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Exergoeconomic Analysis of the Hellisheiði Geothermal Power Plant

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ABSTRACT

The Hellisheiði geothermal flash power plant has been operating since 2005, with an installed capacity of 303 MW of electricity and 200 MW of heat for district heating. As a combined heat and power facility, it must allocate production costs between electricity and heat to set appropriate tariffs. While electricity generation is flexible to some extent and can adapt to market demands, heat production for district heating must meet seasonal needs but at the same time always have the capacity (200 MW) available to the district heating service. The peak heat load for the district heating network depends on the growth of the market (new buildings growing the system by 2-3% annually). This means that if the heat market is growing by about 20 MW per year, new heat production capacity is added in 120–130 MW stages. At that growth rate, it takes 6–7 years for the additional capacity to be fully utilized.

This study analyzes the plant's operations using exergoeconomic optimization, which combines exergy (useful energy) analysis with economic evaluation. A detailed thermodynamic model calculates heat, and exergy flows at key points within the plant, while a value analysis model estimates monetary flows based on capital and operational expenditures (CAPEX & OPEX). Diagrams such as Sankey, Grassmann, and value flow charts are used to visualize plant performance. Key metrics include the exergoeconomic factor, which relates investment cost to inefficiency costs for each component, and the component cost ratio, which highlights components with the greatest impact on product value.

These metrics help identify over- or under-engineered components and assess whether component quality aligns with overall plant performance. The findings provide insights into improving plant efficiency and cost-effectiveness, support cost allocation between heat and electricity, and the paper concludes with practical design recommendations for similar geothermal plants.

1 DISCLAIMER

The views, opinions, and conclusions expressed in this presentation and the research project it is based on are solely those of the author and do not necessarily reflect the views or positions of ON Power. Any statements or interpretations should not be construed as representing the official stance of the company unless explicitly stated otherwise.

2 INTRODUCTION

Thermoeconomic or exergoeconomic analysis makes it possible to identify "gold-plated" (over-engineered) and "junkyard" (under-engineered) components in a plant. A high-quality, high-cost (gold-plated) plant will be hurt by using a low-quality, low-cost (junkyard) component in the plant. In the same way it is a waste of investment to build a junkyard plant with a single "gold-plated" component in the vain hope that this component will make the poor-quality plant good.

2.1 Data available for this work

ON Power has made process data for the power plant available, and an operation model of the Hellisheiði plant is presented by (Jakobsson 2024) serves as the main source of data for this work. The analysis is based on a snapshot of plant capacity and operation taken on 2023-01-17 at 16:00.

Financial data is confidential and was not available for this work. The necessary financial inputs for the modeling are estimates, based on the best knowledge of the authors regarding market prices and on good engineering practice. These estimates will be treated further later in the paper. The authors are aware that the costs of certain parts of the plant are underestimated. The cooling towers and gas extraction systems are an example of this, where the auxiliary power consumption is only guesswork as well as the component installation cost itself.

The absolute values in this paper must therefore be taken with a grain of salt, but the results show the importance of exergoeconomic plant analysis.

3 EXERGOECONOMICS

Exergoeconomics combines exergy analysis with economic analysis. A brief overview of the main concepts is provided here, while more comprehensive treatments can be found in the literature (Bejan et al 1996; Adefila et al 2015; Fujii et al 2011). Earlier exergoeconomic analyses applied to geothermal plants are found in (Andal 2019; Dorj 2005). The exergy principles and plant-analysis methods on which this work is based are drawn from established references such as (Kotas 1985; Valdimarsson 2010).

3.1 The environmental state (dead state)

The environmental state sets the base for heat flow and exergy analysis. This is the lowest energy state that is possible in the given environment. The environmental state is defined by temperature and pressure. Further treatment of the dead and environmental states can be found in (Szargut 1988).

For reactive systems a dead state is used, where a base chemical potential is defined. This is not necessary here, as no chemical reactions are considered.

The selected environmental state used here is the outside summer day temperature. It is independent of the exact time of the snapshot; the value should be valid for the whole year. The selected values are 10°C for T_0 and 1 bar absolute for P_0.

3.2 The flows in a component

The flows of a component in a plant are as follows:

- ***Input flows:*** Each component in the plant has an input, where heat, exergy and value flow into the component. This is also referred to as feed or raw material for the component.
- ***Output flows:*** A component will also have an output, where heat, exergy and value flow from the component into the next component in the chain or to the environment as a final product. This is also referred to as product flow, i.e. the flow of the component's products.
- ***Loss flows:*** The loss flows are streams leaving the components that are not of any use in the plant and are disposed of, usually to the environment.
- ***Destruction:*** Exergy is not conserved. Therefore, exergy is destroyed in a component due to friction or entropy generation, and this is displayed as a stream in the same way as for the loss flows. This is only valid for the exergy analysis.
- ***Value flows:*** The value or cost flow is the monetary flow entering the component. It is carried by the flow of exergy, so a specific value of exergy can be calculated by dividing the value flow amount by the magnitude of the exergy flow.
- ***Investment flows:*** The investment flow is a value flow which is caused by the burden of the investment in the component. It includes capital and operational expenditure (CAPEX & OPEX).
- ***Disposal value flows:*** The second law of thermodynamics states that any plant must reject (dispose of) heat and material to the environment. It is assumed that the environment accepts the disposal flow free of charge. The value of the input flow entering the component that is disposing of the flow to the environment will be negative. There is a cost caused by the investment in the component, and as the outflow has zero value, the inflow will have a negative cost value. The negative value also means that the value flow is in the opposite direction of the exergy flow.

3.3 Heat flow analysis

A component will conserve heat flow. There is no destruction of heat because of the first law of thermodynamics. Heat flow into and out of a component is therefore conserved.

$$\dot{Q}_{F,k} = \sum_n \dot{Q}_{Pn,k} + \dot{Q}_{Lo,k} \quad (1)$$

- $\dot{Q}_{F,k}$: The heat inflows to component k.
- $\dot{Q}_{Pn,k}$: The heat outflows in the products of component k, where n is the number of the product.

- $\dot{Q}_{Lo,k}$: The heat flow in the loss streams from component k.

3.4 Exergy analysis

Exergy is not conserved in a component. A part of the exergy inflow to a component will be destroyed due to irreversibility within the component. The conservation equation for exergy will therefore include destruction as a stream.

$$\dot{X}_{F,k} = \sum_n \dot{X}_{Pn,k} + \dot{X}_{Lo,k} + \dot{X}_{D,k} \quad (2)$$

- $\dot{X}_{F,k}$: The exergy inflow to component k.
- $\dot{X}_{Pn,k}$: The exergy flow in the products of component k, where n is the number of the product.
- $\dot{X}_{Lo,k}$: The exergy flow in the loss streams from component k.
- $\dot{X}_{D,k}$: The exergy destroyed within component k.

3.5 Value analysis

Only exergy carries value. The value is presented as a flow stream, so the cost of the initial capex must be found and presented as a value flow in monetary units per time into the component, just as the heat and exergy flows are presented in watts, which is an energy or exergy unit per time unit (J/second). The OPEX of the component being analyzed is then added. In this paper, all value flows are converted to monetary units per hour. Value inflow is the monetary flow stream, which is added to a component, composed of the contribution to CAPEX and OPEX. Exergoeconomic analysis is value (or cost) based and does not consider the worth of a product on the market. It enables us to estimate the cost of destruction and losses. A component will conserve the value flow. There is no destruction of value flow because the products of a component must "pay for" the input and investment value flows. The loss and destruction streams carry no value.

$$\dot{C}_{F,k} = \sum_n \dot{C}_{Pn,k} + \dot{C}_{Lo,k} + \dot{Z}_k \quad (3)$$

- $\dot{C}_{F,k}$: The value inflow (carried by the exergy flow) to component k.
- $\dot{C}_{Pn,k}$: The value outflow (carried by the exergy flow) in the products of component k, where n is the number of the product.
- $\dot{C}_{Lo,k}$: The cost of disposing of a loss stream from component k.
- $\dot{Z}_k$: The investment cost flows for component k.

The investment cost flow is calculated from the initial investment in the component. The yearly capital cost of the investment is found and estimated operation and maintenance cost is then added. This is then changed to the appropriate unit of time, which in this paper is an hour. The yearly cost parameters used in this paper are 5% interest rate, OPEX of 3% and depreciation 4% (25 years depreciation time). This results in a yearly cost of 12% of the investment. These values are ballpark figures. For some parts of the plant different OPEX and depreciation rates should be used. The selected interest rate could be based on the actual WACC (weighted average cost of capital) for the plant, which will certainly result in a different value. Using consequent set of values for the plant will fulfill the needs of this paper, which is to give an overview of the value flow in the plant.

The exergy stream harvested from the environment is free of charge. The stream value is zero until a component that harvests the stream has been installed. The value input to that component is therefore only the investment flow. With this argumentation, the flow from a geothermal reservoir into the well is free of charge. At the wellhead the value flow is equal to the investment flow into the wells.

This study has shown that this is not good practice. This is explained in Section 6 in this paper, and a different approach is suggested. It is also considered that a loss stream enters the environment free of charge. The components which are necessary to bring this flow from the core plant process to the environment are not free of charge, so a negative disposal cost will have to be assigned to the core process that causes the loss stream to be sent to the environment. An example is the condenser. The flow from the turbine to the condenser will eventually enter the environment as humid air from the cooling tower, which is free of charge. But all the investment and OPEX of the condenser, gas extraction system, and cooling tower must be assigned to the turbine as a negative disposal cost, which will in turn increase the value of the electricity produced by the turbogenerator. The disposal cost is denoted as $\dot{C}_{Lo,k}$.

3.6 The flows in a component in exergoeconomic analysis

The flows within a component in an exergoeconomic analysis are shown in Figure 1 in order to summarize the discussion of the flows in the previous Sections 3.1 to 3.5.

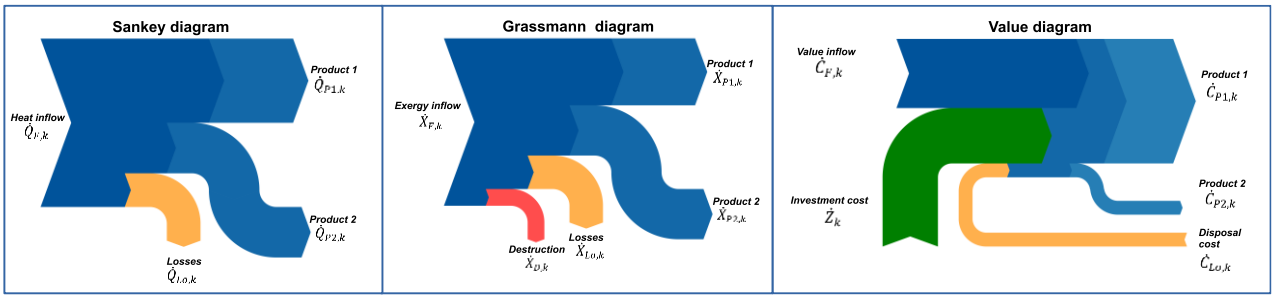


Figure 1. Flow of heat (Sankey diagram), exergy (Grassmann diagram) and value (Value diagram) in a component.

3.7 The exergoeconomic parameters

Here five parameters are used in the exergoeconomic analysis.

3.7.1 Exergy efficiency

The exergy efficiency ε_k is the ratio between the outflow of exergy and the inflow of exergy in component k:

$$\varepsilon_k = \frac{\sum n \dot{X}_{Pn,k}}{\dot{X}_{F,k}} \tag{4}$$

3.7.2 Destruction ratio

The destruction ratio $y_{D,k}$ is the ratio of destroyed exergy to the inflow of exergy in component k:

$$y_{D,k} = \frac{\dot{X}_{D,k}}{\dot{X}_{F,k}} \tag{5}$$

3.7.3 Loss ratio

The loss ratio $y_{Lo,k}$ is the ratio of lost exergy to the inflow of exergy in component k:

$$y_{Lo,k} = \frac{\dot{X}_{Lo,k}}{\dot{X}_{F,k}} \tag{6}$$

3.7.4 Relative cost change

The relative cost change is the ratio between the specific value of the exergy outflow and the exergy inflow. The specific cost for a stream is the ratio between the cost flow and exergy flow in component k:

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{X}_{F,k}} \qquad c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{X}_{P,k}} \tag{7}$$

- $c_{F,k}$: The specific cost for a feed stream.
- $c_{P,k}$: The specific cost for a product.

The relative cost difference is the change in specific cost in component k:

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \tag{8}$$

- r_k : The relative cost difference in component k.

3.7.5 Exergoeconomic factor

The exergoeconomic factor weighs the investment cost against the cost of destruction and losses in the component (or plant). It is then assumed that the lost and destroyed exergy has value, and the cost of destruction and losses is based on the specific value of the inflows. It is the same as saying: "If we can reduce the losses and destruction by one unit, we will need one unit less of the feeds." The exergoeconomic factor for component k is defined as:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_F \cdot (\dot{X}_{Lo,k} + \dot{X}_{D,k})} \quad (9)$$

If the investment cost is large and the cost of losses and destruction is low, then the component is a high-cost, high-quality component and the value of the exergoeconomic factor approaches one.

On the contrary, if the investment cost is small and the cost of losses and destruction is high, then the component is a low-cost, low-quality component and the value of the exergoeconomic factor approaches zero.

A good design for a plant is achieved when the exergoeconomic factor is similar across all components. A good value of the exergoeconomic factor is determined by the market value of the products and the costs (market value) of the feeds to the plant.

3.8 Competitive market and monopoly

For a CHP (Combined Heat and Power) plant, there are two main products: electricity and heat. Electricity is sold on a competitive market, whereas heat for district heating is sold in a regulated monopoly market. Icelandic law clearly states that one product may not be used to subsidize the other, see (Althingi 2003). Iceland is a member of the European Economic Area, so the directives of the European Union are valid in Iceland. Of importance here is the directive on common rules for the internal market in electricity, see (EU 2009). Production of electricity operates in a competitive market, where the price of the product is set by supply and demand. District heating is considered a monopoly product, where the customer has no choice in selecting the supplier. The price of district heating is set by an appropriate authority on a cost-plus basis. This is the same approach that applies for transmission and distribution of electricity.

ON Power sells electricity in a competitive market and is not allowed to subsidize it by using income from a product on a monopoly market. That would cause unfair competition for other vendors in the competitive market. To ensure compliance, the costs of plant components are divided into district heating, electricity, and joint components. The costs of components that belong solely to district heating or electricity are allocated directly to the appropriate cost center. Costs of joint components are divided based on a predefined allocation factor.

This paper considers an allocation method based on exergy, which provides a way of representing the comparative value of the energy streams. This approach is used here for illustrative purposes and is entirely different from the methodology presently used by ON Power and which is approved by the authorities.

4 THE HELLISHEIÐI GEOTHERMAL POWER PLANT

The Hellisheiði Geothermal Power Plant is a double flash combined heat and power plant. The incoming geothermal fluid from the source system is throttled into HP (high-pressure) separators, which supplies steam for six HP turbines. The brine from the HP separators is throttled into a LP (low-pressure) separator, which produces steam for a single LP turbine. The condensers are surface condensers with three passes in total. The top pass of the HP condensers serves to preheat freshwater for district heating, and the two lower passes are supplied with cooling water in circulation with the wet cooling towers. Water for district heating is produced in a bottoming heat exchanger plant. Fresh cold and clean water is taken from groundwater wells, preheated in the condenser before being heated further by the brine from the LP separator.

4.1 The plant as a whole

The plant components may be grouped into eight component groups. Each group is analyzed as if it were a single component. The groups are as follows:

1. Reservoir, wells and collection system
2. HP (high-pressure) separator
3. HP turbine
4. HP disposal system (condenser, cooling tower and gas extraction system)
5. LP (low-pressure) separator
6. LP turbine
7. LP disposal system (condenser, cooling tower and gas extraction system)

8. DH (district heating supply) system

The plant PFD (process flow diagram) together with the component groups is shown in Figure 2.

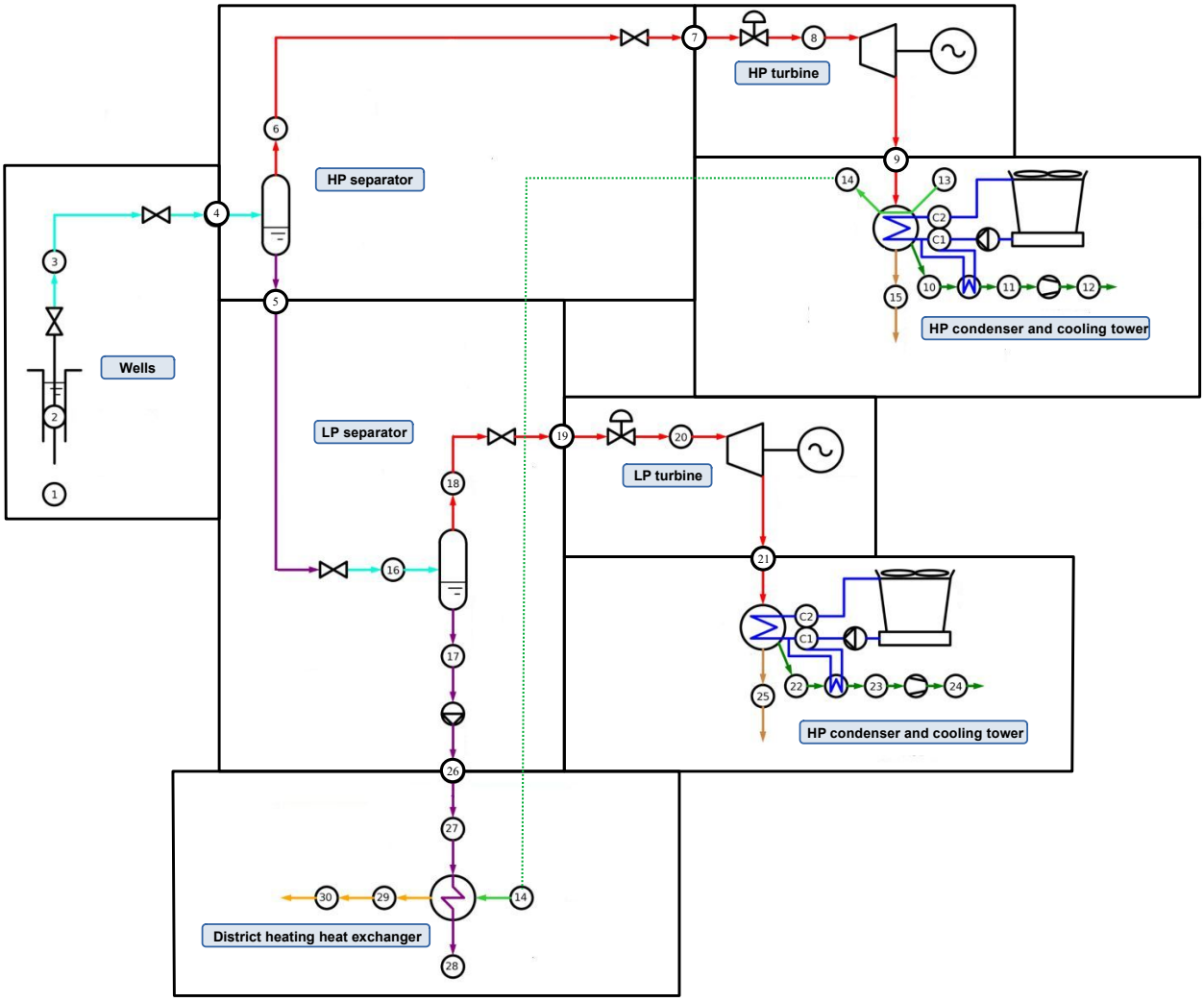


Figure 2. The PDF (Process Flow Diagram) of the Hellisheiði plant (with thermodynamic station numbering and component groups)

The flows to and from the power plant that interact with the environment are as follows:

Feeds: Node 1 is geothermal fluid from the reservoir into the wells and node 13 is fresh water for district heating water production.

Products: Produced electricity from HP and LP turbines, node 30 is water supplied to the district heating system.

Losses: Hot and humid air rejected from the cooling towers, nodes 12 and 24 are non-condensable gas rejected from the condensers, nodes 15 and 25 are rejected condensate and node 28 is brine rejected to re-injection.

5 PLANT ANALYSIS

It was decided to normalize all analysis results, as the paper is based on very rough estimates of all financial data. An analysis of the plant heat flow was made, and a Sankey diagram was made. The heat flows are normalized by setting the heat inflow to the wells at node 1 to a value of 100. An analysis of the plant exergy flow was made, and a Grassmann diagram of the plant was made. The exergy flows are normalized by setting the exergy inflow to the wells at node 1 to a value of 100. An analysis of the plant value flow was made, and a value flow diagram of the plant was made. The value flows are normalized by setting the sum of the product values from the HP turbine, LP turbine and district heating to a value of 100. It is assumed that the water sent to the district heating heat exchangers in node 14 enters the system at the environmental temperature T_0 and does not contribute to the heat or exergy flows. Same is valid for the air entering the cooling towers.

5.1 Heat flow analysis

The energy flows of all components have been evaluated and visualized in the Sankey diagram shown in Figure 3. This representation highlights the flow of energy through the plant. Based on this analysis, the overall first law efficiency of the plant is calculated to be 33.14%.

5.2 Exergy analysis

The exergy flows of all components have been evaluated and visualized in the Grassmann diagram shown in Figure 4. This representation highlights the flow of exergy through the plant as well as the locations of exergy destruction and losses. Based on this analysis, the second-law efficiency of the plant is calculated to be 48.63%.

5.3 Value analysis

The values of the capital cost of each component are confidential, therefore an educated guess for the price of each component is used. These estimated values are taken from (Jakobsson 2024). As an example the turbine cost is estimated to be 0.56 m.€/MW, and the heat exchanger cost is estimated to be 280 €/m^2 of heat transfer surface. The value flow diagram is shown in Figure 5. The value flow diagram of the Hellisheiði plant

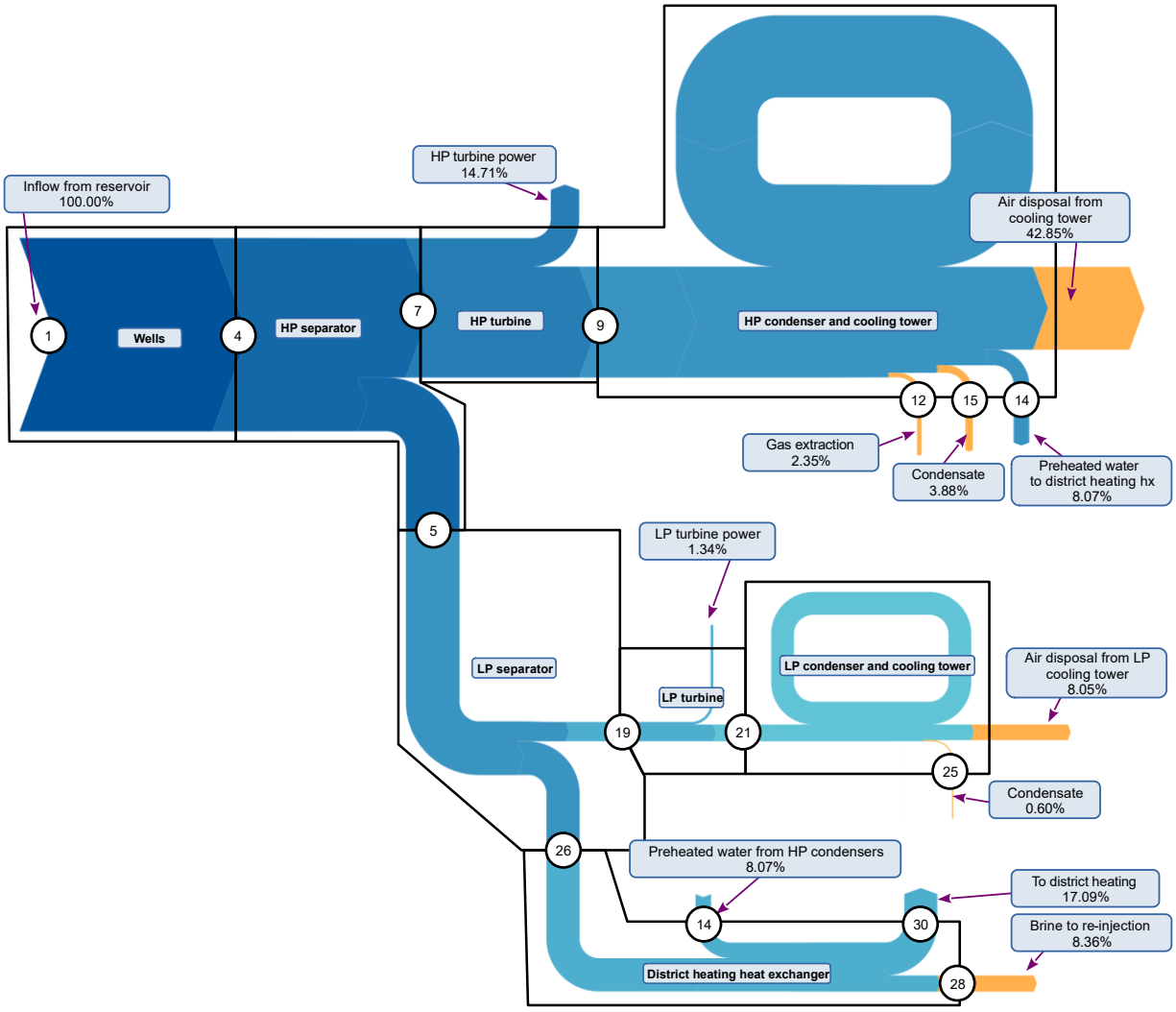


Figure 3. The Sankey (heat flow) diagram of the Hellisheiði plant

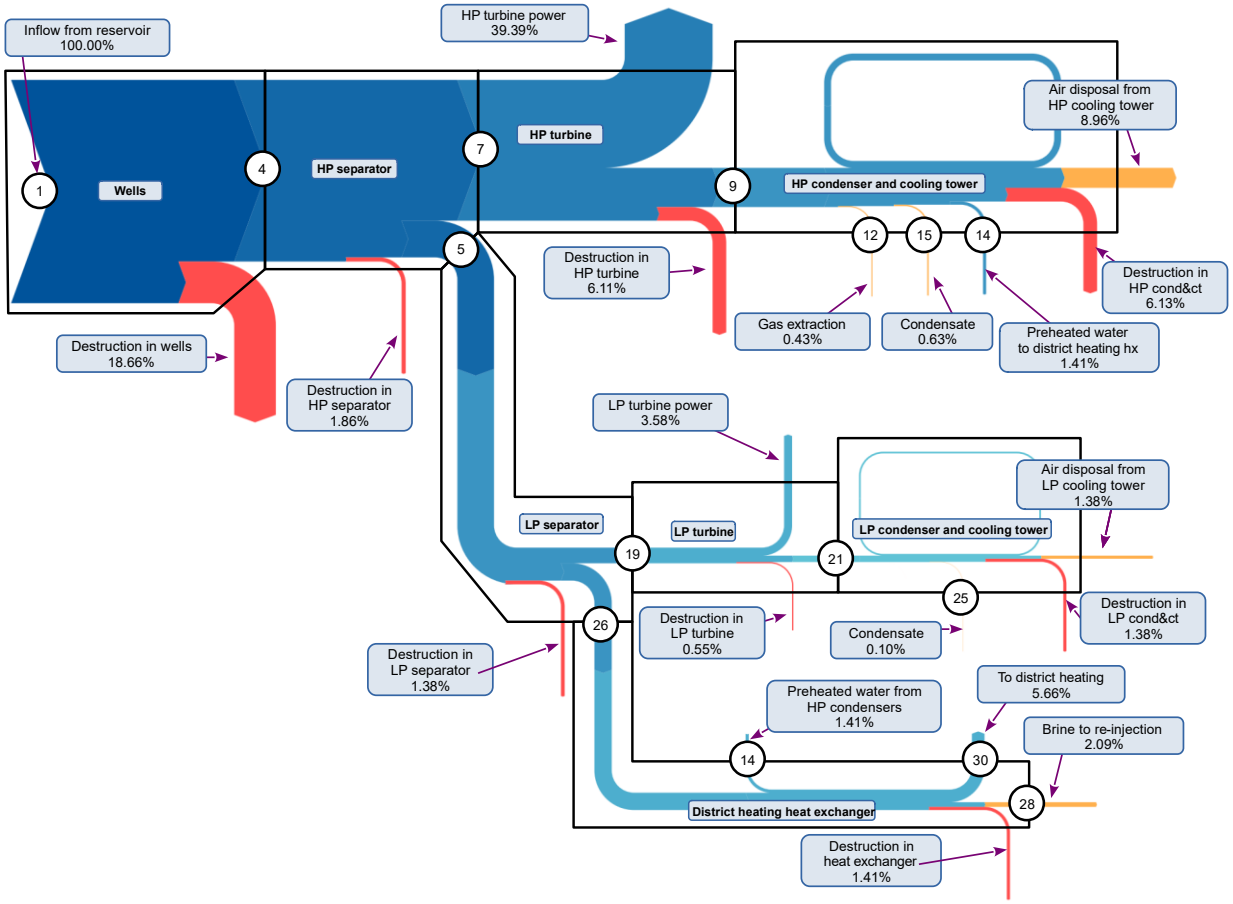


Figure 4. The Grassmann (exergy flow) diagram of the Hellisheiði plant

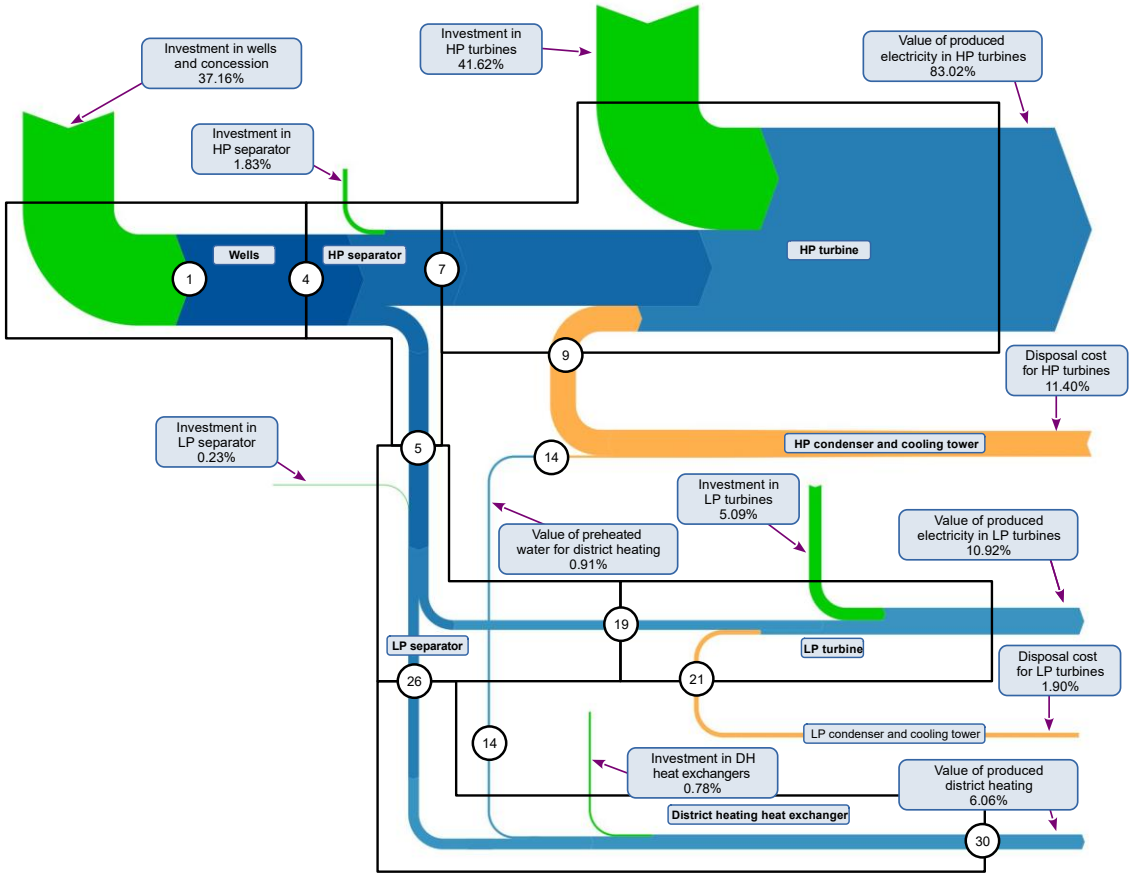


Figure 5. The value flow diagram of the Hellisheiði plant

6 RESULTS AND LEARNINGS

The Hellisheiði plant uses geothermal resources that currently have no associated feed or disposal costs. Losses are released to the environment without charge. This situation is unlikely to persist, as natural resources are typically taxed or priced in market economies. Iceland's fishing industry demonstrates this trend; long-term catch permits have become more valuable than the fish themselves, like how enterprise value can exceed EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortization).

Most exergoeconomic studies concern plants with fuel costs. In geothermal plants, the fuel cost is zero, producing atypical exergoeconomic results for wells and the resource-supply system (see Table 1). The total value of the products equals the total investment cost flows, and the same applies to loss disposal. Disposal value flows counter the direction of exergy flow, and the exergy value at environmental discharge is zero. Future disposal of geothermal non-condensable gases is also unlikely to remain free. Hellisheiði currently disposes of these gases through company Carbfix (https://www.carbfix.com/), but the cost is unknown and excluded from this analysis.

The HP disposal system produces preheated water for district heating system at node 14, which yields different exergoeconomic parameters compared with the LP disposal system, which has no product and only disposal. The exergoeconomic parameters are now calculated as follows:

Table 1. Exergoeconomic parameters for the Hellisheiði geothermal plant.

	Wells	HP separator	HP turbine	HP condenser and cooling tower	LP separator	LP turbine	LP condenser and cooling tower	District heating heat exchanger station
Exergy feed	100	81.3	63.1	17.6	16.4	7.00	2.86	9.17
Exergy in product	81.3	79.4	57.0	1.41	14.8	6.45	0.00	5.66
Exergy losses	0	0	0	10.0	0.00	0.00	1.48	2.09
Exergy destruction	18.7	1.86	6.11	6.13	1.67	0.55	1.38	1.41
Investment value flow	37.2	1.83	41.6	-11.4	0.23	5.09	-1.90	0.78
Feed value flow	0	37.2	41.4	10.5	8.05	5.83	-1.90	5.27
Product value flow	37.2	39.0	83.0	0.91	8.29	10.9	0.00	6.06
Exergy efficiency	81.3 %	97.7 %	90.3 %	8.02 %	90.0 %	92.1 %	0.00 %	61.7 %
Destruction ratio	18.6 %	2.28 %	9.69 %	35.0 %	10.2 %	7.88 %	48.2 %	15.4 %
Loss ratio	0 %	0 %	0 %	57.0 %	0 %	0 %	51.8 %	22.8 %
Specific feed value	0.00	0.45	0.66	0.60	0.49	0.83	-0.66	0.57
Specific product value	0.46	0.49	1.46	0.65	0.56	1.69	0.00	1.07
Cost ratio	infinity	7.37 %	122 %	8.72 %	14.5 %	103 %	-100 %	86.1 %
Exergoeconomic factor	100 %	68.3 %	91.2 %	54.2 %	21.8 %	91.7 %	100 %	28.0 %

All units in the table are normalized, as defined in Section 5. Numerical values for the specific value of feeds and products are calculated by dividing value flow by exergy flow.

The component values show expected trends. Turbines exhibit high exergoeconomic factors and high exergy efficiency. The LP turbine increases total product value by about 10%, which is lower than anticipated. The HP separator performs within expected ranges, while the LP separator may warrant further examination. Disposal costs require additional analysis, and the assessment method may also need reconsideration. However, disposal costs remain small relative to total product value.

7 CONCLUSION

The exergoeconomic analysis and accompanying Sankey, Grassmann, and value-flow diagrams provide a clear overview of the plant's energy and value distribution. The results support discussions on potential taxation of geothermal resource supply and environmental disposal.

The analysis suggests the valuation of district heat, discussed in Section 3.8. Costs are allocated according to exergy flow and specific exergy value. This framework is important for assessing the value of additional heat extraction and for estimating costs of new products previously treated as losses.

It is the view of the authors that this analysis is a good foundation for valuation of the products from a geothermal CHP power plant, for which comparable approaches appear to be absent from the current literature, especially the aspects regarding the division between products on the competitive market and the monopoly operation. It seems that the reason for the lack of literature in this regard is largely because district heating is not a monopoly market in countries with existing natural gas networks. Their district heating competes directly with natural gas heating and ground-source heat pumps. In Iceland there is no natural gas network, and the cost of district heating is so much lower than that of any other alternative that defining district heating as a monopoly becomes the only practical solution.

8 FURTHER WORK

The investment in the wells is assumed to include all associated costs, including permits, land, concession fees, geoscientific research as well as the drilling and collection system. It is reasonable to separate this and allocate the well-related costs into "concessions, permits and resource-related charges" and "wells and drilling". It is also common to treat the power plant as a single unit and the wells and supply system as a separate unit. The boundary between these two units is node 4. Finally, it is reasonable to include a cost block representing disposal to the environment for the relevant parts of the plant.

This suggests conducting a similar analysis as has been done in this paper with only four component groups: resources, wells and drilling, plant and disposal.

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