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BASIC CONCEPTS OF THERMOECONOMICS

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ABSTRACT

The following text is covering the basic principles of thermodynamics to be treated in lectures "Thermoeconomics - striving for optimum component size and efficiency" and "Financial aspects of the geothermal operations".

1. THERMOECONOMICS

Thermoeconomics analyze the power generation economics from the exergetic viewpoint. A thorough treatment of thermoeconomics is found in Bejan et al (1996) and El-Sayed (2003).

Thermoeconomics deal with the value of the energy within a plant, where heat and work conversion finds place. The analysis is based on exergy flows, and breaks the plant up into individual components, where each component can be analyzed separately.

Each component will have one or more exergy input (feed) streams, and one or more output (product) exergy streams. A feed stream is either input to the plant, or is a product of a previous component. An output stream is either a product from the plant or a feed to the next component in the chain. Exergy loss due to irreversibilities will occur in all components of the power plant. This is the so-called exergy destruction, and the stream is termed exergy destruction stream for the subject component. In some components there will be a rejected exergy stream, which is of no further use in the process. This is the exergy loss, and exergy loss stream for the subject component. Figure 1 is a schematic which shows this relationship better.

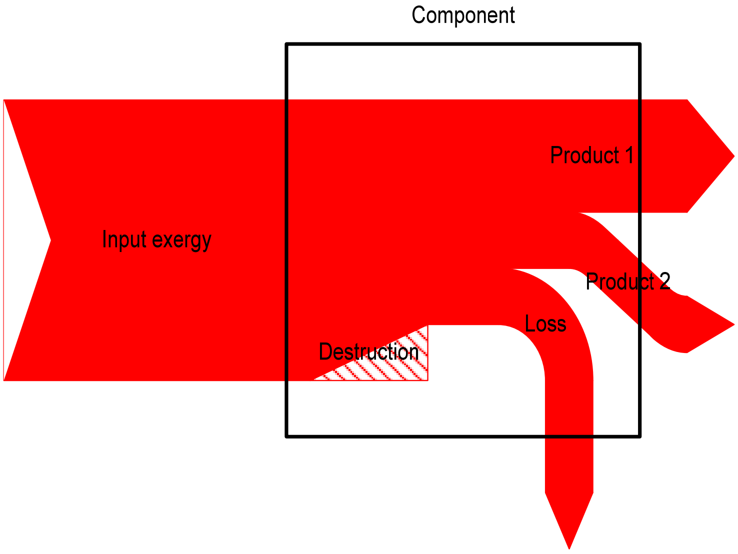

FIGURE 1: Component exergy streams

Anergy is assumed to have no value, as well as all exergy loss streams and destruction streams. The unitary exergy cost is calculated for each point in the energy conversion process, and cost streams are used to gain an overview over the economics of the power generation process. Each component will have three types of cost flows associated, the input exergy cost flow, the component investment cost flow, and the product exergy cost flow. A cost balance, equating the product cost flows (all having the same unitary exergy cost) to the sum of the input exergy cost flows and the component investment cost flow.

The component has to be paid for and maintained. The associated cost is fixed, and is not dependent on the magnitude of the exergy streams entering and leaving the component. The investment cost flow is calculated as:

$$\dot{Z} = \dot{Z}_{CI} + \dot{Z}_{OM} \tag{1}$$

where:

$\cdot$ = Dot above character denotes time derivative (rate) [1/s, 1/h];
CI = Capital and investment (index);
OM = Operation and maintenance (index); and
Z = Fixed cost [$].

The unitary exergy cost is important for the study of the component performance. Each kilowatthour of exergy entering and leaving the component carries cost (or has value), which can be compared to the cost of electricity. The exergy stream is then a product of the unitary exergy cost and the exergy flow:

$$\begin{aligned} \dot{C}_i &= c_i \dot{X}_i = c_i \left(\dot{m}_i x_i \right) \\ \dot{C}_e &= c_e \dot{X}_e = c_e \left(\dot{m}_e x_e \right) \\ \dot{C}_w &= c_w \dot{W} \\ \dot{C}_q &= c_q \dot{X}_q \end{aligned} \tag{2}$$

where:

$\cdot$ = Dot above character denotes time derivative (rate) [1/s, 1/h];
e = Product, output, exit (index);
C = Cost, value [$];
c = Unitary (specific) cost, value [$/kWh];
i = Feed, input (index);
m = Mass [kg];
q = Heat (index);
W = Work [kJ, kWh];
w = Work or power (index);
X = Exergy [kJ, kWh]; and
x = Specific exergy [kJ/kg].

The Sankey diagram in Figure 2 describes cost flow for a sample component graphically.

There is no such thing as a free lunch. The cost flow of the products must be equal to the sum of all incoming cost flows, both those connected with exergy as well as the investment cost flow. This balance is written as:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k \tag{3}$$

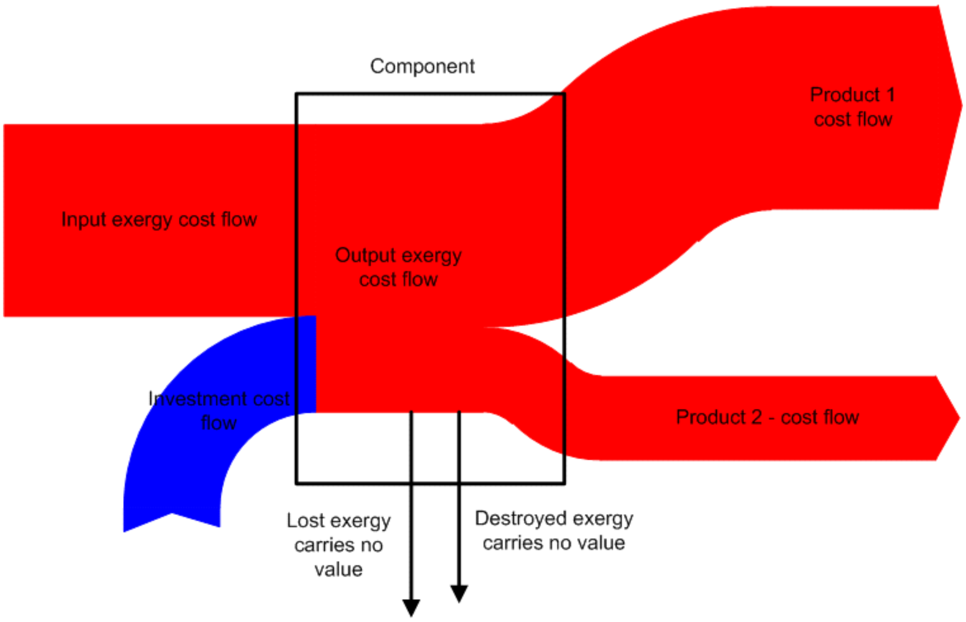

FIGURE 2: Component cost (value) streams

where:

˙ = Dot above character denotes time derivative (rate) [1/s, 1/h];
C = Cost, value [\$];
e = Product, output, exit (index);
i = Feed, input (index);
k = Number of component;
q = Heat (index);
w = Work or power (index); and
Z = Investment cost [\$].

It is traditional in thermodynamics to consider heat flow as input and work flow as output. That is the reason for entering the heat cost flow as input and the work (power) cost flow as output.

The product cost flow can now be solved from this equation, assuming that all previous components in the chain have already been solved.

Equation 1.3 is now modified to include unitary cost values:

$$\sum_e \left(c_e \dot{X}_e\right)_k + c_{w,k}\dot{W}_k = c_{q,k}\dot{X}_{q,k} + \sum_i \left(c_i \dot{X}_i\right)_k + \dot{Z}_k \tag{4}$$

where:

˙ = Dot above character denotes time derivative (rate) [1/s, 1/h];
C = Cost, value [\$];
c = Unitary (specific) cost, value [\$/kWh];
e = Product, output, exit (index);
i = Feed, input (index);
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W = Work [kJ, kWh];
w = Work or power (index);
X = Exergy [kJ, kWh]; and
Z = Investment cost [\$].

Thermoeconomic optimization will not be treated further here, but this discipline has very powerful tools, enabling the designer to keep consistent economic quality in all components in the power production chain.

2. FEASIBILITY AND ECONOMICS

Thermoeconomy is a very powerful tool to optimize individual plant components. One of the main benefits is that the thermoeconomic tools enable us to deign with consistent quality and performance for all of the installed components.

This is a different question to the question if the plant is a good idea at all. A feasibility study should reveal that. In order to make a useable feasibility study, two main estimates have to be done:

a) Estimation of income
b) Estimation of power plant cost

The income estimate cannot be done unless having a good process model at hand, taking into account the climatic conditions over the year, properties of the wells and geothermal fluid, as well as a thorough model of the plant internals.
Such a model will then be able to yield estimates for the power produced by the generator, the power consumed by parasitic components such as circulation pumps and cooling tower and of course thermodynamic process data for the power plant cycle.

The estimation of cost for the plant involves estimating the size of individual components and their price, in addition to installation and secondary cost. It is worth to keep in mind that roads, buildings, fire protection, environmental protection components, control systems, and even lockers and showers for the employees are also a part of the power plant cost.

All this is small compared to the cost invested in the geothermal field, purchase or lease of land, concession fees, field research, and finally drilling of wells. In far too many cases this is considered sunk cost, and is not taken into the account when designing the power plant, with the result that the plant is optimal, assuming that all cost outside the plant is sunk and paid by space aliens.

The cost estimate considering all the cost will yield a larger power plant, suboptimal if only the plant is considered, but giving a higher income and therefore a contribution to the amortization of the field cost.

Renewable energy projects have typically very low variable cost if any at all. The plant has to be built and paid for in the beginning, and will after that produce power without much additional cost. Usually total cost will not be reduced if the plant is run on reduced power.

The value of the parasitic power is sometimes complicating the calculations. The price of produced green energy from the power plant may be substantially higher than the market price on the grid due to green subventions. One possible way of simplifying this is to calculate a net present value for every kilowatt of parasitic power and simply add that to the plant investment cost.

2.1 The mathematics

The three equations of engineering have to be fulfilled, always, everywhere:

a) Conservation of mass
b) Conservation of momentum
c) Conservation of energy.

The only way to make an estimation of the power produced and thus the income is to make a mathematical model of the power plant. The thermodynamic properties of the geothermal fluid and the plant working fluid have to be incorporated, and the model has to be built on the laws of thermodynamics. They are not subject to negotiation, they are absolute.

The plant is then described in a large set of non-linear equations, which have to be solved. A mathematical environment called Engineering Equation Solver (EES) has been used by the author for this purpose. EES has thermodynamic properties of most of the relevant fluids built in, and is already an equation solver, as the name implies.

Heavyweight software such as Aspen or Simulis is of course capable of such modelling, but is expensive and requires much training in order to be an effective tool. Matlab is a standard numerical environment today, but lacks thermodynamic properties. It is possible to integrate Matlab with properties programs made by the US National Institute of Standards (NIST), but this integration is not commercially available and requires in-depth knowledge of programming. Matlab is polished, tried and tested and has a huge user base. But Matlab is also a notorious “hard to learn, easy to use” program.

2.2 Degrees of freedom for the plant design

A binary power plant has around 25-30 design parameters for the thermal design. Some of these parameters have values, which do not change much from case to case. Others are critical optimization parameters. All these parameters are dependent on the plant surroundings, the field parameters, and the market parameters. It is therefore absolutely critical to determine the plant input parameters correctly. The selection of all other parameter values is dependent on that.

The score function for the plant operation is also critical. A common misunderstanding is to take some more or less well founded efficiency value and use that as the only criterion to determine if the plant is good or bad. A power plant is built to produce power as cost effectively as possible. Therefore it is a lot more sensible to base the power plant design on some specific power plant cost in $/kW, ensuring that both the cost model and the power plant model is reflecting the reality as closely as possible.

Geothermal power production is simply a chain of components or processes from the inflow into the well all the way over to the power plant transformer station. The objective is to convert as much of the exergy found in the well inflow to sellable power, electricity or heat. And as typical with any chain, it will never be stronger than the weakest link. The power plant cold end and the associated cooling fluid supply is a part of this chain.

The 25-30 design parameters that have to be selected define an optimization space with a dimension which is one higher that the number of parameters.. The optimization process has therefore a huge number of degrees of freedom, and there are not many general universally usable solutions available, which can give satisfactory performance.

There is no way around a careful design and selection of all these design parameters.

3. GEOTHERMAL FIELD AND WELLS

The well is one of the most expensive part of the power production system. The well will have production dependent on the wellhead pressure. The maximum flow will occur with wellhead pressure zero, and zero flow will yield the well closure pressure, which is again the maximum wellhead pressure. The well characteristic curve will be a deciding factor in the selection of the separator pressure in the flash plants for higher enthalpy fields. Lower separator pressure, higher well flow, higher steam ratio from the separator, but lower quality steam. The lower the wellhead pressure, the lower in the well the boiling of the fluid will start, and finally boiling will occur in the formation, usually with horrible results. Scaling may occur in the formation, destroying the well.

The field enthalpy is a major criterion for the power plant design, and will more or less determine which power plant type can be used. The fluid chemistry is another decisive factor. Scaling behaviour of the fluid usually demands a certain minimum geothermal fluid temperature to be held throughout the entire power plant. Corrosion may require certain materials or the use of additives. Non-condensable gas in the fluid may require gas extraction system with the associated parasitic loss. Therefore the power plant designer is bound by the fluid enthalpy and chemistry for his selection of the design parameters. To disregard the comments of the geochemist is a sure way to failure.

From the viewpoint of thermoeconomics, the inflow to the well is free of charge, but when the fluid has reached the surface the exergy stream from the well has to carry the field development, drilling and well construction investment cost.

4. EXAMPLE OF COST CALCULATION

Assume that the field development and well cost amounts to 5 000 000 € for each well. Two production wells are drilled and one re-injection well. The well production is 150 kg/s, and the well is low enthalpy, producing only liquid water. The environment is taken at 10°C, 1 bar pressure. Yearly capital cost and operation and maintenance are taken as 10% of investment. Utilization time is assumed 8000 hours per year.

Under these assumptions the well exergy flow can be calculated as well as the unitary exergy cost.

These results show, that a substantial part of the final cost of electricity is already defined by the well. If we could buy an ideal lossless power plant at zero price, this would be the final cost of electricity.

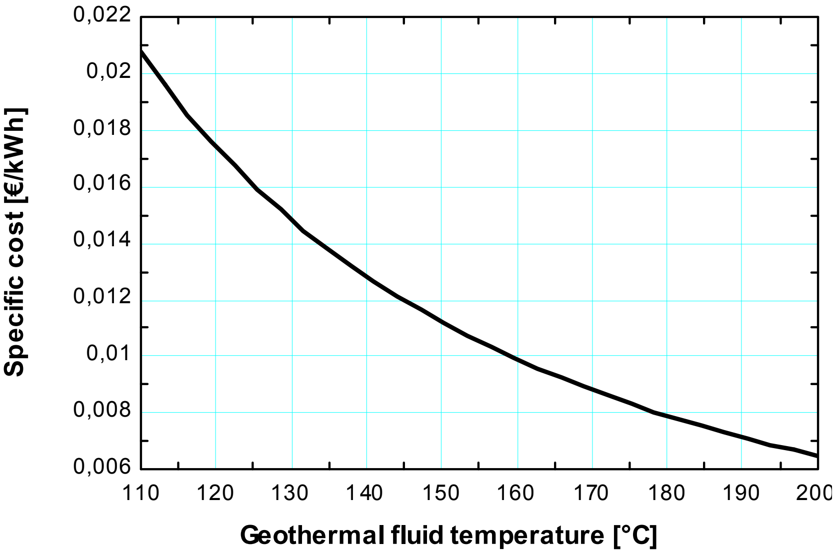

FIGURE 3: Unitary well exergy cost

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