnarflag geothermal CHP plant under Scenario iii. Based on information obtained from Landsvirkjun (2016b) and Hauksson (2015).

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	2.5	1	19.4	21.8	1	7.8	1	16.4	24.2
Conditional	0.58	3.0	0.42	19.8	10.0	0.70	9.3	0.30	17.8	11.9
Functional	0.58	4.2	0.42	46.4	21.8	0.70	11.2	0.30	54.1	24.2

TABLE 12: Simple, conditional and functional efficiencies for Nesjavellir geothermal CHP plant under Scenario iii after the third construction stage (60 MW_e) as reported by Ballzus et al. (2000).

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Summer										
Simple	1	11.8	1	24.6	36.4	1	36.1	1	11.4	47.5
Conditional	0.52	15.7	0.48	27.9	21.5	0.83	40.7	0.17	17.8	36.7
Functional	0.52	22.7	0.48	51.3	36.4	0.83	43.6	0.17	65.7	47.5
Winter										
Simple	1	10.3	1	38.3	48.6	1	31.5	1	17.7	49.3
Conditional	0.25	16.7	0.75	42.7	36.2	0.73	38.3	0.27	25.9	35.0
Functional	0.25	40.9	0.75	51.3	48.6	0.73	43.2	0.27	65.7	49.3

TABLE 13: Simple, conditional and functional efficiencies for Hellisheidi geothermal CHP plant under Scenario iii

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Minimum separator pressure (8 bar); $\dot{\zeta}_{gross}$ = 283.6 MW										
Simple	1	14.1	1	5.7	19.8	1	43.7	1	2.7	46.4
Conditional	0.88	15.0	0.12	6.6	14.0	0.95	45.0	0.05	4.8	43.0
Functional	0.88	16.1	0.12	47.0	19.8	0.95	45.9	0.05	56.0	46.4
Maximum separator pressure (10 bar); $\dot{\zeta}_{gross}$ = 303.6 MW										
Simple	1	15.3	1	5.8	21.1	1	46.3	1	2.6	48.9
Conditional	0.88	16.2	0.12	6.8	15.1	0.95	47.5	0.05	4.9	45.5
Functional	0.88	17.4	0.12	47.0	21.1	0.95	48.6	0.05	56.0	48.9

TABLE 14: Simple, conditional and functional efficiencies for Reykjanes geothermal power plant under Scenario iii. Based on information obtained from Ravazdezh (2015).

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	11.2	1	0	11.2	1	34.5	1	0	34.5
Conditional	1	11.2	0	0	11.2	1	34.5	0	0	34.5
Functional	1	11.2	0	-	-	1	34.5	0	-	-

All of these values are based on reference conditions of (5°C, 1 atm) except for the Reykjanes power plant which is referenced to (8.5°C, 1 atm) (ocean temperature – see appendices). The 5% internal power plant consumption is a rule of thumb reported by fellow energy experts, while the 5% destruction of exergy from wellhead(s) to separator(s) is arbitrary. In the latter case, the author lacks information on wellhead conditions to present a value grounded in real conditions. As some destruction of exergy is bound to take place from the wellhead(s) to the separator(s), the selection of *some* value (hopefully conservative) was considered better than *none*, if only as a reminder of the tendency of natural processes (including those designed by humans) to consume exergy. Consequently, the results are rough.

The tables are based mostly on available process diagrams presenting ideal design conditions, which may differ from actual operating conditions. In the case of Krafla and Bjarnarflag, the calculations are based on conditions as measured over a short period in a particular year and may thus differ slightly from identical calculations made for different years. The process diagram used for Nesjavellir CHP plant was valid after the commissioning of the third construction stage of the plant in late 1998 when electricity production stood at 60 MW_e (Ballzus et al., 2000). The values in Table 12 do therefore not reflect the current configuration of the plant, which was later expanded to 120 MW_e. The values are still presented for demonstration of calculations. Table 12 presents two cases: Summer and winter. Electricity production is constant, while the production of hot water for the Reykjavík district heating system is significantly increased during winter. Table 13 likewise presents two cases for the Hellisheidi CHP plant: One for minimum separator pressure of 8 bar and the other for maximum separator pressure of 10 bar. Electricity production differs between the two cases, while the production of hot water for the Reykjavík district heating system is unchanged. Direct utilization at the Reykjanes power plant has increased in recent years with the establishment of a fish farm that uses discharge cooling water (sea water) from the plant's condensers for its farming processes. However, as pertinent information was not found in the published literature, the plant is treated as an electricity-generation-only plant in accordance with the available process diagram. It should therefore be clear to the reader that the values presented in these table are not to be taken as ultimate values describing the plants in their current states. They are inexact and a more thorough analysis based on real operating data, non-steady conditions (Equations 71-72 and similar), and taking recent additional processes and modifications of the power plants into account, would inevitably change some of the values.

When looking at the first law simple efficiencies of electricity generation, the Krafla, Nesjavellir (arithmetic average between seasons: 11.1%) and Reykjanes power plants show similar values of between 11-12%, while the small back-pressure Bjarnarflag power plant is an outlier on the low side and the Hellisheidi power plant shows significantly higher values (arithmetic average between minimum and maximum separator pressure states: 14.7%). These values are compared to the electricity utilization ratios reported by Haraldsson and Ketilsson (2010b) in Table 15.

TABLE 15: Simple first law efficiencies of (net) electricity generation based on available process diagrams vs. electricity utilization ratio in 2008

	Based on process diagrams			**Haraldsson and Ketilsson (2010b)**			
Power plant	**Year[1]**	**Installed capacity**	$\boldsymbol{\eta_{1s,el}}$ **(%)**	**Year**	**Installed capacity**	$\boldsymbol{\psi}$[2] **(%)**	$\boldsymbol{\psi_{adj}}$[3] **(%)**
Krafla	2014	60 MW_e	11.6	2008	60 MW_e	11.4	11.1
Bjarnarflag	2014	3 MW_e	2.5	2008	3 MW_e	1.7	1.7
Nesjavellir	1998	60 MW_e; 200 MW_{th}[4]	11.1[5]	2008	120 MW_e; 300 MW_{th}[4]	15.3	14.9
Hellisheidi	2012	303 MW_e; 133 MW_{th}[4]	14.7[6]	2008	213 MW_e[7]	12.1	11.8
Svartsengi				2008	76 MW_e	10.6	10.3
Reykjanes	2015	100 MW_e	11.2	2008	100 MW_e	11.9	11.7

1: Year in which the process diagram used for calculations was valid; 2: Electricity utilization ratio at (15°C, 1 bar); 3: Electricity utilization ratio adjusted to reference conditions of (5°C, 1 atm) – Leading to a reduction (by a factor of 0.97-0.98); 4: Reported thermal capacity – reference temperature unclear; 5: Arithmetic average between summer and winter conditions; 6: Arithmetic average between minimum and maximum separator pressure; 7: As of end of year 2008 (90 MW_e were installed in the last trimester of the year) (Hallgrímsdóttir et al., 2012) – No thermal capacity yet.

The electricity utilization ratio reported by Haraldsson and Ketilsson (2010b) for the Icelandic geothermal power plants in 2008 has been adjusted in Table 15 to reflect reference conditions as stated rather than (15°C, 1 bar), leading to a slight reduction from their reported values. For reasons stated in Section 4.3, the electricity utilization ratio should present a lower boundary on the simple thermal efficiency of electricity generation. The calculated efficiencies for Krafla and Bjarnarflag agree with that notion, both being higher than the electricity utilization ratio. The adjusted electricity utilization ratio for Nesjavellir in 2008 is significantly higher than the calculated simple thermal efficiency based on the process diagram valid 10 years earlier. This indicates that the efficiency of electricity generation was improved with further enlargement of the plant after 1998. The higher simple thermal efficiency of electricity generation calculated for Hellisheidi based on the process diagram valid for the plant's current configuration, compared to the electricity utilization ratio reported for 2008, is also indicative that the plant reached higher electrical efficiency as it was developed. It should be noted, however, that the power plant has not been running at full capacity in recent years due to reservoir drawdown and lack of steam, but it is unclear what this deviation from design conditions has had on efficiency. The simple thermal efficiency of electricity generation for Reykjanes as calculated from the available process diagram from 2015 is slightly lower than the electricity utilization ratio for 2008, which may represent changed plant conditions, but the difference is small.

These comparisons indicate that power plant efficiencies are not static. Obviously they tend to change as the plants are developed and changes in reservoir and environmental conditions can have an effect. The same is true for direct utilization processes. The efficiencies reported in Tables 10-14 must therefore be viewed with this in mind and only be taken as representative for the plants for the particular years indicated, and with the reservation that calculations are based on process diagrams.

The reader is referred to Appendix II for comparisons and comments on calculation outcomes (weights, efficiencies and scenarios) for each of the 5 power plants, but comparisons *between* power plants have limited value due to the different times for which data were available.

6. EFFICIENCIES AS DYNAMIC METRICS – EFFICIENCY IMPROVEMENTS

The electricity utilization ratio (ψ) of Icelandic geothermal power plants is shown in Figure 8 up to the year 2008. The figure shows how the average ratio (estimated on an annual basis) has edged upwards through the years.

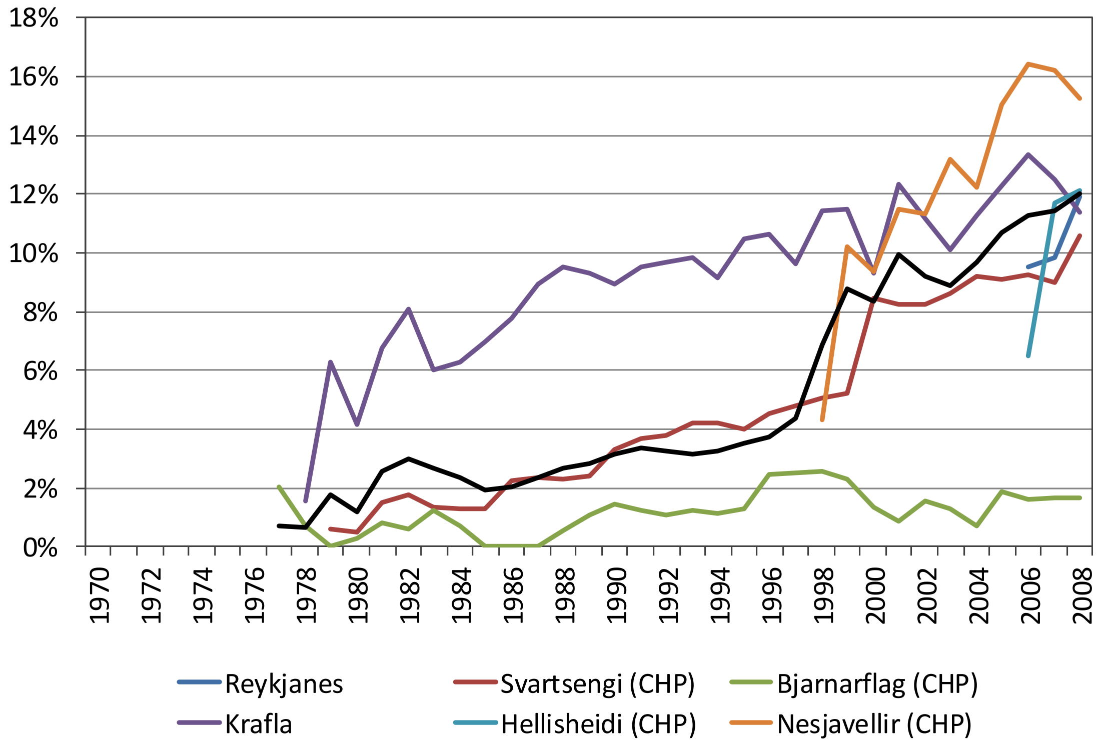

FIGURE 8: Electricity utilization ratio (ψ) of Icelandic geothermal power plants up to the year 2008 based on reported annual electricity generation, and the mass flow and enthalpy of contributing wells. Note that primary energy (heat input) is referenced to (15°C, 1 bar). Although four power plants are labeled as CHP plants, supplying district heating systems, there can be some local direct utilization associated with the other plants, e.g. fish farming at Reykjanes. The black plotline denotes the average ratio. Modified from (Haraldsson and Ketilsson, 2010b).

A few comments on this:

1. The ratio is based on produced fluids in geothermal fields supplying geothermal power plants, including combined heat and power plants. It is blind to whether the fluid is diverted to a turbine, directly to the production of heat, or discarded to the environment. Although some of the early conversion processes for electricity generation were relatively inefficient (e.g. backpressure turbine at Bjarnarflag), the low ratios seen in the beginning are in large part attributable to a considerable part of the production fluid being used directly for heating. The ratio for Krafla (electricity generation only) is for example considerably higher than the ratio for Svartsengi in the beginning, where the focus was on supplying heat to the local district heating system (leaving aside differences in enthalpy between the two fields). However, the ratio rose with increased electricity generation in Svartsengi, with demand for hot water still strong. Hot water production for the Reykjavík area district heating system was the primary goal with the Nesjavellir power plant in the beginning, with electricity generation introduced in steps later. Over time, the overall fraction of fluid used for electricity generation in Icelandic geothermal power plants has increased, and heat for district heating systems in geothermal CHP plants is presently first and foremost supplied by discharge fluids from electricity generation processes.

2. The countrywide average enthalpy of production fluids for electricity generation has increased over the years. The average was 1150 kJ/kg in 1970 (electricity generation having started in Bjarnarflag in 1969), 1293 kJ/kg in 1980 (Krafla, Svartsengi and Bjarnarflag), 1509 kJ/kg in 1990 (Krafla, Svartsengi and Bjarnarflag), and 1643 kJ/kg in 2000 (Krafla, Nesjavellir, Svartsengi, and Bjarnarflag). As seen in previous sections, increased enthalpy should lead to higher efficiencies in line with the higher proportional exergy content of the fluid ($\dot{E}_{in}/\dot{Q}_{in}$).

These improvements in electricity utilization ratio have been brought about by a desire to get the most out of the fluid, resulting in improved management over time, and the successful targeting of high quality resources through concerted geoscientific exploration efforts. Technological advancement has also no doubt contributed to some extent.

Even though Figure 8 does not show efficiencies as defined in this paper, it does imply that those efficiencies are dynamic and have edged upward through the years as is presently encouraged by many world bodies as noted in Section 1. Improvements in efficiency have direct implications for the environment and the planet.

7. EFFICIENCY AND THE ENVIRONMENT

As noted in Section 1, many acclaimed world bodies, such as the United Nations (through the Sustainable Development Goals agenda), the Intergovernmental Panel on Climate Change, the World Energy Council, the International Energy Agency and many more, concern themselves with energy efficiency and encourage its improvement. In fact, one of the targets of SDG 7 is to double the global rate of improvements in energy efficiency by 2030. Such improvements are posed to reduce the strain on resources compared to a business-as-usual scenario, allow a greater number of people to enjoy the comforts of – and empowerment associated with – electricity, reduce pollution and greenhouse gas emissions, and more. Improvements in energy efficiency are a matter of environmental concern.

In the specific context of this paper, particular emphasis must be placed on the importance of using geothermal fluids and the energy / exergy they contain in as efficient a manner as possible and to further push efficiencies upward – albeit within the constraints set by the laws of Nature, economic, technological and other factors. In such an endeavor, the Líndal diagram can be kept in mind (Figure 1).

8. CONCLUSION

The first law efficiency of geothermal electricity generation processes is low compared to most other thermal plants (i.e. fossil fuel fired and nuclear power plants), which use different energy sources with a higher exergy to energy ratio than geothermal power plants. Second law efficiencies of geothermal electricity generation processes, however, compare well with those of other thermal plants and are significantly superior to fossil fuel fired power plants on a carbon emissions parity basis. Geothermal energy should therefore be viewed as an energy source that is compatible with other energy sources and as an important part of the portfolio of environmentally acceptable energy sources.

Despite favorable comparison of second law efficiencies of geothermal electricity generation processes to other types of thermal electricity generation processes, there is still room for an overall improvement in efficiency. It may be possible to increase efficiency of electricity generation through multiple flashing of fluid, using turbines with different inlet pressures, and adding bottoming plants (e.g. binary cycles) to existing power plants, in an attempt to bring the processes a little closer to those of ideal Carnot machines. Although the possibilities for extracting electricity from the fluids may be limited – if not by Nature itself then by technology, economics and other constraints of the real world – it is important to make good use of any remaining heat energy for applications that can be of benefit to society. The Líndal diagram (Figure 1) shows various potential applications. If direct application possibilities are limited, for example due to a remote location of a power plant, it is at the very least ideal to reinject the fluid with the goal of extending the lifetime of the reservoir, hopefully for the benefit of later generations.

This paper has covered the concepts of energy and exergy as relevant in geothermal utilization, both in the context of idealized Carnot machines and real world processes. Three efficiency metrics, dubbed simple, functional and conditional efficiencies have been presented. Furthermore, efficiencies have been presented for various power plants, as reported in the literature and as estimated by the author.

The three efficiency metrics can be applied to electricity generation processes, direct utilization processes, or a combination of those, with each having their advantages and drawbacks. Examples are provided for electricity-generation-only processes as well as combined processes, but none are given for direct-utilization-only processes, which are relevant in many places. However, this application of the efficiency metrics should be straightforward.

In summary, the main objectives of the paper have been as follows:

- To introduce and discuss limitations on converting heat energy of geothermal fluids to work (electricity);
- To introduce and discuss the concept of exergy in the context of geothermal utilization;
- To introduce and discuss first and second law efficiencies;
- To compare efficiencies of geothermal electricity generation processes to those of fossil fuel fired and nuclear power plants, both in terms of first law efficiencies and second law efficiencies;
- To introduce and discuss different efficiency metrics, each with advantages and drawbacks;
- To show examples of the application of the presented efficiency metrics and use the outcome to compare against efficiencies reported in the literature; and
- To advocate the importance of making efficient use of geothermal energy resources.

While improvements can be made in the efficiency of energy conversion processes (as noted in Section 6), as well as in transmission and delivery to consumers, the overall efficiency of utilization based on final output is also up to the end user. In this paper, the efficiency of electricity generation processes has focused on the conversion of heat energy of geothermal fluids to electricity without regard for the final use of the electricity. If one looks at the whole process of extracting exergy from a geothermal fluid and transmitting it to an end user, for example to light a living room or power a computer, the overall efficiency can, for example, be defined in terms of luminous power or computer hours per unit of primary energy or exergy. As money, electricity is not of much use in and of itself, but its value lies in what can be done with it. Any complete efficiency metrics should thus probably not look only at conversion processes, but also at end use. Thus, improvements in the electricity usage of end use contraptions and equipment would be factored in. Improvements in light bulbs (e.g. replacement of incandescent bulbs with LEDs) and more efficient computer processors matter, just as well as improvements in conversion processes (e.g. introducing a greater number of flashing steps or adding a bottoming plant). When looking at heat usage, the insulation of buildings can do wonders to improve end use efficiency.

While improvements in the efficiency of end use processes (e.g. conversion of electricity to light) are important, the behavior of the consumer will also always play a role. The consumer thus has the power to conserve resources through rational habits. This is important, as *large own energy use of the energy sector result[s] in high indirect multiplication effects of energy savings from end users* (Bruckner et al., 2014).

Increasing the rate of improvements in energy efficiency is thus dependent on and influenced by developers, society as a whole and the choices of individual consumers. While environmental consciousness can play an important role in this regard, from the scale of the individual to the scale of society, economic incentives to conserve energy are also important.

The International Energy Agency claims that *an entire 70% of the world's energy use takes place outside of any efficiency performance requirements* (OECD/IEA, 2016). The fact that the average efficiencies of public electricity-only and CHP fossil fuel power plants over the period 2001-2005, as reported in Table 6, are higher in OECD countries than in non-OECD countries, indicates that there is room for improvement in the latter group of countries, including developing countries and emerging economies. And the bar can still be set higher in the former group of countries.

Improvements in energy efficiency can in some cases be made in leaps and in other cases in small steps, but it is unlikely that possibilities for further improvements will be exhausted in the quest to approach the ideal.

9. RECOMMENDATIONS

The evaluations in the appendices have been referred to as back-of-the-envelope analysis, as there is some inherent coarseness to them. At the heart of this coarseness is lack of information.

In most cases the desired information was simply not available in the published literature to the best knowledge of the author (e.g. time series of thermodynamic parameters at wellheads; operational data), but in some cases values were simply assumed as time did not allow for extensive (exhaustive) research on particular parameters (e.g. average delivery and return temperatures in district heating systems (not to mention a more detailed study of district heating system utilization); discarding temperature in the Mývatn Nature Baths etc.). Some of those parameters may well exist in the literature unbeknownst to the author. However, as calculations on the efficiency of direct utilization processes were first and foremost carried out as first approximations – as updates are needed based on recent data – this is considered warranted.

9.1 More information!

First and second law (simple) efficiencies of electricity generation processes of geothermal and other types of thermal power plants are reported on in the literature. Information is relatively scarce, however, especially on second law efficiencies, although the frequency of new articles appearing seems to have increased in recent years. The author calls for more of the same. The available articles tend to focus on electricity generation and little attention is placed on the utilization of heat that must be left over from the electricity generation. Reporting on this would be informing and is in fact essential to assess the overall energy efficiencies of the power plants.

The author has applied the formualae presented in the paper to 5 Icelandic power plants in an attempt to estimate the efficiencies of their utilization processes. Unfortunately published data are again scarce in this realm and therefore the author has had to rely on process diagrams from different periods that are often based on design conditions. A more elaborate study would need to be based on operating conditions, whether it be based on instantaneous conditions or conditions over specific periods, e.g. a year. A comparison of performance between seasons can be informing due to changes in demand for energy (heating), changes in environmental reference states etc. Primary energy and exergy should be evaluated at wellheads rather than separators. Again, more information is needed in order to carry out such detailed assessments.

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REFERENCES

Baldvinsson, Í., Thórisdóttir, Th.H., and Ketilsson, J., 2010: *Gas emissions of geothermal power plants in Iceland 1979-2009* (in Icelandic). Orkustofnun – National Energy Authority, Reykjavík, Iceland, report OS-2011/02, 31 pp.

Ballzus, C., Frímannsson, H., Gunnarsson, G.I., and Hrólfsson, I., 2000: The geothermal power plant at Nesjavellir, Iceland. *Proceedings of the World Geothermal Congress 2000,* Kyushu – Tohoku, Japan, 3109-3114.

Bertani, R. and Thain, I., 2002: Geothermal power generating plant CO_2 emission survey. *IGA News Quarterly, 49*, 1-3.

Bilgen, S. and Kaygusuz, K., 2008: The calculation of the chemical exergies of coal-based fuels by using the higher heating values. *Applied Energy, 85,* 776-785.

Bloomfield, K.K., Moore, J.N., and Neilson, R.M., 2003: Geothermal energy reduces greenhouse gases. *Geothermal Resource Council Bulletin, 32,* 77-79.

Bloomster, C.H. and Fassbender, L.L., 1980: The role of second law analysis in geothermal economics. *Energy, 5,* 839-851.

Bödvarsson, G. and Eggers, D.E., 1972: The exergy of thermal water. *Geothermics, 1,* 93-95.

Bruckner, T., Bashmakov, I.A., Mulugetta, Y., Chum, H., de la Vega Navarro, A., Edmonds, J., Faaij, A., Fungtammasan, B., Garg, A., Hertwich, E., Honnery, D., Infield, D., Kainuma, M., Khennas, S., Kim, S., Nimir, H.B., Riahi, K., Strachan, N., Wiser, R., and Zhang, X, 2014: Energy systems. In: Edenhofer, O., Pichs Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., and Minx, J.C. (editors), *Climate change 2014: Mitigation of climate change.* Intergovernmental Panel on Climate Change, Contribution of Working Group III to the Fifth Assessment Report, 1454 pp.

Cerci, Y, 2003: Performance evaluation of a single-flash geothermal power plant in Denizli, Turkey. *Energy*, *28*, 27-35.

Coskun, C., Oktay, Z., and Dincer, I., 2011: Performance evaluations of a geothermal power plant. *Applied Thermal Engineering, 31*, 4074-4082.

DiPippo, 1987: Exergy analysis of combined electricity and direct-heat geothermal flash-steam plants. *Geothermal Resources Council Transactions*, *11*, 411-416.

DiPippo, R., 2004: Second law assessment of binary plants generating power from low-temperature geothermal fluids. *Geothermics, 33*, 565-586.

DiPippo, R., 2008: *Geothermal power plants: Principles, applications, case studies and environmental impact* (2nd edition). Elsevier, Oxford, United Kingdom and Burlington, Massachusetts, United States, 494 pp.

DiPippo, R. and Moya, P., 2013: Las Pailas geothermal binary power plant, Rincón de la Vieja, Costa Rica: Performance assessment of plant and alternatives. *Geothermics, 48*, 1-15.

Dunbar, W.R., Moody, S.D., and Lior, N., 1995: Exergy analysis of an operating boiling-water-reactor nuclear power station. *Energy Conversion and Management*, *36-3*, 149-159.

Durmayaz, A. and Yavuz, H., 2001: Exergy analysis of a pressurized-water reactor nuclear-power plant. *Applied Energy, 69*, 39-57.

Erdem, H.H., Akkaya, A.V., Cetin, B., Dagdas, A., Sevilgen, S.H., Sahin, B., Teke, I., Gungor, C., and Atas, S., 2009: Comparative energetic and exergetic performance analyses for coal-fired thermal power plants in Turkey. *International Journal of Thermal Sciences*, 48, 2179-2186.

Flóvenz, Ó.G., Árnason, F., Gautason, B., Axelsson, G., Egilson, Th., Steindórsson, S.H., and Gunnarsson, H.S., 2010: Geothermal district heating in Eyjafjördur, N-Iceland: Eighty years of problems, solutions and success. *Proceedings of the World Geothermal Congress 2010*, Bali, Indonesia, 8 pp.

Ganjehsarabi, H., Gungor, A., and Dincer, I., 2012: Exergetic performance analysis of Dora II geothermal power plant in Turkey. *Energy, 46*, 101-108.

Georgsson, L.S., 2010: Geothermal activity in Borgarfjördur, W-Iceland, and the exploration, development and utilization of the Varmaland/Laugaland geothermal field. *Proceedings of the World Geothermal Congress 2010*, Bali, Indonesia, 10 pp.

Georgsson, L.S. and Haraldsson, I.G., 2016: The role of geothermal energy and capacity building in achieving the UN Sustainable Development Goals in Latin America and the Caribbean. *Papers presented at "SDG Short Course I on Sustainability and Environmental Management of Geothermal Resource Utilization and the Role of Geothermal in Combating Climate Change", organized by UNU-GTP and LaGeo*, Santa Tecla, El Salvador, 20 pp.

Gíslason, G., Ívarsson, G., Gunnlaugsson, E., Hjartarson, A., Björnsson, G., and Steingrímsson, B., 2005: Production monitoring as a tool for field development – A case history from the Nesjavellir field, Iceland. *Proceedings of the World Geothermal Congress 2005*, Antalya, Turkey, 9 pp.

Gunnarsson, G., 2011: Mastering reinjection in the Hellisheidi field, SW-Iceland: A story of successes and failures. *Proceedings of the Thirty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, California, United States, 8 pp.

Hallgrímsdóttir, E., Ballzus, C., and Hrólfsson, I., 2012: The geothermal power plant at Hellisheidi, Iceland. *Geothermal Resources Council Transactions, 36*, 1067-1072.

Haraldsson, I.G., 2011: Environmental monitoring of geothermal power plants in operation. *Papers presented at "Short Course III on Geothermal Drilling, Resource Development and Power Plants", organized by UNU-GTP and LaGeo,* Santa Tecla, El Salvador, 25 pp.

Haraldsson, I.G., 2012: Geothermal project funding through the Clean Development Mechanism. *Presented at "Short Course IV on Geothermal Development and Geothermal Wells", organized by UNU-GTP and LaGeo*, Santa Tecla, El Salvador, 31 pp.

Haraldsson, I.G. and Ketilsson, J., 2010a: *The utilization of geothermal energy for electricity generation and direct uses up to 2009* (in Icelandic). Orkustofnun – National Energy Authority, Reykjavík, Iceland, report OS-2010/02, 62 pp.

Haraldsson, I.G. and Ketilsson, J., 2010b: *Primary energy use of geothermal power plants and district heating systems in Iceland up to 2009* (in Icelandic). Orkustofnun – National Energy Authority, Reykjavík, Iceland, report OS-2010/03, 43 pp.

Haraldsson, I.G. and Lloret Cordero, A., 2014: Geothermal baths, swimming pools and spas: Examples from Ecuador and Iceland. *Papers presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo*, Santa Tecla, El Salvador, 14 pp.

Hauksson, T., 2015: *Well output and chemical content of geothermal fluids in wells and production pipelines in 2014* (in Icelandic). Landsvirkjun – National Power Company of Iceland, Reykjavík, Iceland, report LV-2015-081, 91 pp.

HS Orka, 2016: *Power plants*. HS Orka, Grindavík, Iceland. Website: *https://www.hsorka.is/en/power -plants/*

Jalilinasrabady, S., Itoi, R., Gotoh, H., and Kamenosono, H., 2010: Energy and exergy analysis of Takigami geothermal power plant, Oita, Japan. *Geothermal Resources Council Transactions, 34*, 1057-1062.

Kanoglu, M., 2002: Exergy analysis of a dual-level binary geothermal power plant. *Geothermics, 31*, 709-724.

Kanoglu, M. and Bolatturk, A., 2008: Performance and parametric investigation of a binary geothermal power plant by exergy. *Renewable Energy, 33*, 2366-2374.

Keller, T., 2016: *Here's why the latest Guinness world record will keep France lit up long after soccer fans leave.* General Electric, GE Reports. Website: *https://www.ge.com/reports/bouchain/*

Kępińska, B., 2003: Geothermal energy in human history, culture, and practices – selected highlights. In: Kępińska, B., *Geothermal resources and utilization in Poland and Europe*. United Nations University Geothermal Training Programme, Reykjavík, Iceland, 107 pp.

Kinyanjui, S., 2013: Direct use of geothermal energy in Menengai, Kenya: Proposed geothermal spa and crop drying. Report 9 in: *Geothermal training in Iceland 2013*. United Nations University Geothermal Training Programme, Reykjavík, Iceland, 33 pp.

Kwambai, C.B., 2010: Exergy analysis of Olkaria I power plant, Kenya. *Proceedings World Geothermal Congress 2010*, Bali, Indonesia, 12 pp.

Landsvirkjun, 2016a: *Kröflustöd power station*. Landsvirkjun – National Power Company of Iceland, Reykjavik, Iceland. Website: *https://www.landsvirkjun.com/Company/PowerStations/KraflaPowerStation/*

Landsvirkjun, 2016b: *Bjarnarflag power station*. Landsvirkjun – National Power Company of Iceland, Reykjavik, Iceland. Website: *https://www.landsvirkjun.com/Company/PowerStations/BjarnarflagPowerStation*

Lund, J.W. and Boyd, T.L., 2015: Direct utilization of geothermal energy 2015 worldwide review. *Proceedings of the World Geothermal Congress 2015*, Melbourne, Australia, 31 pp.

Merida, L., 2000: Curing blocks and drying fruit in Guatemala. *Geothermal Resources Council Transactions*, 24, 43-47.

Mirzaei Zarandi, S.S.M. 2007: Waste water disposal at the Nesjavellir geothermal power plant, apparent problems and possible solutions. Report 13 in: *Geothermal training in Iceland 2007*. United Nations University Geothermal Training Programme, Reykjavík, Iceland, 277-301.

Mirzaei Zarandi, S.S.M. and Ívarsson, G., 2010: *A review on waste water disposal at the Nesjavellir geothermal power plant*. Proceedings of the World Geothermal Congress 2010, Bali, Indonesia, 11 pp.

Moon, H. and Zarrouk, S.J., 2012: Efficiency of geothermal power plants: A worldwide review. *Proceedings of the New Zealand Geothermal Workshop 2012*, Auckland, New Zealand, 13 pp.

Orkustofnun, 2016: *Installed electrical capacity and electricity generation of geothermal power plants*. Orkustofnun – National Energy Authority, Reykjavík, Iceland, information sheet OS-2016-T003-01, 3 pp.

Ragnarsson, Á. and Hrólfsson, I., 1998: Akranes and Borgarfjördur district heating system. *Geo-Heat Center Quarterly Bulletin, 19-4*, 10-13.

Ravazdezh, F., 2015: A study on operation and maintenance of flash steam geothermal power plants: Reykjanes power plant. Report 31 in: *Geothermal training in Iceland 2015*. United Nations University Geothermal Training Programme, Reykjavík, Iceland, 689-726.

Rosen, M.A., 2001: Energy- and exergy-based comparison of coal-fired and nuclear steam power plants. *International Journal of Exergy*, 3, 180-192.

Self, S.J., Reddy, B.V., and Rosen, M.A., 2015: Energy and exergy analysis of geothermal power plants with and without re-injection. *Research Journal of Environmental Sciences, 9*, 74-87.

Sukaryadi, D. and Dictus, B., 2014: Utilization of heat energy from geothermal hot spring water for agriculture drying process in Bakan village, North Sulawesi. *Proceedings of the Indonesia International Geothermal Convention and Exhibition 2014*, Jakarta, Indnonesia, 5 pp.

Sveinbjörnsson, B.M., 2016: *Medium enthalpy geothermal systems in Iceland. Thermal and electric potential*. ÍSOR – Iceland GeoSurvey, Reykjavík, Iceland, report ÍSOR-2016/008, 126 pp.

Taylor, P., d'Ortigue, L., Trudeau, N., and Francoeur, M., 2008: Energy efficiency indicators for public electricity production from fossil fuels. Organisation for Economic Cooperation and Development / International Energy Agency, Paris, France, 23 pp.

Unverdi, M. and Cerci, Y., 2013: Performance analysis of Germencik geothermal power plant. Energy, 52, 192-200.

Valdimarsson, 2014: Geothermal utilization – Production of power. *Papers presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo*, Santa Tecla, El Salvador, 34 pp.

OECD/IEA, 2005: *Energy statistics manual*. Organisation for Economic Cooperation and Development, International Energy Agency, Paris, France, 196 pp.

OECD/IEA, 2016: *Energy efficiency market report 2016*. Organisation for Economic Cooperation and Development / International Energy Agency, Paris, France, 142 pp.

ON, 2016: *Nesjavellir power plant* (in Icelandic). Orka Náttúrunnar – ON Power, Reykjavík, Iceland. Website: *https://www.on.is/nesjavallavirkjun*

WEC, 2016: *World energy perspectives. Energy efficiency: A straight path towards energy sustainability*. World Energy Council, London, United Kingdom, 152 pp.

APPENDIX I: A back-of-the-envelope assessment of first and second law efficiencies of electricity generation of Icelandic geothermal power plants

Following goes what can be referred to as back-of-the-envelope assessment of simple efficiencies of electricity generation of Icelandic geothermal power plants for which published data are available, as captured by Equations 12 and 13 in Section 4.2. As the author does not have information on the thermodynamic state at wellheads and annual mass production from individual wells, the inlet exergy to electricity generation processes is approximated by separator exergy. Separator conditions are mostly obtained from process diagrams and are assumed to be representative of a steady state power plant. Also, the electrical power output is read from the diagrams without taking internal electricity consumption into account initially. This leads to:

1. The inlet exergy being underestimated, considering the boundaries of the power plant observation space (Haraldsson, 2011) at the wellheads, as some exergy is bound to be destroyed from the wellheads to a separator;
2. The work output in the form of electricity being overestimated; and
3. The second law efficiency consequently being overestimated.

An attempt will be made to correct for these shortcomings at the end of the appendix.

In the case where process flow diagrams are used for the estimation, mass and energy balances are applied at nodes as necessary.

Calculations are done using an excel spreadsheet with in-built thermodynamic functions, developed by Magnus Holmgren (www.x-eng.com).

The electricity utilization ratio reported by Haraldsson and Ketilsson (2010b) is used as a reference for checking results of thermal efficiency estimations, keeping in mind the points listed in Section 4.3. As noted there, the ratio is based on primary energy inflow referenced to an environmental state of 15°C at 1 bar and reported net electricity generation. If the reference state were the same as that which is mostly used in this report (5°C, 1 atm), the ratio should present a lower boundary to thermal efficiency. However, due to the higher temperature of the reference state, the ratio will be slightly higher than if referenced to (5°C, 1 atm). The difference in enthalpy between the two states is:

$$\Delta h(T, P) = h(15°C, 1 \text{ bar}) - h(5°C, 1 \text{ atm}) = 63.1 \text{ kJ/kg} - 21.1 \text{ kJ/kg} = 42.0 \text{ kJ/kg}$$

Assuming an average inlet enthalpy of 1400-1800 kJ/kg, the difference in the calculated primary energy content of the incoming geofluid between the two reference states is between 2-3%. It is therefore considered reasonable to use the electricity utilization ratio as a reference.

1. KRAFLA GEOTHERMAL POWER PLANT

Krafla geothermal power plant consists of two 30 $MW_{installed}$ two-step turbines, owned and operated by Landsvirkjun (National Power Company of Iceland) in the North of Iceland. According to the company's website, the turbines accept 110 kg/s of 7.7 bar high-pressure saturated steam and 36 kg/s of 2.2 bar low-pressure saturated steam when operating at full potential (Landsvirkjun, 2016a).

Landsvirkjun has published annual reports on well output and chemical content of geothermal fluids in wells and production pipelines at Krafla and Bjarnarflag power plants, that are available online. Two approaches are used to estimate the efficiencies of the power plant: 1) Using the information supplied in the previous paragraph, supplanted with information on enthalpy from the annual report for 2014; and 2) Using only information from the 2014 report.

1.1 First approach

Table 4 of the report for 2014 (Hauksson, 2015) shows enthalpy and total flow from wells supplying the Krafla power plant. This table is used to roughly estimate the average enthalpy of geothermal fluid coming from high-pressure and low-pressure wells. The weighted average enthalpy of high-pressure fluid is estimated to be 1778 kJ/kg and the weighted average enthalpy of low-pressure fluid to be 934 kJ/kg. The mass flow and pressure of steam supplied to the turbines is taken as that provided on Landsvirkjun's website and noted above. Mass flow from high pressure and low pressure wells is determined from mass and energy balances and specific exergy is estimated based on the estimated enthalpies and separator pressures (assumed to be the same as the stated turbine inlet pressures). The reference state is taken as T = 5°C (close to the annual average temperature in Iceland) and P = 1 atm (as a standard unit of atmospheric pressure (although Iceland is prone to relatively low atmospheric pressure)). The exergy inflow is calculated according to Equation 2. Reference conditions are shown in Table 1 and the results of the calculation are shown in Tables 2 and 3 (see also Figure 1).

TABLE 1: Reference state / environmental conditions

Property	Values
Temperature	5°C; 278.15 K
Pressure	1 atm; 1.01325 bar
Enthalpy	21.1 kJ/kg
Entropy	0.0763 kJ/(kgK)

TABLE 2: Assumed values and calculation results. HP: High pressure; LP: Low pressure.
See Table 1 for reference state conditions.

	Property	HP separator	LP separator
Given / Estimated	Enthalpy from wells	1778 kJ/kg	934 kJ/kg
	Mass flow steam out	110 kg/s	36 kg/s
	Pressure	7.7 bar	2.2 bar

TABLE 2 cont'd: Assumed values and calculation results

	Property	HP separator	LP separator
Calculated	Temperature	168.8°C	123.3°C
	Steam enthalpy out	2767 kJ/kg	2711 kJ/kg
	Water enthalpy out	714 kJ/kg	518 kJ/kg
	Mass flow from wells	212 kg/s	141 kg/s
	Entropy in	4.44 kJ/(kgK)	2.61 kJ/(kgK)
	Exergy from wells	544 kJ/kg	207 kJ/kg
	Energy flow in	373 MW	129 MW
	Exergy flow in	115 MW	29 MW

TABLE 3: Estimated first and second law efficiencies

Property	Values
Total energy flow (thermal power) in	502 MW
Total exergy flow in	145 MW
Electrical output (gross)	60 MW
Thermal efficiency (η_1)	12%
Exergetic efficiency (η_2)	41%

1.2 Second approach

The process diagram for the Krafla power plant as presented by Hauksson (2015) is shown in Figure 1. Along with the estimated average enthalpies of high- and low-pressure fluid (see previous section) and a reported outflow temperature of 124°C from the low-pressure separator, the diagram is used to estimate first and second law efficiencies with reference to the same environmental state as before.

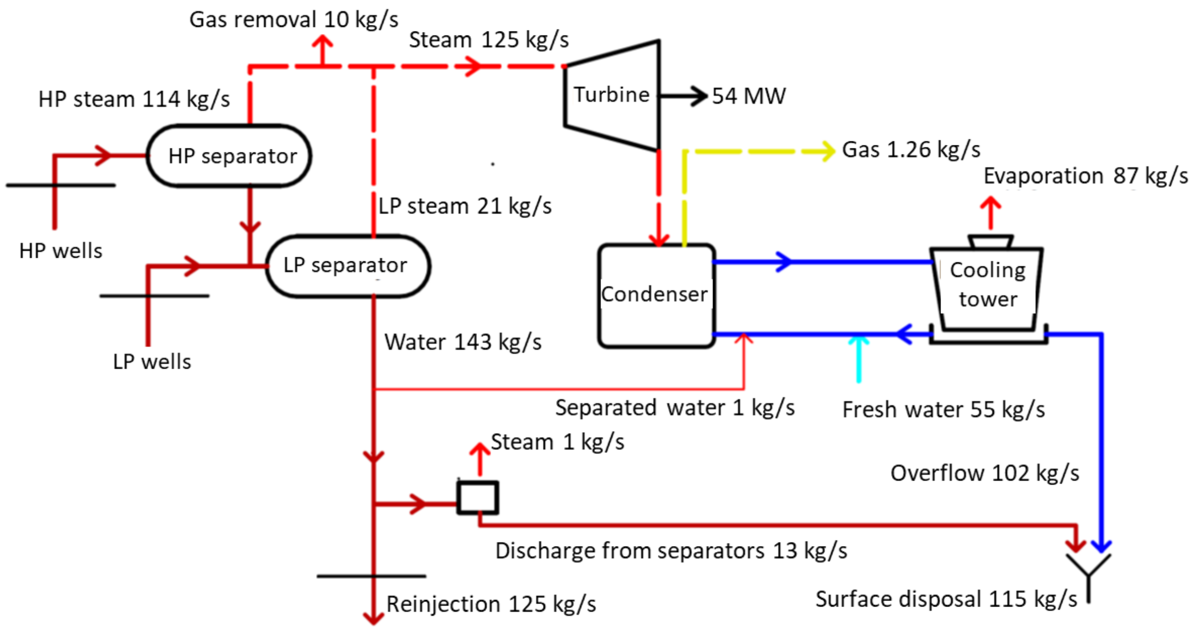

FIGURE 1: Process flow diagram for Krafla geothermal power plant in Northern Iceland. Values as of June 2014. HP: High pressure; LP: Low pressure. Adopted and translated from Hauksson (2015).

The calculations indicate a thermal efficiency of 12% and exergetic efficiency of 41%. This is in agreement with the first approach.

The estimated first law efficiency compares well with the electricity utilization ratio of 11.4% shown in Table 1 of the main text. The estimate of second law efficiency of 41% can therefore be considered reasonable, with the drawbacks of not accounting for exergy destruction between wellheads and separators and electricity consumption within the plant not being taken into account.

2. BJARNARFLAG GEOTHERMAL CHP PLANT

The Bjarnarflag geothermal power plant is operated by Landsvirkjun. It is the oldest of the Icelandic geothermal power plants, having been commissioned in 1969. It consists of a simple back-pressure turbine with an installed capacity of 3 MW (Landsvirkjun, 2016b). The annual report mentioned in the previous section covers Bjarnarflag as well as Krafla. The process flow diagram for the power plant as operated in 2014 is shown in Figure 2.

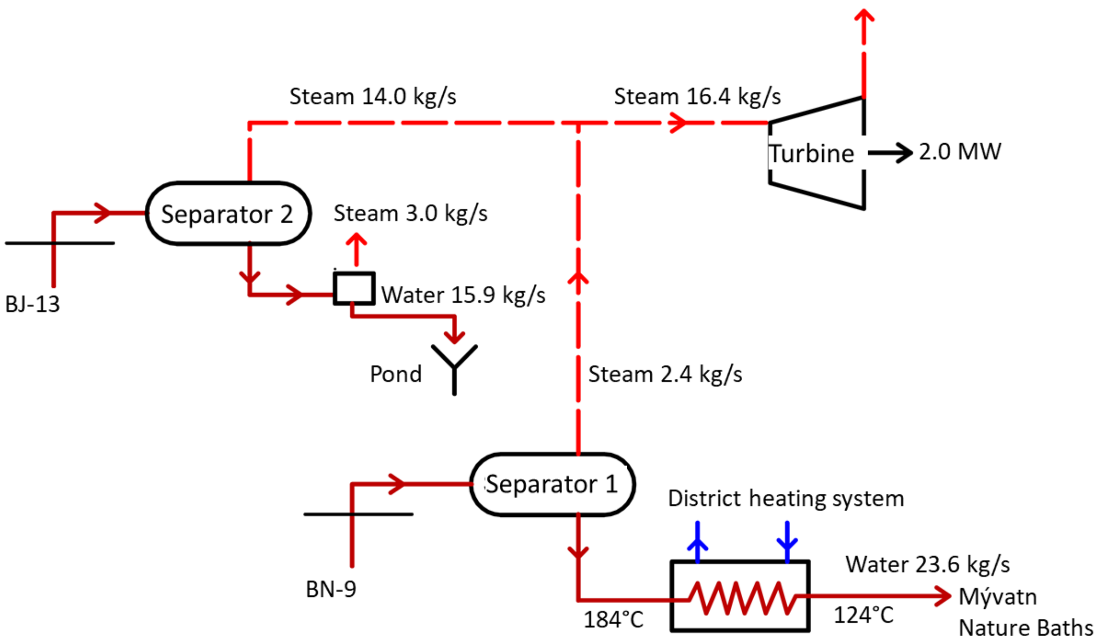

FIGURE 2: Process flow diagram for Bjarnarflag geothermal power plant in Northern Iceland. Values as of June 2014. Adopted and translated from Hauksson (2015).

The power plant was supplied by only two wells in 2014: BJ-13 with a measured enthalpy of 1632 kJ/kg and BN-09 with a measured enthalpy of 964 kJ/kg. The information in Figure 2 is used to estimate the thermal and exergetic efficiencies of the power plant, applying mass and energy balances to nodes as necessary. The reference state is the same as in the previous example: 5°C and 1 atm. The thermal efficiency of the generation process is calculated as 2.6% and the exergetic efficiency as 8.6%. The thermal efficiency is considerably higher than the electricity utilization ratio reported for 2008 (1.7%), as shown in Table 1 of the main text. The reason is probably to be found in the fact that mass production was reported from a greater number of wells in 2008, with different enthalpies, and the fluid may not all have been delivered to the electricity generation process.

3. NESJAVELLIR GEOTHERMAL CHP PLANT

Nesjavellir geothermal power plant is owned and operated by Orka Náttúrunnar (On Power), a subsidiary of Orkuveita Reykjavíkur (Reykjavík Energy). It is a combined heat and power (CHP) plant with an installed capacity of 120 MW_e and 300 MW_{th} (ON, 2016). The site was originally developed with the primary aim of supplying the Reykjavík area district heating system with additional hot water to meet increasing demand. The power plant therefore started out as a thermal plant in 1990 (Ballzus et al., 2000) and was built up in stages to its present capacity.

3.1 Efficiencies after the third construction stage

First and second law efficiencies are estimated for the power plant based on a process diagram from the published literature, applicable after the third stage of construction which was completed in 1998 (Ballzus et al., 2000). At the time, the installed capacity was 60 MW_e and 200 MW_{th} (reference state not indicated). The process diagram is shown in Figure 3.

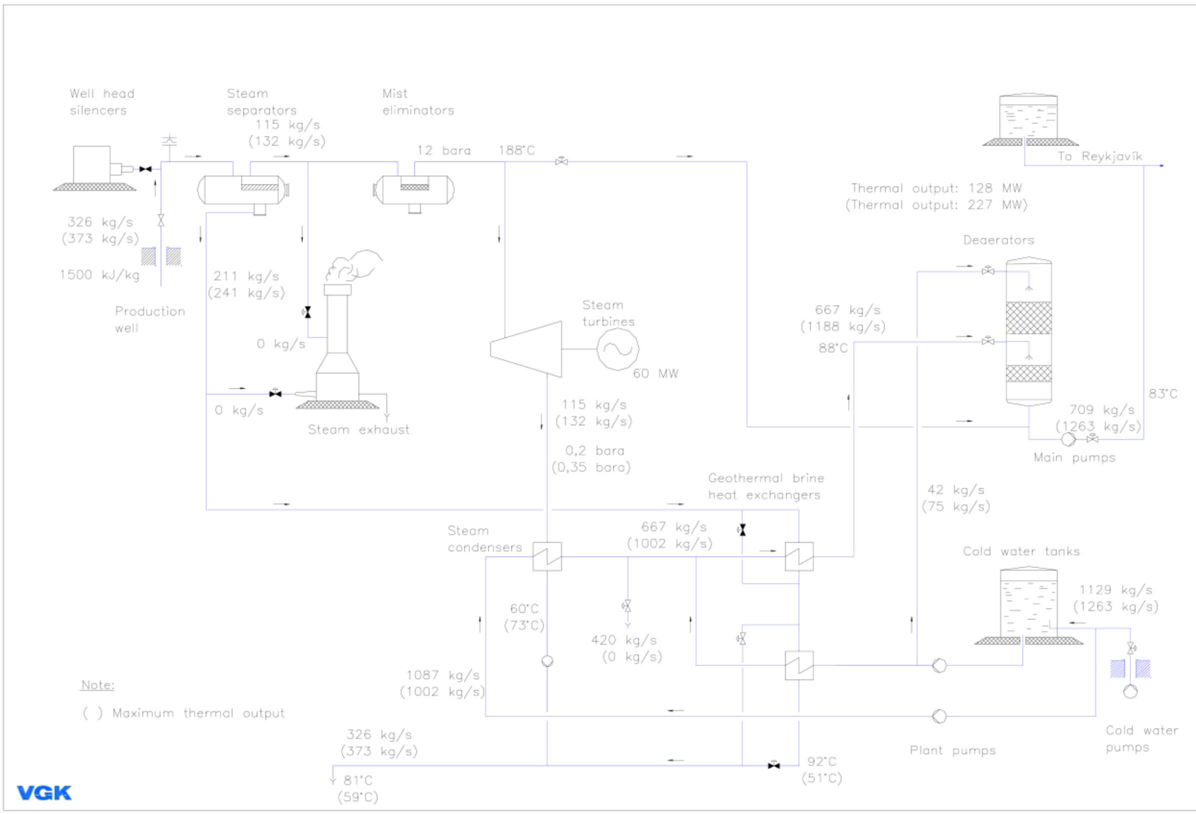

FIGURE 3: Process diagram of the Nesjavellir geothermal CHP plant (Ballzus et al., 2000)

Ballzus et al. (2000) report that the condensing temperature of the plant could be varied between 60°C and 73°C, and that the output of the thermal plant could be varied between 128 MW_{th} and 227 MW_{th} depending on demand (reference conditions not stated). They further note that steam and geothermal water are utilized in the most efficient way possible for co-generation of electric and thermal power. The data in parentheses in Figure 3 is relevant for high-demand conditions for hot water (winter), while that without parentheses is relevant to low-demand conditions (summer). Based on the diagram, the summer and winter efficiencies are estimated as shown in Table 4.

TABLE 4: Estimated first and second law efficiencies of the Nesjavellir geothermal CHP plant after its third construction stage, in summer and winter. Reference conditions are the same as before: 5°C and 1 atm.

Season	Thermal efficiency (η_1)	Exergetic efficiency (η_2)
Summer	12%	40%
Winter	11%	35%

As in previous examples, the enthalpy of the incoming fluid and separator conditions are used to estimate the inflow of exergy. Exergy destruction from wells to separator is unaccounted for. Some internal electricity consumption of the power plant is reported by Ballzus et al. (2000), e.g. two water ring pumps to remove non-condensable gases from each turbine-generator-condenser unit, with a total consumption of 300 kW. As the total internal consumption is not given, and to keep in line with previous examples, this is not accounted for in the assessment. The separator pressure and turbine power output are assumed to stay constant over the seasons in accordance with the information available in the diagram.

The estimated thermal efficiencies are considerably lower than the electricity utilization ratio in 2008 (15.3%) as shown in Table 1 in the main text. This suggests that the efficiency of the electricity generation process increased with the addition of further 60 MW_e capacity.

3.2 Efficiencies after further enlargement of the plant

Some values reported for the Nesjavellir power plant in the literature are shown in Table 5.

TABLE 5: Some reported values for the energy utilization process at Nesjavellir geothermal CHP plant (Mirzaei Zarandi, 2007; Mirzaei Zarandi and Ívarsson, 2010)

Property	Value	Source
Mass flow of steam to turbines	240 kg/s	Mirzaei Zarandi, 2007; Mirzaei Zarandi and Ívarsson, 2010
Separator pressure	12 bar	Ballzus et al., 2000; Mirzaei Zarandi and Ívarsson, 2010
Enthalpy of produced fluid	1715 kJ/kg	Haraldsson and Ketilsson, 2010b; Gíslason et al., 2005

The average enthalpy of 1715 kJ/kg of all produced fluid in the Nesjavellir geothermal field in 2008 was reported by Haraldsson and Ketilsson (2010b). Gíslason et al. (2005) report that the average discharge enthalpy of wells in the field has varied greatly through the years as shown in Figure 4. The figure matches well with the intake enthalpy of 1500 kJ/kg reported by Ballzus et al. in 2000. The reasons for the variations can be found in new higher enthalpy wells being drilled, different contributions of wells between years and evolution of reservoir conditions in response to production. Gíslason et al. (2005) further note that the enthalpy was fairly level at about 1700-1800 kJ/kg between 2000 and 2005, which matches well with the value reported by Haraldsson and Ketilsson for 2008.

Assuming electricity generation of 120 MW_e and using the values presented in Tables 1 and 5 leads to an estimated thermal efficiency of 14% and exergetic efficiency of 42%. This estimate of thermal efficiency is closer to the electricity utilization ratio of 15.3% reported by Haraldsson and Ketilsson (2010b) than the previous calculation, as would be expected. If the reference state is changed to (15°C, 1 bar) as in Haraldsson and Ketilsson, the thermal efficiency stays roughly at 14%, while the exergetic efficiency increases to 46%. The different origins of the values reported in Table 5 serves to increase uncertainty.

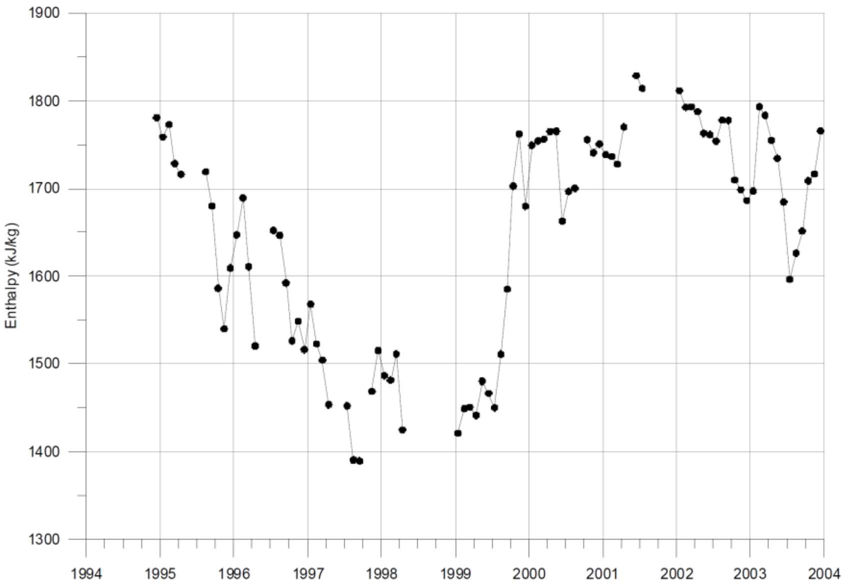

FIGURE 4: Average monthly enthalpy calculated from measured steam and water ratio in the separator station (Gíslason et al., 2005)

4. HELLISHEIDI GEOTHERMAL CHP PLANT

Hallgrímsdóttir et al. (2012) report on the Hellisheidi geothermal CHP plant. The plant has an installed capacity of 303 MW_e and 133 MW_{th} (reference conditions not stated), with thermal generation capacity additions of 133 MW_{th} expected in 2020 and 2030, for a total thermal output of roughly 400 MW_{th}. They report flexibility in some operation parameters, e.g. to respond to variability in demand for district heating water. The design process flow diagram for the plant shows mass flow, temperature and pressure at various points in the process for two instances: minimum and maximum pressure in the primary separator(s), while hot water production for the Reykjavík district heating system is held constant at maximum production capacity. Some key values are as shown in Table 6.

TABLE 6: Some key values of the Hellisheidi geothermal CHP plant process diagram at design conditions. Reference conditions as in Table 1.

	Property	**Min primary separator pressure**	**Max primary separator pressure**
Process diagram	Primary separator pressure	8 bar	10 bar
	Mass flow from wells	1165 kg/s	1151 kg/s
	Enthalpy at wellheads	1660 kJ/kg	1660 kJ/kg
	Mass flow groundwater in	650 kg/s	650 kg/s
	Temperature groundwater in	5°C	5°C
	Mass flow DH water out	650 kg/s	650 kg/s
	Temperature DH water out	90°C	90°C
	Reinjection mass flow	719 kg/s	718 kg/s
	Temperature reinjection fluid	66°C	63°C
	Electricity output (gross)	283.6 MW	303.6 MW

TABLE 6 cont'd: Some key values of the Hellisheidi geothermal CHP plant process diagram at design conditions. Reference conditions as in Table 1.

	Property	Min primary separator pressure	Max primary separator pressure
Calculated	Entropy in	4.16 kJ/(kgK)	4.12 kJ/(kgK)
	Exergy from wells	502 kJ/kg	514 kJ/kg
	Energy flow in	1909 MW	1886 MW
	Exergy flow in	585 MW	592 MW

The electricity output includes a 33.6 MW bottoming unit.

The estimated first and second law efficiencies are shown in Table 7.

TABLE 7: Estimated first and second law efficiencies of the Hellisheidi geothermal CHP plant based on data from Hallgrímsdóttir et al. (2012). Reference conditions as in Table 1.

Case	Thermal efficiency (η_1)	Exergetic efficiency (η_2)
Min primary separator pressure (8 bar)	15%	48%
Max primary separator pressure (10 bar)	16%	51%

Without the bottoming unit, the thermal efficiency is calculated as 13-14% and the exergetic efficiency as 43-46%.

The calculated thermal efficiencies are considerably higher than the electricity utilization ratio of 12.1% reported by Haraldsson and Ketilsson (2010b) for 2008. As mentioned before, the thermal efficiency (as calculated based on fluid going directly to the electricity generation process) can be expected to be higher than the electricity generation ratio if some of the fluid accounted for in the latter case is not directed to the electricity generation process. Furthermore, the efficiencies in Table 7 are estimated on gross electricity generation basis, which also leads to a higher estimate. It should also be kept in mind that the thermal plant and last two turbines had yet to be added in 2008 – the year for which the electricity utilization ratio was reported.

It should be noted that due to drawdown and limitations of the production field, the operational capacity of the power plant decreased in subsequent years. To counteract this, a pipeline was constructed from the nearby Hverahlíd geothermal field to supply additional steam to the plant. It is unclear what effect this has had on efficiency.

5. REYKJANES GEOTHERMAL POWER PLANT

Reykjanes geothermal power plant is located at the tip of the Reykjanes peninsula in Iceland. Operations started in 2006 and the installed capacity is 100 MW_e. Energy for the plant is obtained from twelve of the fifteen boreholes drilled in the area (HS Orka, 2016).

Ravazdezh (2015) presents a process flow diagram for the power plant (Figure 5).

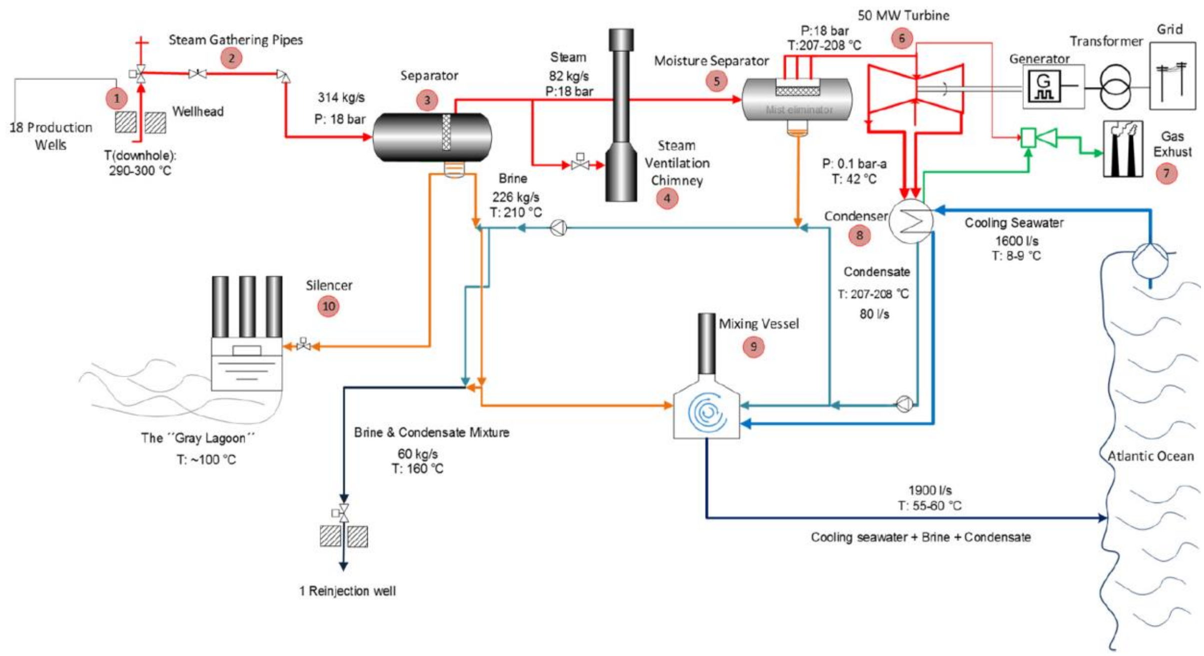

FIGURE 5: Process flow diagram of Reykjanes power plant (Ravazdezh, 2015)

In this case there are two environmental thermal reservoirs to which unused energy and exergy are discarded: the atmosphere (e.g. through the Gray Lagoon and steam ventilators) and the North Atlantic Ocean. The atmospheric conditions are approximated as (5°C, 1 atm) to keep in line with other cases, although the true average conditions may differ slightly. The ocean temperature is reported in the process diagram as 8-9°C. As most of the leftover energy / exergy is discarded to the ocean, the latter conditions are considered more relevant (if only a single reference state is to be considered – a detailed analysis would take into account the fluid streams reaching each reservoir and accounting separately for the energy / exergy flowing into each). The thermal efficiency at (8.5°C, 1 atm) is calculated as 12% (11.8%), while the exergetic efficiency is estimated as 38%. Considering also a (single) reference state of (5°C, 1 atm) and taking into account the energy / exergy flowing into the plant with the ocean cooling water (3.5°C warmer than the ambient conditions), the thermal efficiency is calculated as 11% (11.1%) and the exergetic efficiency as 37%. Assuming that the reference conditions are accurate for each reservoir, the true efficiency should lie between those values, albeit closer to the ocean reference scenario.

The calculated thermal efficiency compares well with the electricity utilization ratio of 11.9%, as reported by Haraldsson and Ketilsson (2010b) for 2008.

6. SUMMARY

The efficiencies as reported in the previous sections of this appendix are summarized in Table 8.

Assuming internal electricity consumption of 5% for geothermal power plants and 5% destruction of exergy from wellhead to separator leads to the thermal efficiency estimates being lowered by a factor of 0.95, while the exergetic efficiency estimates are lowered by a factor of 0.95^2 ≈ 0.90, as shown in Table 9.

TABLE 8: Summary of estimated efficiencies of electricity generation of Icelandic geothermal power plants as calculated in previous sections. Based on gross electricity generation, and exergy destruction from wellheads to separator unaccounted for.

Power plant	Thermal efficiency (η_1)	Exergetic efficiency (η_2)	Ratio (η_1/η_2)
Krafla	12%	41%	0.29
Bjarnarflag	3%	9%	0.30
Nesjavellir	14%	42%	0.32
Hellisheidi	15-16%	48-51%	0.31
Reykjanes	12%	38%	0.31

TABLE 9: Estimated efficiencies of electricity generation of Icelandic geothermal power plants assuming 5% internal electricity consumption and 5% destruction of exergy from wellhead to separator. Reference state as in Table 1.

Power plant	Thermal efficiency (η_1)	Exergetic efficiency (η_2)	Ratio (η_1/η_2)
Krafla	11-12%	37%	0.31
Bjarnarflag	2.5%	8%	0.31
Nesjavellir	13%	38%	0.34
Hellisheidi	14-15%	44-46%	0.32-0.33
Reykjanes	11%	35%	0.32

APPENDIX II: An estimation of simple, conditional and functional efficiencies for some Icelandic power plants

Following are estimations of simple, conditional and functional efficiencies, as presented in Section 5, of Icelandic geothermal power plants, building on information and cases presented in Appendix I.

1. KRAFLA GEOTHERMAL POWER PLANT

Referring to the process flow diagram shown in Figure 1 of Appendix I (corresponding to the second approach), one will note reinjection of 125 kg/s from the low pressure separator at a reported temperature of 124°C. Assuming separator pressure of 2.25 bar, the reinjection primary energy flow is estimated as 62.5 MW and the corresponding exergy flow as 10.5 MW, with the same reference conditions as before. The primary energy inflow (thermal power) to the high pressure separator from high pressure wells is estimated as 382.8 MW and the energy inflow to the low pressure separator from low pressure wells is estimated as 57.7 MW, for a total inflow of 440.5 MW. The exergy inflow to the high pressure separator from high pressure wells is estimated as 117.2 MW and the exergy inflow from low pressure wells is estimated as 13.8 MW, for a total exergy inflow of 131.0 MW. The electrical output is 54 MW and there is no direct utilization.

Some examples of calculations follow:

The simple first law efficiency of electricity generation based on net input (i.e. taking reinjection into account), is calculated in accordance with Equation 39:

$$\eta_{1s,el,NI} = \frac{\dot{\zeta}}{\dot{Q}_{in} - \dot{Q}_r} = \frac{54\ MW}{(440.5 - 62.5)\ MW} = 14.3\%$$

and the second law efficiency (Equation 42):

$$\eta_{2s,el,NI} = \frac{\dot{\zeta}}{\dot{E}_{in} - \dot{E}_r} = \frac{54\ MW}{(131.0 - 10.5)\ MW} = 44.8\%$$

The conditional first law efficiency of electricity generation based on net input is estimated in accordance with Equation 53 as:

$$\eta_{1c,el,NI} = \frac{\dot{\zeta}}{\dot{Q}_{in} - \dot{Q}_r - \dot{Q}_{DU}} = \frac{54\ MW}{(440.5 - 62.5 - 0) MW} = 14.3\%$$

On the other hand, if internal electricity use is taken into account (5%), the thermal efficiency becomes:

$$\eta_{1c,el,NI} = \frac{\dot{\zeta}}{\dot{Q}_{in} - \dot{Q}_r - \dot{Q}_{DU}} = \frac{0.95 \cdot 54\ MW}{(440.5 - 62.5 - 0) MW} = 13.6\%$$

The conditional second law efficiency of electricity generation based on net input is estimated in accordance with Equation 55:

$$\eta_{2c,el,NI} = \frac{\dot{\zeta}}{\dot{E}_{in} - \dot{E}_r - \dot{E}_{DU}} = \frac{54\ MW}{(131 - 10.5 - 0)\ MW} = 44.8\%$$

Assuming 5% internal consumption of electricity and 5% exergy destruction from wellhead to separator gives:

$$\eta_{2c,el,NI} = \frac{\dot{\zeta}}{\dot{E}_{in} - \dot{E}_r - \dot{E}_{DU}} = \frac{0.95 \cdot 54\ MW}{(131/0.95 - 10.5 - 0) MW} = 40.3\%$$

The functional efficiencies are the same.

Table 1 sums up the main input variables to the Equations.

TABLE 1: Calculated energy and exergy values for input into efficiency equations

	Basic variables		
$\dot{\zeta}_{gross}$	54	54	MW
Subscript	**Q**	**E**	**Unit**
in	440.5[1]	130.9[1]	MW
m*	0[2]	0[2]	MW
r	62.5	10.5	MW
DU	0	0	MW
Δ(EP)[3]	324.0 (74%)	66.4 (51%)	MW

1: The total primary energy / exergy content of the two inflowing streams (high and low pressure wells); 2: All of the energy / exergy is used for the electricity generation process; 3: $\Delta(EP) = X_{\alpha,in} - \dot{\zeta} - X_{\alpha,m^*} - X_{\alpha,r}$ where EP refers to "Electricity generation Process" and X_α is Q or E. This quantity must be positive and shows losses to the environment that are not specifically accounted for here.

Based on the input variables in Table 1, the various efficiencies are reported in Tables 2-5.

TABLE 2: Simple, conditional and functional efficiencies based on gross input (without taking reinjection into account) and gross generation, without an attempt to correct for exergy destruction from wellheads to separators

	$W_{1,el}$[1] (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	12.3	1	0	12.3	1	41.3	1	0	41.3
Conditional	1	12.3	0	0	12.3	1	41.3	0	0	41.3
Functional	1	12.3	0	-[2]	-	1	41.3	0	-	-

1: Weight; 2: Division by zero. It should be understood that the direct use (DU) efficiencies are irrelevant when none of the fluid is directed towards direct use applications.

TABLE 3: Simple, conditional and functional efficiencies based on net input (taking reinjection into account) and gross generation, without an attempt to correct for exergy destruction from wellheads to separators

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	14.3	1	0	14.3	1	44.9	1	0	44.9
Conditional	1	14.3	0	0	14.3	1	44.9	0	0	44.9
Functional	1	14.3	0	-	-	1	44.9	0	-	-

TABLE 4: Simple, conditional and functional efficiencies based on gross input (without taking reinjection into account), net generation (internal use assumed 5%) and correction for assumed exergy destruction from wellheads to separators (5%)

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	11.6	1	0	11.6	1	37.2	1	0	37.2
Conditional	1	11.6	0	0	11.6	1	37.2	0	0	37.2
Functional	1	11.6	0	-	-	1	37.2	0	-	-

TABLE 5: Simple, conditional and functional efficiencies based on net input (taking reinjection into account), net generation (internal use assumed 5%) and correction for assumed exergy destruction from wellheads to separators (5%)

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	13.6	1	0	13.6	1	40.3	1	0	40.3
Conditional	1	13.6	0	0	13.6	1	40.3	0	0	40.3
Functional	1	13.6	0	-	-	1	40.3	0	-	-

One will observe that the weights on electricity production are unity, while those on direct use are zero, as should be. The overall efficiencies are therefore identical to the efficiencies of electricity generation. Also, the simple, conditional and functional forms of the latter turn out identical values, as is to be expected in the absence of direct use. Looking at Tables 2 and 3 that do neither attempt to correct for internal electricity use of the plant nor exergy destruction from wellheads to separators, the efficiencies increase when reinjection is taken into account, as is expected. Taking the internal use and exergy destruction into account lowers the values as may be observed by comparing Tables 2 and 4 on one hand and Tables 3 and 5 on the other.

2. BJARNARFLAG GEOTHERMAL CHP PLANT

Figure 2 in Appendix I shows the effluent water from Separator 1 being used for district heating and then for the Mývatn Nature Baths, where it is assumed that the fluid can be used down to a temperature of 35°C before being disposed of at 1 atm. Variables are used as shown in Table 6.

TABLE 6: Given and calculated values for the Bjarnarflag CHP power plant based on Figure 2 in Appendix I. The reference state is (5°C, 1 atm).

	Separator 1	Separator 2	Unit
Temperature	184	184	°C
Pressure	11.0	11.0	bar
Mass flow in	26.0	32.9	kg/s
Enthalpy in	965.5	1631.8	kJ/kg
Entropy in	2.6	4.0	kJ/(kgK)
Mass flow steam out	2.4	14.0	kg/s
Enthalpy steam out	2780.6	2780.6	kJ/kg
Entropy steam out	6.6	6.6	kJ/(kgK)
Mass flow brine out	23.6	18.9	kg/s
Enthalpy brine out	780.9	780.9	kJ/kg
Entropy brine out	2.2	2.2	kJ/(kgK)

A conserved mass flow of 23.6 kg/s from Separator 1 enters the district heating process at 184°C and is delivered to Mývatn Nature Baths at 124°C (no temperature losses are assumed in transmission pipelines). The fluid is taken to be discarded to the environment at 35°C. Although the exergy is assumed to be fully utilized, it is worth noting that some of it is bound to be destroyed through cooling/dilution at the baths, taking into account the nature of the utilization and the assumed temperature at delivery point.

Energies and exergies are calculated as shown in Table 7.

TABLE 7: Calculated energy and exergy values for input into efficiency equations

	Basic variables		
$\dot{\zeta}_{gross}$	2	2	MW
Subscript	**Q**	**E**	**Unit**
in	77.5[1]	23.2[1]	MW
m*	32.3[2]	7.4[2]	MW
r	0[3]	0[3]	MW
DU	15.0[4]	4.0[4]	MW
Δ(EP)	43.2 (56%)	13.8 (59%)	MW

1: Total primary energy / exergy content of the two inflowing streams; 2: In this case m* is the same for both separators, i.e. m* = (P,T) = (184°C, 11.0 bar) and the reported energy / exergy is the combination of the fluid streams from both separators; 3: There is no reported reinjection; 4: Geothermal fluid enters the DU process at 184°C (district heating system) and is discarded at 35°C (Mývatn Nature Baths), no mass or temperature losses.

Some examples of calculations follow:

First law conditional efficiency of electricity generation based on net input (Equation 53):

$$\eta_{1c,el,NI} = \frac{\dot{\zeta}}{(\dot{Q}_{in} - \dot{Q}_r) - \dot{Q}_{DU}} = \frac{2.0\ MW}{((77.5 - 0) - 15.0)\ MW} = 3.2\%$$

First law conditional efficiency of direct utilization based on net input (Equation 54):

$$\eta_{1c,DU,NI} = \frac{\dot{Q}_{DU}}{\dot{Q}_{in} - \dot{Q}_r - \dot{\zeta}} = \frac{15.0\ MW}{(77.5 - 0 - 2.0)\ MW} = 19.9\%$$

First law overall conditional efficiency based on net input (Equation 57):

$$\eta_{1c,overall,NI} = \left(\frac{\dot{Q}_{in} - \dot{Q}_{r,el} - \dot{Q}_{m^*}}{\dot{Q}_{in} - \dot{Q}_r}\right)\eta_{1c,el,NI} + \left(\frac{\dot{Q}_{m^*} - \dot{Q}_{r,DU}}{\dot{Q}_{in} - \dot{Q}_r}\right)\eta_{1c,DU,NI} =$$

$$= \left(\frac{77.5 - 0 - 32.3}{77.5 - 0}\right)3.2\% + \left(\frac{32.3 - 0}{77.5 - 0}\right)19.9\% = (0.58)3.2\% + (0.42)19.9\% = 10.2\%$$

Based on the input variables in Table 7, the various efficiencies are reported in Tables 8-11.

TABLE 8: Simple, conditional and functional efficiencies based on gross input (without taking reinjection into account) and gross generation, without an attempt to correct for exergy destruction from wellheads to separators

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	2.6	1	19.4	21.9	1	8.6	1	17.2	25.9
Conditional	0.58	3.2	0.42	19.9	10.1	0.68	10.4	0.32	18.9	13.1
Functional	0.58	4.4	0.42	46.4	21.9	0.68	12.7	0.32	54.1	25.9

TABLE 9: Simple, conditional and functional efficiencies based on net input (taking reinjection into account) and gross generation, without an attempt to correct for exergy destruction from wellheads to separators

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	2.6	1	19.4	21.9	1	8.6	1	17.2	25.9
Conditional	0.58	3.2	0.42	19.9	10.1	0.68	10.4	0.32	18.9	13.1
Functional	0.58	4.4	0.42	46.4	21.9	0.68	12.7	0.32	54.1	25.9

TABLE 10: Simple, conditional and functional efficiencies based on gross input (without taking reinjection into account), net generation (internal use assumed 5%) and correction for assumed exergy destruction from wellheads to separators (5%)

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	2.5	1	19.4	21.8	1	7.8	1	16.4	24.2
Conditional	0.58	3.0	0.42	19.8	10.0	0.70	9.3	0.30	17.8	11.9
Functional	0.58	4.2	0.42	46.4	21.8	0.70	11.2	0.30	54.1	24.2

TABLE 11: Simple, conditional and functional efficiencies based on net input (taking reinjection into account), net generation (internal use assumed 5%) and correction for assumed exergy destruction from wellheads to separators (5%)

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	2.5	1	19.4	21.8	1	7.8	1	16.4	24.2
Conditional	0.58	3.0	0.42	19.8	10.0	0.70	9.3	0.30	17.8	11.9
Functional	0.58	4.2	0.42	46.4	21.8	0.70	11.2	0.30	54.1	24.2

As there is no reinjection to the original reservoir, Tables 8 and 9 on one hand and Tables 10 and 11 on the other are identical. Looking at Table 8, one will note that the weights on the conditional and functional efficiencies are identical for each component (electricity generation on one hand and direct use on the other) as should be. For each component, the functional efficiencies are higher than the conditional efficiencies, which in turn are higher than the simple efficiencies. However, the overall conditional efficiencies are significantly lower than the other two (which are identical). While the simple overall efficiencies are simple additions of the two component efficiencies, the conditional and functional overall efficiencies are weighted means of the component efficiencies. One will observe that a greater percentage of the overall incoming exergy (68%) is used in the electricity generation process than of the overall incoming primary energy (58%). When looking at first law efficiencies (primary energy) there is a greater proportional difference between the simple and conditional efficiencies of electricity generation (24% increase from simple to conditional) than between the corresponding efficiencies of direct utilization (3% increase from simple to conditional). This is due to the large difference between the primary energy of electrical output (2 MW) on one hand and that of direct use (15.0 MW) on the other. Looking at the second law efficiencies (exergy) the proportional difference is 21% in the case of electricity generation and 9% difference in the case of direct utilization. The lower gap between the two ratios compared to the preceding case is explained by the fact that primary energy and exergy output of electricity is one and the same, while direct exergy use is significantly lower than the primary energy use (7.4 MW vs. 32.3 MW).

One will note the relatively small effect that a correction for internal use of electricity and exergy destruction between wellheads and separators has on the first law simple and conditional efficiencies of direct utilization, while the correction is seen to a somewhat greater extent in the corresponding second law efficiencies. This can be attributed to the fact that the denominator of the second law efficiencies increases with the correction, while it stays unchanged in the case of first law efficiencies, as both simple and conventional efficiencies include $X_{\alpha,in}$ in the denominator. E_{in} increases with the correction, while Q_{in} stays unchanged. However, the denominator of the direct use functional efficiencies is not affected by changes in $X_{\alpha,in}$ or power plant internal electricity consumption and is therefore identical to the same efficiencies before correcting for internal use and exergy destruction from wellheads to separators.

Taking internal use and exergy destruction from wellhead to separators into account lowers both thermal and exergy efficiencies. There is no effect on the weights of the thermal efficiencies as primary energy is assumed to be conserved between wellheads and separators (and is therefore unchanged between the two scenarios), while the weight on electricity generation increases slightly for the exergetic efficiencies due to the higher assumed exergy input to the electricity generation process – while the exergy delivery to the direct use application processes stays constant.

One will also note that the second law efficiencies of electricity generation are in all cases higher than the first law efficiencies, while the simple and conditional exergetic efficiencies of direct utilization are lower than the corresponding thermal efficiencies. In the case of efficiencies of electricity generation, the numerator is the same regardless of whether one is dealing with primary energy or exergy. As the exergy is (considerably) lower than the primary energy, the second law efficiencies must be higher. In the case of direct utilization, the numerator is different depending on whether one is dealing with primary energy or exergy, so such a large jump between first and second law efficiencies as is seen in the case of electricity generation is hardly to be expected. As is seen in Figure 3 of the main text, the ratio of exergy to enthalpy decreases with decreasing enthalpy. If all of the exergy and thereby primary energy delivered to a direct utilization process were used (100% efficiency), one would expect the ratio of available exergy to incoming exergy (to the electricity generation process) to be lower than the corresponding primary energy ratio, i.e.

$$\frac{\dot{E}_{m^*}}{\dot{E}_{in}} < \frac{\dot{Q}_{m^*}}{\dot{Q}_{in}} \text{ because } \frac{\dot{E}}{\dot{Q}} \text{ decreases as h decreases.}$$

The simple and conditional exergetic efficiencies of direct utilization, with $\dot{X}_{\alpha,in}$ dominating in the denominator can thus be expected to be lower than the thermal efficiencies, although the constant $\dot{\zeta}$ also has an effect in the case of the conditional efficiencies.

However, direct utilization is rarely 100% efficient and thereby $X_{\alpha,DU} < X_{\alpha,m^*}$.

It should be kept in mind that the direct utilization exergetic efficiency is sensitive to the temperature interval over which the exergy is extracted. Thus, while almost the same primary energy would be extracted over any 40°C interval within [80, 0]°C, the extracted exergy decreases as the starting temperature is lowered. For example, cooling water from 80°C to 40°C at 1 atm will yield Δh = ~167.4 kJ/kg and Δe = ~27.5 kJ/kg, while cooling from 50°C to 10°C will yield Δh = ~167.3 kJ/kg and Δe = ~13.6 kJ/kg. The exergy extraction in direct utilization processes is thus sensitive to temperature (and pressure) losses from the delivery points to transmission pipelines (m*), to the end user. The same is true of losses between different direct utilization processes. In other words, extracting energy / exergy from water over, say, the intervals [80, 40]°C, [50, 10]°C, and [80, 60]°C + [30, 10]°C (at constant pressure, greater than saturation pressure) will result in roughly the same primary energy extraction, while the exergy extraction will differ and this will affect the thermal and exergetic efficiencies differently.

Conversely, the functional exergetic efficiencies of direct utilization are higher than the corresponding thermal efficiencies. As the dominating term of the denominator is $\dot{X}_{\alpha,m^*}$ the efficiencies are only dependent on the energy / exergy content of the fluid that is delivered to the direct utilization process. In this case it will matter over which temperature interval(s) the energy / exergy is extracted. If the fluid is utilized towards the higher temperature end one would expect the exergetic functional efficiencies to be higher than the thermal efficiencies, but if the fluid is utilized towards the lower temperature end, the reverse would be expected.

3. NESJAVELLIR GEOTHERMAL CHP PLANT

The different efficiencies for Nesjavellir geothermal CHP plant are estimated based upon the available process diagram valid after the third construction stage, as a comparable diagram valid after the enlargement of the plant to its present state was not found in the published literature.

As information is not available on primary energy or exergy consumption of district heating system consumers, and for the sake of simplicity, the assumption made here is simply that mass flow is conserved and that consumers receive hot water at 75°C and discard the water at 35°C, e.g. for house heating. In reality, some of the water will be used for direct consumption, swimming pools, industrial activities etc., and some of the discarded water will be used for snow melting or other purposes.

Based on Figure 3 of Appendix I the inflow and outflow to/from the electricity generation process is as shown in Table 12. Note that cold groundwater flows into the process at reference conditions and is thus considered to be devoid of both primary energy and exergy.

There are two mass streams into the electricity generation process (geothermal fluid and groundwater), but only one energy/exergy stream (geothermal fluid). There are three energy / exergy streams out of the process: Electricity, and those associated with district heating water and fluid discarded to the surface / groundwater bodies. Table 12 summarizes basic variables, mostly from Figure 3 of the preceding appendix.

TABLE 12: Basic variables of the Nesjavellir geothermal CHP plant process for summer and winter conditions, obtained from Figure 3 in Appendix I. Values are from Ballzus et al. (2000) unless otherwise noted.

Peripheral point (subscript)	**Basic variable**	**Summer**	**Winter**	**Unit**
Inflow to separators (in)	Mass flow ($\dot{m}$)	326	373	kg/s
	Enthalpy (h)	1500	1500	kJ/kg
	Pressure (P)	12	12	bar
To district heating transmission pipeline (m^*)	Mass flow ($\dot{m}$)	709	1263	kg/s
	Temperature (T)	83	83	°C
	Pressure (P)	0.53[1]	0.53[1]	bar
Surface disposal	Mass flow ($\dot{m}$)	326	373	kg/s
	Temperature (T)	81	59	°C
	Pressure (P)	1[2]	1[2]	bar
Surface disposal	Mass flow ($\dot{m}$)	420	0	kg/s
	Temperature (T)	?	-	°C
	Pressure (P)	1[2]	1[2]	bar

1: Saturation pressure in deaerators; 2: An assumed value (note that neither liquid energy nor exergy are very sensitive to pressure in the vicinity of the stated temperatures).

It is worth pointing out that reinjection is only to a cold shallow groundwater reservoir (Gíslason et al., 2005) and does therefore not fulfill the criterion for being included in the calculation of efficiencies as stated in Section 5, with only reinjection to the original reservoir from whence the geothermal fluid came being acknowledged.

From the basic variables, energy and exergy streams can be calculated at different points as shown in Table 13, presented in the same format as in earlier cases.

TABLE 13: Calculated energy and exergy values for input into efficiency equations

	Basic variables				
$\dot{\zeta}_{gross}$	60		60		MW
	Q		**E**		
Subscript	**Summer**	**Winter**	**Summer**	**Winter**	**Unit**
in	482.1	551.6	150.1	171.8	MW
$\mathbf{m^*}$	231.4	412.3	27.4	48.8	MW
r	0	0	0	0	MW
DU	118.6	211.3	18.0	32.1	MW
$\mathbf{\Delta(EP)}$	190.7 (39.6%)[1]	79.3 (14.4%)[1]	62.7 (41.8%)[1]	63.0 (36.7%)[1]	MW

1: Mostly disposal to the surface / groundwater bodies.

Based on the input variables in Table 13, the various efficiencies are reported in Tables 14-17.

TABLE 14: Simple, conditional and functional efficiencies based on gross input (without taking reinjection into account) and gross generation, without an attempt to correct for exergy destruction from wellheads to separators

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Summer										
Simple	1	12.4	1	24.6	37.0	1	40.0	1	12.0	52.0
Conditional	0.52	16.5	0.48	28.1	22.1	0.82	45.4	0.18	20.0	40.8
Functional	0.52	23.9	0.48	51.3	37.0	0.82	48.9	0.18	65.7	52.0
Winter										
Simple	1	10.9	1	38.3	49.2	1	34.9	1	18.7	53.6
Conditional	0.25	17.6	0.75	43.0	36.6	0.72	43.0	0.28	28.7	38.9
Functional	0.25	43.1	0.75	51.3	49.2	0.72	48.8	0.28	65.7	53.6

TABLE 15: Simple, conditional and functional efficiencies based on net input (taking reinjection into account) and gross generation, without an attempt to correct for exergy destruction from wellheads to separators

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Summer										
Simple	1	12.4	1	24.6	37.0	1	40.0	1	12.0	52.0
Conditional	0.52	16.5	0.48	28.1	22.1	0.82	45.4	0.18	20.0	40.8
Functional	0.52	23.9	0.48	51.3	37.0	0.82	48.9	0.18	65.7	52.0
Winter										
Simple	1	10.9	1	38.3	49.2	1	34.9	1	18.7	53.6
Conditional	0.25	17.6	0.75	43.0	36.6	0.72	43.0	0.28	28.7	38.9
Functional	0.25	43.1	0.75	51.3	49.2	0.72	48.8	0.28	65.7	53.6

TABLE 16: Simple, conditional and functional efficiencies based on gross input (without taking reinjection into account), net generation (internal use assumed 5%) and correction for assumed exergy destruction from wellheads to separators (5%)

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Summer										
Simple	1	11.8	1	24.6	36.4	1	36.1	1	11.4	47.5
Conditional	0.52	15.7	0.48	27.9	21.5	0.83	40.7	0.17	17.8	36.7
Functional	0.52	22.7	0.48	51.3	36.4	0.83	43.6	0.17	65.7	47.5
Winter										
Simple	1	10.3	1	38.3	48.6	1	31.5	1	17.7	49.3
Conditional	0.25	16.7	0.75	42.7	36.2	0.73	38.3	0.27	25.9	35.0
Functional	0.25	40.9	0.75	51.3	48.6	0.73	43.2	0.27	65.7	49.3

TABLE 17: Simple, conditional and functional efficiencies based on net input (taking reinjection into account), net generation (internal use assumed 5%) and correction for assumed exergy destruction from wellheads to separators (5%)

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Summer										
Simple	1	11.8	1	24.6	36.4	1	36.1	1	11.4	47.5
Conditional	0.52	15.7	0.48	27.9	21.5	0.83	40.7	0.17	17.8	36.7
Functional	0.52	22.7	0.48	51.3	36.4	0.83	43.6	0.17	65.7	47.5
Winter										
Simple	1	10.3	1	38.3	48.6	1	31.5	1	17.7	49.3
Conditional	0.25	16.7	0.75	42.7	36.2	0.73	38.3	0.27	25.9	35.0
Functional	0.25	40.9	0.75	51.3	48.6	0.73	43.2	0.27	65.7	49.3

In Tables 14-17 one will note many of the same features and relations as in previous cases. Of particular note here is how primary energy is roughly evenly divided between the electricity generation process and the direct utilization process in summer, while the weighting tilts significantly towards the direct utilization in winter when demand for district heating water is high. During this period, a quarter of the energy is used for electricity generation, while three quarters are used for district heating. As a result the overall conditional and functional efficiencies are roughly evenly spaced between the component efficiencies in summer, while direct utilization contributes more to the overall efficiency in the winter and thereby increases the overall efficiency of the power plant. A large part of the incoming exergy content of the fluid is used for electricity generation during both seasons, though the fraction is reduced somewhat during winter (from 0.83 to 0.73, or thereabouts).

One will also note how the simple first law efficiency of electricity generation is reduced between summer and winter as may be expected considering the fact that the incoming mass flow is increased between the two periods while electricity production stays constant. However, the corresponding conditional efficiency increases due to the fact that the increase in direct utilization between the periods has a greater (negative) effect on the denominator than the increase in incoming primary energy. The corresponding functional efficiency increases by almost a factor of 2 as the (negative) effect of increased power conveyed to the district heating transmission pipeline outweighs the effect of increased incoming energy on the denominator. The simple and conditional first law efficiencies of direct utilization increase between summer and winter due to the increase in direct consumption while the corresponding functional efficiency stays constant. This is due to the fact that the proportionality between consumption (as assumed here) and input to the direct utilization process is unchanged. Similar can be said of the second law efficiencies, except that the conditional second law efficiency of electricity generation decreases between summer and winter as the positive effect of increased incoming exergy (increase of 21.7 MW; Table 13) on the denominator is greater than the negative effect of increased direct utilization (14.1 MW; Table 13; it is interesting to note here that the increased mass flow in the former case is 47 kg/s, while the increase in the latter is 554 kg/s and yet the exergy flow of the former outweighs the latter by close to 50%). There is greater exergy destruction in the electricity generation process in winter than in summer due to the larger exergy flow through the process, while the work output is unchanged.

The first law overall efficiencies change markedly between summer and winter, while the change in the second law overall efficiencies is less pronounced. In the latter case, the change in weights roughly evens out the change in component efficiencies. This is in line with the thermal efficiencies quantifying the property for which demand increases in winter (heat), while the latter quantifies the property that is of greater significance in electricity generation, which stays constant between the two seasons.

4. HELLISHEIDI GEOTHERMAL CHP PLANT

The different efficiencies are estimated for the Hellisheidi CHP plant based on the information given in Appendix I.

From the basic variables of the available process diagram, energy and exergy streams can be calculated at different points as shown in Table 18.

TABLE 18: Calculated energy and exergy values for input into efficiency equations

	Basic variables				
$\dot{\zeta}_{gross}$	283.6		303.6		MW
	Min. separator pressure (8.0 bar)		**Max. separator pressure (10 bar)**		
Subscript	**Q**	**E**	**Q**	**E**	**Unit**
in	1909.3	585.0	1886.4	592.0	MW
m*	231.3	29.5	231.3	29.5	MW
$\mathbf{r_{el}}$	183.5	17.5	174.2	15.9	MW
$\mathbf{r_{DU}}$	0	0	0	0	MW
DU	108.7	16.5	108.7	16.5	MW
$\mathbf{\Delta(EP)}$	1210.9 (63.4%)	254.5 (43.5%)	1177.3 (62.4%)	243.1 (41.1%)	MW

Based on the input variables in Table 18, the various efficiencies are reported in Tables 19-22.

TABLE 19: Simple, conditional and functional efficiencies based on gross input (without taking reinjection into account) and gross generation, without an attempt to correct for exergy destruction from wellheads to separators

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Minimum separator pressure (8 bar); $\dot{\zeta}_{gross}$ = 283.6 MW										
Simple	1	14.9	1	5.7	20.5	1	48.5	1	2.8	51.3
Conditional	0.88	15.8	0.12	6.7	14.7	0.95	49.9	0.05	5.5	47.6
Functional	0.88	16.9	0.12	47.0	20.5	0.95	51.0	0.05	56.0	51.3
Maximum separator pressure (10 bar); $\dot{\zeta}_{gross}$ = 303.6 MW										
Simple	1	16.1	1	5.8	21.9	1	51.3	1	2.8	54.1
Conditional	0.88	17.1	0.12	6.9	15.8	0.95	52.8	0.05	5.7	50.4
Functional	0.88	18.3	0.12	47.0	21.9	0.95	54.0	0.05	56.0	54.1

TABLE 20: Simple, conditional and functional efficiencies based on net input (taking reinjection into account) and gross generation, without an attempt to correct for exergy destruction from wellheads to separators

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Minimum separator pressure (8 bar); $\dot{\zeta}_{gross}$ = 283.6 MW										
Simple	1	16.4	1	6.3	22.7	1	50.0	1	2.9	52.9
Conditional	0.87	17.5	0.13	7.5	16.2	0.95	51.5	0.05	5.8	49.1
Functional	0.87	19.0	0.13	47.0	22.7	0.95	52.7	0.05	56.0	52.9
Maximum separator pressure (10 bar); $\dot{\zeta}_{gross}$ = 303.6 MW										
Simple	1	17.7	1	6.4	24.1	1	52.7	1	2.9	55.6
Conditional	0.86	18.9	0.14	7.7	17.4	0.95	54.3	0.05	6.1	51.8
Functional	0.86	20.5	0.14	47.0	24.1	0.95	55.5	0.05	56.0	55.6

TABLE 21: Simple, conditional and functional efficiencies based on gross input (without taking reinjection into account), net generation (internal use assumed 5%) and correction for assumed exergy destruction from wellheads to separators (5%)

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Minimum separator pressure (8 bar); $\dot{\zeta}_{gross}$ = 283.6 MW										
Simple	1	14.1	1	5.7	19.8	1	43.7	1	2.7	46.4
Conditional	0.88	15.0	0.12	6.6	14.0	0.95	45.0	0.05	4.8	43.0
Functional	0.88	16.1	0.12	47.0	19.8	0.95	45.9	0.05	56.0	46.4
Maximum separator pressure (10 bar); $\dot{\zeta}_{gross}$ = 303.6 MW										
Simple	1	15.3	1	5.8	21.1	1	46.3	1	2.6	48.9
Conditional	0.88	16.2	0.12	6.8	15.1	0.95	47.5	0.05	4.9	45.5
Functional	0.88	17.4	0.12	47.0	21.1	0.95	48.6	0.05	56.0	48.9

TABLE 22: Simple, conditional and functional efficiencies based on net input (taking reinjection into account), net generation (internal use assumed 5%) and correction for assumed exergy destruction from wellheads to separators (5%)

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	15.6	1	6.3	21.9	1	45.0	1	2.8	47.8
Conditional	0.87	16.7	0.13	7.5	15.4	0.95	46.3	0.05	5.0	44.3
Functional	0.87	18.0	0.13	47.0	21.9	0.95	47.4	0.05	56.0	47.8
Simple	1	16.8	1	6.4	23.2	1	47.5	1	2.7	50.2
Conditional	0.86	18.0	0.14	7.6	16.6	0.95	48.8	0.05	5.2	46.7
Functional	0.86	19.5	0.14	47.0	23.2	0.95	49.9	0.05	56.0	50.2

According to Table 21, the simple first law efficiency of electricity generation, based upon the design conditions presented in the available process diagram, is quite impressive at 14.1%, even at the minimum reported separator pressure of 8 bar, correcting for internal electricity consumption of the power plant and without considering reinjection to the producing reservoir. The same efficiency metric is at 15.3% at maximum separator pressure of 10 bar. This high thermal efficiency may partially be explained by the 33 MW bottoming unit, as without it the efficiencies would drop to 12.4% and 13.6% respectively – still respectable and above the world average of 12% reported by Moon and Zarrouk (2012). A rather high enthalpy is also a factor.

When reinjection is taken into account, the same two efficiencies are calculated as 15.6% and 16.8% respectively. With 9-10% of the primary energy reinjected (Table 18), the efficiencies increase by roughly the same percentage. The process diagram shows around 62% of the production fluid mass being reinjected. Gunnarsson (2011) has reported on some challenges of reinjection at Hellisheidi power plant and that some brine has been discharged into a shallow groundwater reservoir. Probably, the information shown in the process diagram is based on ideal conditions.

When observing simple efficiencies, it is also notable how low the thermal direct utilization efficiency is, at 5.7-5.8% as shown in Table 21 and 6.3-6.4% when considering reinjection (Table 22). This can, at least partly, be ascribed to the fact that only around a third of the DU production potential is being utilized, with additional capacity to be added in 2020 and 2030 according to Hallgrímsdóttir et al. (2012). Those capacity addition will lead to increases in the simple direct utilization efficiency.

As seen in the tables, 86-88% of the thermal energy is used for the electricity generation process, while only 12-14% is used for direct utilization. This is somewhat misleading though as the production for the district heating system is not running at full potential, so some of the thermal energy that is discarded could be ascribed to the direct utilization process, but not solely to the electricity generation process. The low weighting on the direct utilization process also leads to a large difference between the functional thermal efficiency of direct utilization on one hand and the corresponding simple and conditional efficiencies on the other.

Most of the exergy is ascribed to the electricity generation process (95%), while only 5% is transferred to the district heating transmission pipeline.

5. REYKJANES GEOTHERMAL POWER PLANT

Figure 5 in Appendix I shows a process diagram for a single 50 MW unit of the Reykjanes geothermal power plant. The values used for calculation of the different efficiencies are as shown in Table 23.

TABLE 23: Basic variables of the Reykjanes geothermal power plant process obtained from Figure 5 in Appendix I. Values are from Ravazdezh (2015) unless otherwise noted.

Peripheral point (subscript)	Basic variable	Value	Unit
Inflow to separator (in)	Mass flow ($\dot{m}$)	314	kg/s
	Enthalpy (h)	1384[1]	kJ/kg
	Pressure (P)	18	bar
Reinjection	Mass flow ($\dot{m}$)	60	kg/s
	Temperature (T)	160	°C
	Pressure (P)	6.2[2]	bar

1: Calculated from given values in the process diagram; 2: Saturation pressure.

Table 24 shows the input values to the efficiency equations in the usual format.

TABLE 24: Calculated energy and exergy values for input into efficiency equations. Reference conditions are taken as (8.5°C, 1 atm).

	Basic variables		
$\dot{\zeta}_{gross}$	50	50	MW
Subscript	**Q**	**E**	**Unit**
in	423.3	130.7	MW
m*	0	0	MW
r	38.4	7.7	MW
DU	0	0	MW
$\boldsymbol{\Delta}$(**EP**)	334.9 (79%)[1]	73.0 (56%)[1]	MW

1: Disposal to the ocean

Based on the input variables in Table 24, the various efficiencies are reported in Tables 25-28.

TABLE 25: Simple, conditional and functional efficiencies based on gross input (without taking reinjection into account) and gross generation, without an attempt to correct for exergy destruction from wellheads to separators

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	11.8	1	0	11.8	1	38.3	1	0	38.3
Conditional	1	11.8	0	0	11.8	1	38.3	0	0	38.3
Functional	1	11.8	0	-	-	1	38.3	0	-	-

1: Weight; 2: Division by zero. It should be understood that the direct use (DU) efficiencies are irrelevant when none of the fluid is directed towards direct use applications.

TABLE 26: Simple, conditional and functional efficiencies based on net input (taking reinjection into account) and gross generation, without an attempt to correct for exergy destruction from wellheads to separators

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	13.0	1	0	13.0	1	40.7	1	0	40.7
Conditional	1	13.0	0	0	13.0	1	40.7	0	0	40.7
Functional	1	13.0	0	-	-	1	40.7	0	-	-

TABLE 27: Simple, conditional and functional efficiencies based on gross input (without taking reinjection into account), net generation (internal use assumed 5%) and correction for assumed exergy destruction from wellheads to separators (5%)

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	11.2	1	0	11.2	1	34.5	1	0	34.5
Conditional	1	11.2	0	0	11.2	1	34.5	0	0	34.5
Functional	1	11.2	0	-	-	1	34.5	0	-	-

TABLE 28: Simple, conditional and functional efficiencies based on net input (taking reinjection into account), net generation (internal use assumed 5%) and correction for assumed exergy destruction from wellheads to separators (5%)

	$W_{1,el}$ (-)	$\eta_{1,el}$ (%)	$W_{1,DU}$ (-)	$\eta_{1,DU}$ (%)	$\eta_{1,overall}$ (%)	$W_{2,el}$ (-)	$\eta_{2,el}$ (%)	$W_{2,DU}$ (-)	$\eta_{2,DU}$ (%)	$\eta_{2,overall}$ (%)
Simple	1	12.3	1	0	12.3	1	36.6	1	0	36.6
Conditional	1	12.3	0	0	12.3	1	36.6	0	0	36.6
Functional	1	12.3	0	-	-	1	36.6	0	-	-

As no direct utilization is reported in the process diagram, the tables are quite straightforward to read, with the electricity generation efficiencies at reasonable values. In recent years, however, there has been increasing direct use associated with the plant. Direct use applications have benefitted from discharge fluids from the power plant, most notably the Stolt Sea Farm where Senegalese Soles are cultivated for human consumption. This is not taken into account here due to lack of information, but it is noted that this will increase the overall efficiencies of the power plant.