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Development of an exergo-economic and exergo-environmental tool for power plant assessment: evaluation of a geothermal case study

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Abstract:

Exergo-Economic and Exego-environmental analyses are extremely powerful tools that allow designers to understand the mechanism of economic and environmental cost build-up inside an industrial power plant process. The knowledge of such mechanisms is of paramount importance in order to identify the components that have a greater impact on the final costs, allowing to focus on them for the improvement design effort. For that reason in this study, an application to allow less experienced users to perform such analyses is presented and discussed. The application has been developed in Matlab and Python and presents a spreadsheet interface that allows the user to recreate the analysed plant configuration. Once the scheme has been defined the application will automatically generate and solve the economic or environmental cost matrix.
The application and the cost correlations have been tested over several cases and the results have been compared with other in-house tools. A geothermal case study is thus presented, in order to display the easiness and powerfulness of the developed tool.

Keywords:

Exergo-economic, Exergo-environmental, Thermodynamic, geothermal, software, innovative tool

1. Introduction

In order to meet the goal of limiting global warming to 1.5°C compared to pre-industrial levels, several countries are acting towards a renewable cleaner energy production. However, renewable energies cannot be the only solution in the short term, therefore energy efficiency and energy optimization of industrial systems seem to be a necessary step. Energy system optimization comprises several aspects, from thermodynamic optimization, to cost and environmental. It deals with both energy systems and industrial projects and tries to describe the best design solution depending on the target goal, which could be lower production cost, lower environmental impact, etc.

Among energy systems optimization methods, exergo-economic (EEA) and exergo-environmental (EEvA) analyses have seen an outstanding rise since the 1980s. EEA and EEvA combine exergy analysis with economic and environmental analysis, respectively. Exergy is the net available energy that can be converted into work during a thermodynamic transformation with the environment. Exergy comprehends in its definition both the first and second law of thermodynamics, as it includes the concept of irreversible process. Indeed, exergy losses and destruction are defined as the energy which is not properly converted in available work. Exergy losses comprise of energy discharged to the environment, like heat losses, discharge of fluid flows with non-zero energy, direct work losses, etc., while exergy destructions are connected to the irreversibility of a system of a component, such as friction losses, heat transfer from high to low temperature fluids, etc. Therefore, exergy analysis has become a powerful tool to assess energy conversion systems. Exergy analysis has therefore been applied for the improvement in the design of the power plant, in order to understand the inefficiency of the system. Coupling this powerful tool to the aspect of economic and environmental assessments allows the creation of a robust, reliable method to identify along with the power plant configuration, which are the most impacting components, or systems, from an economic and environmental point of view.

Particularly, the joint of exergy and economic analysis gives birth to the exergo-economic analysis, which is an assessment method to determine the production costs of all services provided (costs of products of a given element of the system, e.g. electricity, or heat produced). The exergo-economic approach follows the cost balance equation (Eq. 1), which can be defined for each component of the system.

$$\dot{C}_{p_{tot}} = \dot{C}_{F_{tot}} + \dot{Z}_{tot} \qquad (1)$$

Where:

- $\dot{C}_{p_{tot}}$ and $\dot{C}_{F_{tot}}$ are the cost rates associated with the exergy products (p) and fuels (f), respectively
- $\dot{Z}_{tot}$ is the sum of the cost rates associated with the investments for the k-th component

Similar to the exergo-economic analysis, the exergo-environmental analysis couples the exergy and the environmental analysis. The environmental analysis is developed through the life cycle assessment (LCA), which allows obtaining the environmental impact of each component of a system. Successively, these impacts can be assigned to each exergy stream of the analysed system in order to highlight at the same time the contributions of the use of resources, such as material, production, services, and the effects of the irreversibility and the inefficiencies of the components of a system. Following the analogy with the exergo-economic analysis, also the exergo-environmental analysis is based on the environmental balance equation (Eq. 2).

$$\sum \dot{\mathrm{B}}_{\mathrm{k,in}} + \dot{\mathrm{Y}}_{\mathrm{k}} = \sum \dot{\mathrm{B}}_{\mathrm{k,out}} \qquad (2)$$

Where:

- $\dot{\mathrm{B}}_{\mathrm{k,in}}$ and $\dot{\mathrm{B}}_{\mathrm{k,out}}$ are the environmental impact rate, expressed in single score eco-points for the exergy streams in the input (in) and output (out) of the components respectively
- $\dot{Y}_k$ is the environmental impact rate associated with the life cycle of component k.

Exego-economic and exego-environmental analyses have therefore found a productive range of applications, as they have been applied to several fields, such as in energy systems like gas turbine [1], steam power plants [2], combined cycles [3], organic Rankine cycles [4,5], inverse cycles [6], in renewable energy assessment, such as in solar [7,8], biomass [9], or geothermal power plants [10-12], or applied to storage assessment applications, like thermoelectric storage [13,14], or phase change materials [15].

The development of such analyses is most of the time based on in-house coding [16], starting from commercial software, such as Aspen Plus [17], EES[18], Matlab[19], Unisim Design[20], Ebsilon[21], for the thermodynamic analysis and then computing exergy, exergo-economic and exergo-environmental analyses on their on. Only some tentative codes have been developed in order to schematically solve the exergy, exergo economic and exergo-environmental analyses. One of the proposed code one developed by Zhao, 2015, during his Ph.D. work. His work involved the development of a computer program for the exergo economic analysis for energy conversion systems. The inputs for his software (thermodynamic variables of the systems) were obtained from Aspen Plus, but they could have been derived from any other simulation software. After that, the exergo economic software was developed in C++ programming, with Microsoft visual studio 2008. The software developed demonstrated the high capability of utilization, through the simulation of several case studies, however, it is still not available online.

The only software that is actually available online for exergo-economic assessment is TAESS [22], the Thermo-economic Analysis and Energy Systems Software, developed by CIRCE and the department of Mechanical Engineering of the University of Zaragoza. TAESS is a tool based on Microsoft Excel 2007/2010 interface, which requires as input data the thermodynamic model and the configuration of the system. Once the system is defined within the excel environment, and all the thermodynamic properties of streams are appropriately reported, the code automatically generates a Fuel-Product table, as well as an assessment on the formation of the build-up costs. This software has been used by several researchers [23,24] for the development of exergo-economic analysis, however, it did not find widespread success, probably due to the not-so-intuitive interface.

The literature review showed that exergo-economic and exergo-environmental analyses are finding an uprising interest for the assessment of energy systems, but it seems that a clear and complete design tool for the development of such analyses, assuring a simple and flexible utilization seems to be missing. Therefore, the main goals of this study are (i) to develop a tool for exergy-based tool for exergo-economic and exergo-environmental analyses (ii) to provide a clear explanation of its features.

The current version of the software still does not include a drag and drop user interface, however, the beta version is already accessible https://pypi.org/project/3ETool/ and could be freely tested by any researcher.

2. Methodology

The methodology described hereafter is presented in relation to the exergo-economic analysis. However, due to the symmetry between them, that is evident comparing Eqs. (2) and (3), exergo-environmental and exergo-economic analyses are performed with the same methodology considering different input sets, as they will be been presented in this section.

2.1. Inputs Definition

In order to perform the analysis, the application requires four main inputs:

- The physical **topology** of the plant;
- The **exergy flows** for each stream ($\dot{e}_x$ [kW]);
- The **cost / environmental impact** of each component of the plant ($\dot{Z}$ [€/s] / $\dot{Y}$ [Pts/s]);
- The specific **cost / env. impact** of each connection coming from the ambient ($\dot{c}_0$ [€/kJ] / $\dot{b}_0$ [Pts/kJ]);

Topology

In the program's convention, the plant topology is described as a *directed graph*. This means that a group of *blocks,* representing the components of the plant, is linked by a series of *connections*, i.e. the material streams or the energy flows. For each block, the user must specify the *type* of the represented component (e.g. "*expander*" or "*valve*") in order to allow the program to correctly identify product and fuel streams. In figure 2.1 is presented how this description applies to a simple regenerated gas turbine system.

Exergy Flows

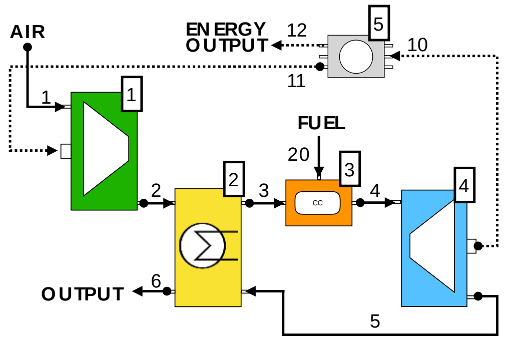
The program requires the exergy value of each stream of the connection list. These values can be retrieved from the software used to perform the thermodynamic modelling of the components and can be provided to the program in an excel sheet or a *.dat* file.

Component and Connection Costs

The user must provide the cost, or the environmental impact for the exergo-environmental analysis, of each component in the block list. Such cost can be directly provided by the user or evaluated by the software using some built-in cost correlation, in the latter case the user must provide the parameter of the cost correlation, e.g. the area of a heat exchanger. The user must also provide the cost of the input streams of the system, if no cost is provided the program automatically sets it to 0.

The inputs just described must be provided by the user through a precompiled excel input. This approach has proven to be extremely error-prone especially for the topology definition. A more intuitive drag and drop user interface is, therefore, under development and should be a major improvement in ensuring the accuracy of the calculation, especially for the user who, because of a lack of experience, is unable to immediately assess the correctness of the obtained results.

A)



B)

Blocks

ID	Name	Type
1	*Compressor*	*Compressor*
2	*Regenerator*	*Heat Exchanger*
3	*Combustion Chamber*	*Combustion Chamber*
4	*Turbine*	*Expander*
5	*Power Shaft*	*Generic*

Connections

ID	Name	From ID	To ID
1	*Air Inlet*	*Ambient*	*1*
2	*Compressor Outlet*	*1*	*2*
3	*CC Inlet*	*2*	*3*
4	*Turbine Inlet*	*3*	*4*
5	*Turbine Outet*	*4*	*2*
6	*Air Outlet*	*2*	*Ambient*
10	*Turbine Power Output*	*4*	*5*
11	*Comp Power Input*	*5*	*1*
12	*Net Power Output*	*5*	*Output*

Fig. 2.1. Description of a simple regenerated gas turbine power plant according to our topology convention. A) Graphical description, B) Block and connections representation.

2.2. Cost Matrix Generation

The goal of an exergo economic analysis is to calculate the specific cost [€/kW] of each exergy stream of the process, this is done by solving the linear system composed by the cost balance equation for each component. Unfortunately, balance equations are not enough to close the system as the process has usually more streams than components; for this reason, most of the authors define a set of *auxiliary equations* to make the system solvable.

The approach of this work is slightly different: instead of solving the system for the specific cost of each connection, we use as unknowns the cost of the product of each block, implicitly assuming that, in case of a component having multiple products, they all have the same specific cost. The latter assumption is consistent with the "*P principle*" described by Lazzaretto e Tsatsaronis in defining the SPECO methodology [25].

The advantage of this approach is that it eliminates the need for the *auxiliary equations* in the system definition, making the matrix generation algorithm extremely easy to implement and reducing the matrix dimension. Indeed, the system resulting from this new approach is simply composed of the cost balance equations for each component, i.e. *Eq. (1)*, that can be rewritten as:

$$\sum_{prod} \dot{c}_p \dot{e}_p - \sum_{fuels} \dot{c}_f \dot{e}_f = \dot{Z}_{tot} \quad (3)$$

Or, considering the "*P principle*" assumption:

$$\dot{c}_p \sum_{prod} \dot{e}_p - \sum_{fuels} \dot{c}_f \dot{e}_f = \dot{Z}_{tot} \quad (4)$$

In eq. (5), $\dot{c}_f$, namely, the specific cost of fuel, can be both a known value, if the fuel is a global input of the process, or equal to $\dot{c}_p$ of the component that generates such a fuel stream. Hence the summation over fuels in eq. (5) can be rewritten as:

$$\dot{c}_{p_i} \sum_{prod} \dot{e}_{ik} - \sum_{f_{int}} \dot{c}_{p_j} \dot{e}_{ij} = \dot{Z}_{tot} + \sum_{f_{ext}} \dot{c}_0 \dot{e}_{oi} \quad (5)$$

Where:

- f_{ext} are fuels entering into the system from the ambient, e.g. the gas entering in a combustion chamber, their cost is known and must be provided by the user; if no cost is provided, the program automatically sets it to 0.
- f_{int} are internal fuels, hence they are generated by another component of the process.
- $\dot{e}_{ik}$ represent an exergy flow that is a product of the i-th component and fuel for the k-th one, i = 0 represent the ambient

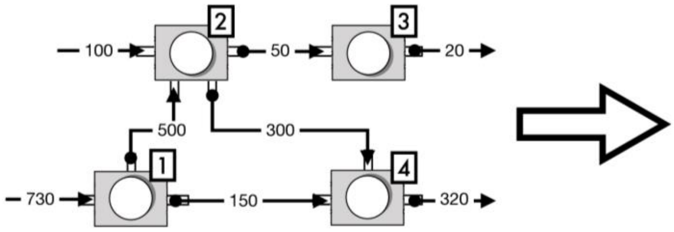
Eq. (5) is the balance equation for the i-th component and is the one used for the matrix generation purpose in our application.

Considering that the unknowns of the system are the product costs $\dot{c}_{p_i}$, the class *block,* which represents a component in the topology, is able to generate an array that represents its cost balance, i.e. eq. (6). Another part of the software collects all the arrays and stacks them to form the matrix that has to be solved.

The arrays are generated following these simple rules:

- For each *internal fuel* f_{int}, hence for each input connection that originates from another block of the system, the specific exergy $\dot{e}_{ij}$ must be added with a negative sign in the j-th position, where j, in our formalism, is the index of the block from where the connection comes.
- $\sum_{prod} \dot{e}_{ik}$, namely the sum of the exergies of the connections that originate from the block, is placed in the i-th position (the diagonal of the matrix).
- $\dot{Z}_{tot} + \sum_{f_{0i}} \dot{c}_0 \dot{e}_{x_{oi}}$, will be collected separately in order to form the known variable vector.

In *fig. 2.2* is shown an example of such array generation.



500 + 150	0	0	0	**730** $\dot{c}_{in_1} + \dot{Z}_1$
-500	**300 + 50**	0	0	**100** $\dot{c}_{in_2} + \dot{Z}_2$
0	**-50**	**20**	0	$\dot{Z}_3$
-500	**-300**	0	**320**	$\dot{Z}_4$

Fig. 2.2. Array generation example, each row in the matrix has been generated by the corresponding block according to the procedure described above. $\dot{c}_{in_i}$ *is the cost of the stream entering in the system;* $\dot{Z}_i$ *is the cost of the i-th block.*

Topology Modification

Unfortunately, it is not possible to directly perform the described calculation on the topology as it is provided by the user. In most of the applications, indeed, the definition of products and fuel did not match with the physical incoming and outcoming streams from a block. In order to deal with this problem, the program automatically adapts the topology through two-steps, before performing the calculation:

- **STEP 1: Block fuels and product identification:**

The first step is to make sure that the input and output connections of each component represent an actual fuel or product respectively. The program does so employing some *support bocks,* which are blocks in which exergy is preserved and $\dot{Z}_{tot} = 0$.

To make the working principle of this methodology clearer is useful to start with an example: consider a simple expander, like the one shown in figure 2.3. As explained in many articles [25, 26] the fuel of an expander is the differences between the input and output exergies, namely:

$$\dot{e}_{fuel} = (\dot{e}_{flow\_in} - \dot{e}_{flow\_out}) \quad (6)$$

Besides, according to the SPECO "*F-Principle*":

$$\dot{c}_{fuel} = \dot{c}_{flow\_in} = \dot{c}_{flow\_out} \quad (7)$$

This is reproduced in our code by inserting a support block at the input of the expander and by connecting all the fluid streams to it, as shown in *figure 2.3*. Each support block sets the exergy value of the stream connected to the main block in order to preserve the exergy that passes through itself:

$$\dot{e}_{main} = \sum_{in} \dot{e}_{in} - \sum_{out} \dot{e}_{out} \quad (8)$$

Eq. (8) is reduced to eq. (6) in the expander case. Moreover, eq. (7) results from the cost balance of the support block. Recalling that $\dot{Z}_{supp\_block} = 0$ and noticing that, in the expander case, *flow$_{out}$* and *fuel* are considered as products by the program, which consider "*products*" each output stream and "*fuels*" the input ones, eq. (5) reduces to:

$$\dot{c}_{out}(\dot{e}_{fuel} + \dot{e}_{flow_{out}}) - \dot{c}_{flow\_in}\dot{e}_{flow_{in}} = 0 \quad (9)$$

Where $\dot{c}_{fuel} = \dot{c}_{flow\_out} = \dot{c}_{out}$, according to the implicit "*P-principle*" resulting from our approach. Substituting eq. (6) in eq. (9) will result in $\dot{c}_{flow\_in} = \dot{c}_{out}$ that is equivalent to eq. (7).

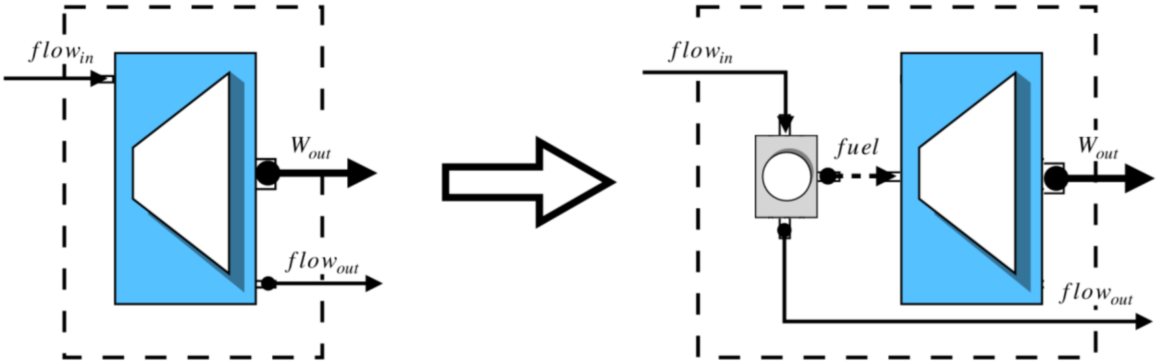


Fig. 2.3. Support block generation for an expander.

This method can be applied to all the situations in which the fuel or the product of a particular process is the difference between input and output exergy and that requires the cost to be preserved. The program automatically generates and connects the support blocks according to the component type.

Solving the system using the matrix generated by the described set of blocks and support blocks, considering input connections in a block as "*fuels*" and output as "*products*", is equivalent to solving the system resulting from the SPECO analysis. In fact, for normal blocks inputs and outputs are the actual fuel and product as defined in SPECO, hence the cost balances are the same. Moreover, as just demonstrated, the support block's balances correspond to the *F-Principle* auxiliary equations, resulting in the same system.

- ***STEP 2: Product-Fuel Diagram* generation:**

A second topology modification is needed in order to allow the system to properly redistribute the costs of the exergy loss through the components. For understanding the need of this step is important to know how the program handles the exergy loss streams, hence a brief description of this issue is provided hereafter.

Exergy Loss Treatment

An *exergy loss* is a stream of exergy leaving the system without being a useful effect, e.g. the remaining heat in the exhaust gases of a gas turbine or the unburnt particles of fuels leaving a coal boiler. In the literature there are two main alternative approaches on pricing the *exergy losses,* the user has the capability to select the approach that is more suitable to his need:

- $\dot{c}_{loss} = \dot{c}_{fuel}$. This is the approach proposed by Lazzaretto and Tsatsaronis for the SPECO methodology. It has the advantage of not breaking the "F-principle" and identifying an actual price to the loss stream. The main disadvantage is that this approach does not preserve the overall cost balance of the plant. Pricing the loss with $\dot{c}_{loss} \neq 0$ is equivalent to stating that there will be a buyer for that exergy stream that is willing to pay such a price. This results in a reduction of the price for the actual product of the system that will become lower to the one that ensures a positive return of investment.[1]

- $\dot{c}_{loss} = 0$, this approach resolves the issues of the previous ones but, on the contrary, does not provide a clear expense for the dispersed energy. Moreover, it breaks the "*F-Principle*". For example, in the regenerator of *figure 2.1*, $\dot{c}_6$ should be equal to $\dot{c}_5$ according to the "*F-Principle*" but, as stream 6 is an exergy loss, $\dot{c}_6 = 0$. This fact poses the problem of the cost redistribution because solving the system with the topology just described, will drop all the cost increase on the component that is directly connected with the loss, like the regenerator, even if such component is not directly responsible for such loss, as in this case. To solve this problem, the topology has to be modified to reflect the *fuel-product diagram* as described by Torres and Valero [23]. *Figure 2.4* shows this transformation for the

1 Sometimes this approach can cause some confusion in less experienced user also because of the fact that we call **cost** of the loss what it's actually, in the perspective of the component, the **price** at which you are selling the outgoing exergy. In this perspective, it's easy to understand that, pricing the losses with $\dot{c}_{loss} \neq 0$ is an economic advantage for the system, despite intuition suggesting otherwise.

system of *Figure 2.1*. As it is clear from the figure, after this transformation a modification on $\dot{c}_6$ impact on both the fuel cost of the turbine and the regenerator, resulting in a better redistribution.

In order to perform this transformation, the program simply identifies the fuels calculated by the means of the support blocks and connects them to the block that actually convert the related exergy, for example the combustion chamber in *figure 2.3*, skipping the ones that simply conveys such exergy, like the turbine for the 5th exergy stream.

The specific costs evaluated using the *P-F diagram* are then assigned to the corresponding streams.

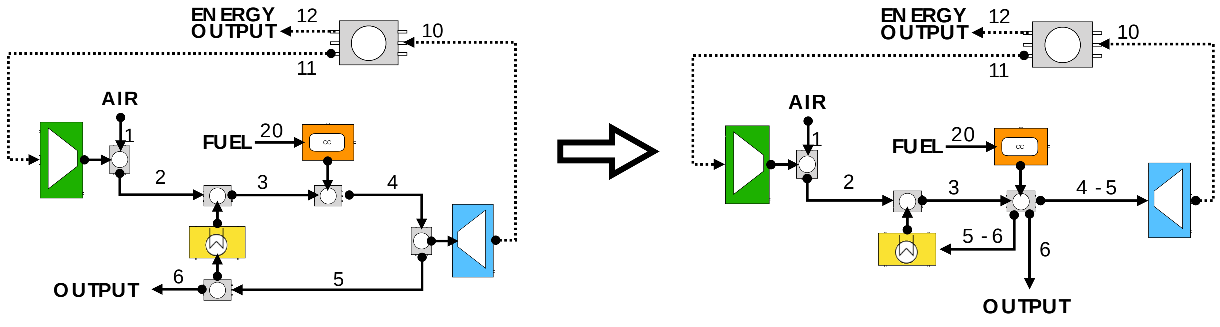


Fig. 2.3. Product Fuel diagram generation for plant represented in figure 2.1. Left Side: Topology with support blocks; Right Side: P-F diagram representation.

3. Results

3.1. Geothermal Case Study: Hellisheiði Power Plant

The selected case study is the combined heat and power double-flash geothermal power plant of Hellisheiði. The power plant presents several interesting points to be highlighted with exergo-economic and exergo-environmental analysis, such as the treatment of the cooling towers and the combined generation of heat and power. A simplified schematic of the power plant is presented in *Fig. 3.1*. The geothermal fluid extracted from the production well is reduced at a pressure of 10 bar within the first steam separator. After that, the steam is expanded in the HP turbines (6 turbines of 45 MW each) and then condensed in the HP steam condenser. Part of the heat recuperated from the condensing steam is used for heating the cold fresh water extracted which will be then sent to the Reykjavìk district heating system. The condensed liquid from the HP separator is flashed again and the steam is sent to a low pressure turbine (of 33 MW), while the condensed heat finish heating the fresh water for the district heating network.

In the following sections, the passages needed for a complete exergo-economic analysis are presented, and the result provided by the application are shown. Moreover, an in-house code in EES environment has been developed in order to validate the results of the developed tool. The EES code allows the calculation of both exergo-economic and exergo-environmental analysis.

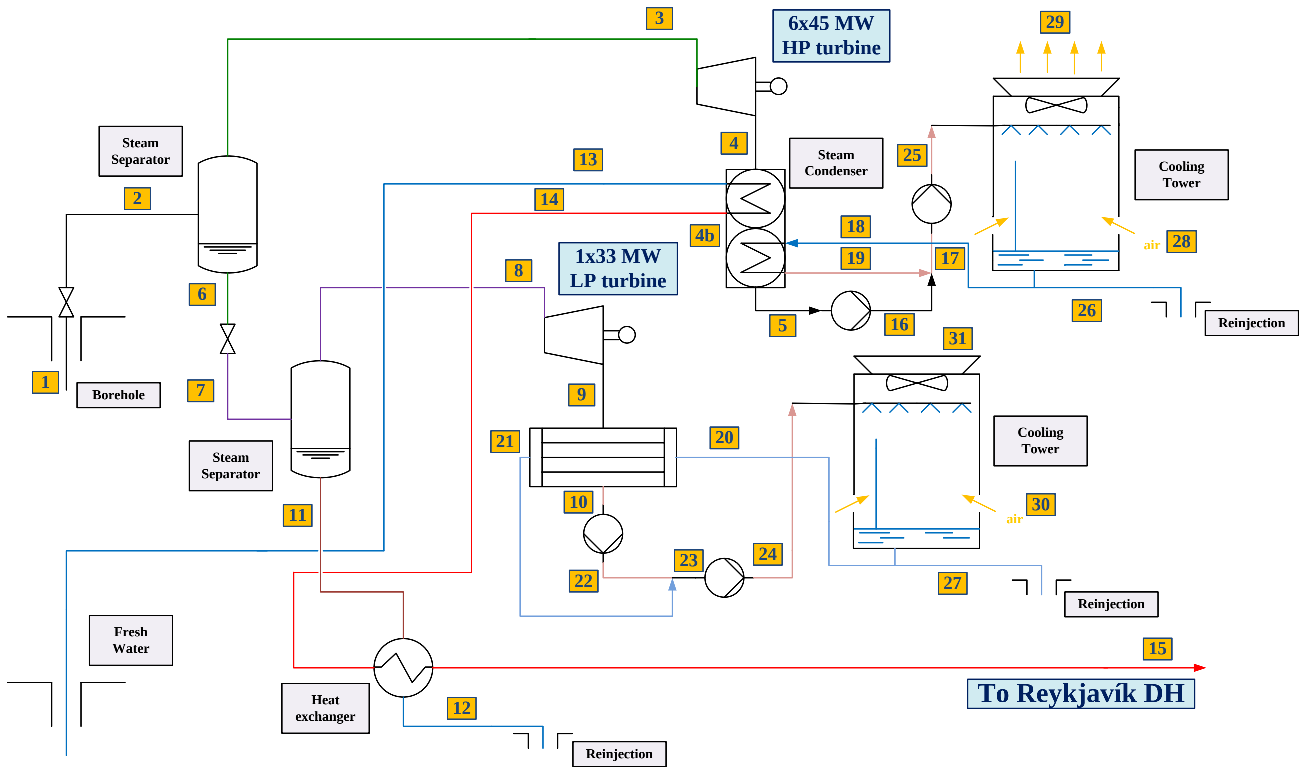


Fig. 3.1. Simplified schematic of Hellisheiði power plant.

Exergo-Economic Analysis:

- ***Inputs Calculations***

In order to determine the investment and O&M costs ($\dot{Z}_{tot}^{CI} + \dot{Z}_{tot}^{OM}$) of the power plant, an economic analysis was carried out. The first step was the calculation of the component's costs, which was done following the methodologies proposed in [27-31]. The components costs were determined from a standard mathematical relationship, which was subsequently improved with correction factors accounting for component class, working pressure, and equipment materials. The costs are expressed in $ and then converted in € with the 0.92 [€/$] conversion factor. Finally, the obtained value was actualized to the reference year (2015) through the CEPCI (Chemical Engineering Plant Cost Index) inflation index [32]. The Operation and Maintenance costs (O&M) of each component were determined as a fraction (1.5%) of the Purchased equipment costs (PEC), as suggested by Schuster et al. [33].

The calculation of the Total Capital Investment cost (TCI) is presented in detail in [11]. Once the TCI was calculated, knowing the total yearly working hours of the power plant, it was possible to determine $\dot{Z}$ in €/s. In this case, we assumed 7446 [h/year] working time over 30 years of expected life time, which is a realistic value for geothermal power plants [34]. The cost of the incoming geothermal brine has been set to 2.9 c€/kWh to take into account the wells' drilling costs, other input streams are considered to be costless.

Exergy values have been calculated, together with the thermodynamic modelling of the plant, using an EES script as described in [10].

- ***Results***

The exergo-economic analysis allows the assessment of the cost of electricity and heat generation. The obtained LCOE is around 3.3 c€/kWh, which is within the expected values of 3 - 5 c€/kW as suggested in [34]. Currently, the average national electricity production cost in Icelandic from geothermal powerplants is about 5.8 c€/kWh [35]. The cost of the cogenerated heat is much influenced by the calculation setting and it's between 8.1 and 4.5 c€/kWh.

In the table below, the calculation settings influence is analysed. $\dot{c}_{electricity}$ is the specific cost of the electricity, $\dot{c}_{heat}$ is the specific cost, referred to unit of exergy, of the cogenerated heat and $\dot{C}_{tot}$ is the overall production cost, calculated as $\sum_{prod} \dot{c}_{prod}\dot{e}_{prod}$, that has to be compared with the overall investment in order to understand if the economic balance is respected.

Table 1. Settings comparison

Calculation Topology	$\dot{c}_{loss}$ setting	$\dot{c}_{electricity}$, [€/kWh]	$\dot{c}_{heat}$, [€/kWh]	$\dot{C}_{tot}$, [€/s]
Support Block	$\dot{c}_{loss} = 0$	0.0325	0.0814	3.1577
PF Diagram	$\dot{c}_{loss} = 0$	**0.0335**	0.0546	3.1577
Support Block	$\dot{c}_{loss} = \dot{c}_{fuel}$	0.0325	0.0450	2.9698
PF Diagram	$\dot{c}_{loss} = \dot{c}_{fuel}$	0.0325	0.0450	2.9698

As can be seen from the table, changing the loss costing approach has a significant impact on $\dot{c}_{heat}$, moreover, the overall production cost decreases considering $\dot{c}_{loss} = \dot{c}_{fuel}$, showing that this approach results in an underestimation of the production costs. Besides, it is interesting to notice that the calculation topology representation has an impact only considering $\dot{c}_{loss} = 0$, because otherwise no redistribution is needed, and that the "*PF Diagram*" topology succeeded in obtaining a better redistribution effect.

Please notice that the program returns specific cost with respect to the *unit of exergy*. This is not a problem for electricity, because electrical energy and exergy are equivalent, but can lead to some misunderstanding for the district heating energy production price. Anyway, the resulting price per unit of energy can be easily calculated as:

$$\dot{c}_{en} = \dot{c}_{ex}\, \dot{e}/\dot{W} \qquad (11)$$

Where $\dot{e}$ is the exergy and $\dot{W}$ is the energy value of the stream. In Hellisheiði plant, production cost per *unit of energy* of the cogenerated heat is between 1.14 and 0.63 c€/kWh, again influenced by the calculation setting, considering a district heating power of 133 MW. Costs relative to other parameters can be calculated as well using the same approach, e.g. for a district heating network is interesting to access the cost in €/m^3: in this case, the range is between 1.08 and 0.601 €/m^3, considering a mass flow of 0.387 m^3/s.

EES calculation result has been performed only considering the "*support block*" topology and $\dot{c}_{loss} = 0$. As expected, the results are *exactly the same* as the ones reported in *table 1*. As was expected considering the fact that they both solve the same linear system.

Other results that can be obtained from the application are the specific and total cost for each stream, *figure 3.2*. Moreover, for each block the app returns the following information:

- The overall investment cost **PEC [€]**
- The specific cost $\mathbf{\dot{Z}_k}$ **[€/s]**
- The **exergy lost** $\dot{e}_L$ **or destroyed** $\dot{e}_D$ by the component **[kW]** and their ***"cost"*** **[€/kJ]**. The cost will be evaluated considering the average cost of the fuels, hence following the SPECO approach, regardless of the actual costing approach selected by the user. This is reasonable because in both cases it represents the cost that would have been spared if those losses had not existed.
- Multiple adimensional performance indicators:
    - **Specific cost increase** $\boldsymbol{r_k}$ across the component: $r_k = (\dot{c}_{prod} - \dot{c}_{fuel})/\dot{c}_{fuel}$
    - component **exergetic efficiency** $\boldsymbol{\varepsilon_k}$: $\varepsilon_k = \dot{e}_{prod}/\dot{e}_{fuel}$
    - **Exergo-Economic factor** $\boldsymbol{f_k}$: $f_k = \dot{Z}_k/\left(\dot{Z}_k + \dot{c}_{fuel}(\dot{e}_L + \dot{e}_D)\right)$
    - **Specific exergy destruction** $\boldsymbol{y_k}$: $y_k = \dot{e}_D/\sum_{comp} \dot{e}_D$

Stream	Name	Exergy Value [kW]	Specific Cost [Euro/kJ]	Specific Cost [Euro/kWh]	Total Cost [Euro/s]
1	GEO Fluid Extraction	716166	5,09E-06	0,02	3,64
2	HP Steam Separator Input	607152	6,00E-06	0,02	3,64
3	HP Turbine Input	492082	6,03E-06	0,02	2,97
4	DH Condenser Input	154952	6,03E-06	0,02	0,93
4,1	HP Condenser Input	146569	6,03E-06	0,02	0,88
5	HP Condenser Output	7231	6,03E-06	0,02	0,04
6	HP Steam Separator Brine Output	115070	6,03E-06	0,02	0,69
7	LP Steam Separator Input	106698	6,51E-06	0,02	0,69
8	LP Turbine Input	57361	8,96E-06	0,03	0,51
9	LP Condenser Input	20430	8,96E-06	0,03	0,18
10	LP Condenser Output	775,8	8,96E-06	0,03	0,01
11	LP Steam Separator Brine Output	49337	8,96E-06	0,03	0,44

Fig. 3.2. Excel program output example, stream costs. (for more information about the please check the user manual that can be downloaded here)

Exergo-Environmental Analysis:

As already said, an exergo-environmental analysis is performed following the same methodology of the exergo-economic analysis using different inputs.

- ***Inputs Calculations***

In order to determine the environmental impact rate associated with the life cycle of components, the recently published work [10] has been taken as a reference for the input of this analysis. Concerning the total environmental impact ($\dot{B}_{TOT,k}$), the wells and main valve emerged as the most impacting component, representing about 35% of the global effect. Both the HP turbine and HP Condenser contribution are mainly attributable to the specific cost of the component $\dot{Y}_k$, while for the HP cooling tower, the environmental cost is dominated by exergy destruction.

- ***Results***

The same results presented for the exergo-economic are returned also for the exergo-environmental analysis. The environmental cost of electricity is of **1.82cPts/MWh**, generated by 81% by the specific cost of the component and by 19% by the exergy destruction, the environmental cost of heat is **4.42*10^{-2} cPts/m^3** of generated hot water, derived by 73% by the specific cost of the components and 27% by the exergy destruction. These results are retrieved considering $\dot{c}_{loss} = 0$ and the "*PF diagram*" calculation topology. The environmental cost of heat is much dependent on the calculation setting, as seen in the exergo-economic analysis.

4. Conclusions

The developed tool allows non-experienced users to correctly perform exergo-economic and exergo-environmental analyses by ensuring that they are not forced to select the correct auxiliary equations set. In fact, the users are only required to provide the topology, the exergy values for each stream, and the input costs in order to perform the analysis. Some basic knowledge of the topic is still required by the user in order to understand the results. Nevertheless, according to the experience of the authors, understanding what has generated a specific outcome is much easier than understanding the choice of an auxiliary equation which, in appearance, may seem arbitrary. Moreover, the usage of such a tool speeds up the calculation process also for standard users as it removes the need of manually implementing the analysis in some thermodynamic simulation environments like EES.

The tool has been developed in Python hence it is extremely portable and easy to download. Furthermore, a new feature, that is still under development, will allow the tool to be launched by other programming languages, such as EES or MATLAB, in order to perform run time calculation on a topology that has been previously defined. To conclude, other features that are currently under development are:

- A much detailed exergetic analysis, modelled on the equation developed by Lozano and Valero [26]
- The implementation of the analysis for systems where different forms of exergy interact, such as chemical reactors or LNG regasification processes.
- A drag and drop user interface for the definition of the plant topology

Nomenclature

$\dot{b}$ stream specific environmental impact, Pts/kJ
$\dot{B}$ stream environmental impact flow, Pts/s
$\dot{c}$ stream specific exergy cost, €/kJ
$\dot{C}$ stream exergy cost flow, €/s
$\dot{e}$ stream exergy, kW
f_k exergo economic factor, -
r_k specific cost increase, -
$\dot{W}$ stream energy, kW
y_k specific exergy destruction, -
$\dot{Y}$ component environmental impact, Pts/s
$\dot{Z}$ component specific investment cost, €/s

Greek symbols

ε_k exergetic efficiency, -

Subscripts and superscripts

0	ambient
comp	component
D	exergy destruction
prod	product exergy flow
fuel	fuel exergy flow
loss, L	exergy loss
i, j, k	indices

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