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EXERGOECONOMIC EVALUATION OF SMALL SCALE CHP SYSTEMS

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Abstract. Exergy and exergoeconomic analysis of small scale CHP systems: micro gas turbine (GT) and micro Organic Rankine Cycle (ORC) CHP system has been conducted. Thermodynamic cycles have been simulated using a modelling tool Cycle-Tempo. Specific Exergy Costing (SPECO) exergoeconomic method has been applied and exergy costs of the products: electricity and heat have been calculated.
Performance of micro GT CHP system is better than micro ORC CHP system as electricity exergy cost is lower. Large exergy costs of heat and electricity generated in the ORC CHP system have been found due to the large exergy destruction rate in the boiler. Using another energy source, such as waste low grade heat from industrial processes, for the ORC system may reduce exergy cost of generated electricity and heat and improve exergy efficiency of the system.

Keywords: CHP, exergy analysis, exergoeconomics, gas turbine, ORC, thermoeconomics.

1. Introduction

Thermodynamic analysis, consisting of energy and exergy analysis has become a standard tool assessing energy conversion technologies nowadays. In the first half of the last century, the first attempts to link thermodynamics and monetary costs were made (Sciubba and Wall 2007). Later in early 1960s the term "thermoeconomics" was coined (Evans and Tribus 1962). Thermoeconomics combines energy and exergy concepts with economics. Different thermoeconomic methodologies were subsequently developed. In 1984 Tsatsaronis proposed the new term exergoeconomics (Tsatsaronis 1984). Exergoeconomics is a methodology which combines exergy analysis with an economic analysis and provides information which is crucial for the design and operation of a cost-effective plant (Tsatsaronis 1996). Exergoneconomics is a part of thermoeconomics. In exergoeconomics the exergy is the only basis for assigning costs (Tsatsaronis 1996).

The main objectives of exergoeconomic analysis are (Tsatsaronis 1993):

- to identify the location, magnitude and sources of exergy destruction and losses in an energy system;
- to calculate the cost associated with these losses;
- to assess the production costs of each product in the energy conversion system, which has more than one output;
- to facilitate feasibility and optimization studies for energy system;
- to assist in decision-making procedures concerning plant operation and maintenance;
- to compare technical alternatives.

Exergoeconomic analysis was applied by many researchers to assess different energy conversion systems. Exergoeconomic evaluation and optimization of regenerative gas turbine systems was conducted by Tsatsaronis and Pisa (Tsatsaronis and Pisa 1994). It was a part of a larger project, known as CGAM problem (Valero *et al.* 1994). The objective of this project was to show different thermoeconomic methods developed by different specialists and to facilitate unification of nomenclature and methodology.

Later exergoeconomic analysis was applied to investigate solar thermal power plants (Kaushik *et al.* 2001) and to optimise heat exchagers (D'Accadia *et al.* 2002). In most recent works exergoeconomic analysis was applied to study PEM fuel cells (Kazim 2005), ground source heat pumps (Ozgener and Hepbasli 2005), combined cycle power plants with carbon sequestration (Hammond and Ondo Akwe 2007), heat exchangers network (Jin *et al.* 2008), geothermal district heating systems (Oktay and Dincer 2009), thermo-chemical cycles for hydrogen production (Orhan *et al.* 2010) and cogeneration pulp and paper mill plant (Cortes and Rivera 2010).

Using exergoeconomic analysis the cost of each material and energy stream is calculated using cost balances for each system component and auxiliary costing equations. Applying LIFO (Last In First Out) accounting principle (Tsatsaronis and Lin 1990) fuels, products and costs are defined by systematically registering exergy and cost additions to and removals from each material and energy stream. Later based on LIFO method Specific Exergy Costing (SPECO) method was developed (Lazzaretto and Tsatsaronis 2006). This approach is sufficient for systematically defining fuels and products of the components and for formulating the auxiliary costing equations (Lazzaretto and Tsatsaronis 2006).

In this paper the Specific Exergy Costing method (SPECO) (Lazzaretto and Tsatsaronis 2006) was applied to evaluate micro CHP systems available on the market: micro gas turbine (GT) CHP and Organic Rankine Cycle (ORC) CHP.

2. Micro CHP systems

Two micro CHP systems were evaluated using exergoeconomic analysis. CHP systems were modelled using the Cycle-Tempo modelling tool developed in Delft University. Ambient temperature $T_0 = 288.15$ K and pressure $P_0 = 101.3$ kPa were assumed for exergy calculation. Most data for simulations were obtained from manufactures' data sheets.

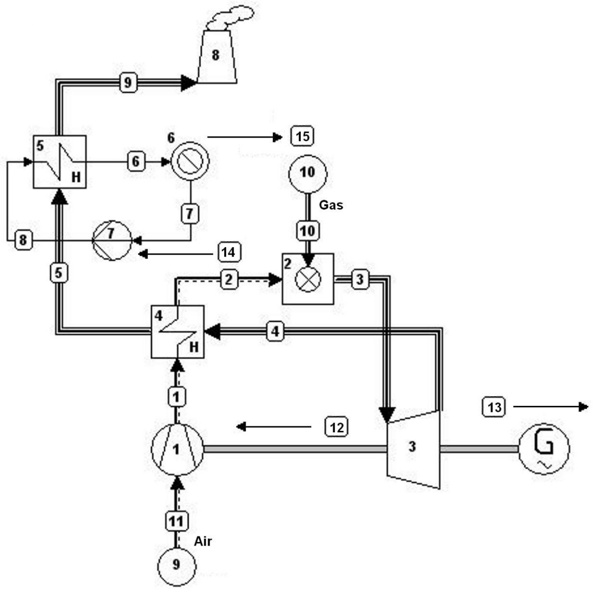

Fig 1. Micro gas turbine CHP system model

Gas Turbine CHP

A micro gas turbine CHP unit available on the market was chosen (Fig 1).

Air for combustion is compressed by the compressor 1 and supplied to the combustion chamber 2 through the recuperator 4, where the temperature is further increased (Fig 1). The gas expands in the gas turbine 3 and is supplied to the heat exchanger 5, passing by the recuperator 4, where incoming air stream is preheated. In the heat exchanger 5, high temperature exhaust gas energy is used to heat water. Pump 7 in used to circulate water in the heating system 6. Exhaust cooled gas is delivered to the stack 8.

Performance data, taken from manufacture's data sheet, and simulation data are presented in table 1.

Table 1. Gas turbine performance and simulation data

Parameter	Performance	Model
Fuel energy, kW	333	333.4
Electrical output, kW	100	100.2
Thermal output, kW	165	165.8
Electrical efficiency, %	30	30.1
Total efficiency, %	80	79.8
Exhaust gas temp., °C	270	270
Stack gas temperature, °C	70	70
Exhaust gas flow, kg/s	0.8	0.792
Heating system temp, °C	-	50°/70°

Performance data of the expander (gas turbine) and compressor was not available; therefore isentropic efficiencies were found performing iterative calculations. The isentropic efficiency of the expander is 0.8, compressor – 0.78.

Organic Rankine Cycle (ORC) CHP

The Organic Rankine Cycle (ORC) is often considered in the systems where large quantities of low temperature heat are available, for example in industrial manufacturing processes, solar power plants and geothermal power plants. In practice the ORC is also used for high temperature processes, especially where biomass as fuel is used.

One of the important tasks designing an ORC system is to choose a suitable working fluid. For larger industrial installations, where higher temperatures are available, for example where biomass is used for combustion, silicon oil (octamethyltrisiloxane OMTS) is successfully used (Obernberger *et al.* 2002). Studies show that some other fluids, such as: butylbenzene, propylbenzene or ethylbenzene may be considered (Drescher and Bruggemann 2007). The main advantage of these fluids is higher efficiency of power cycle. For smaller applications (up to 250 kW_e), however, refrigerants are usually considered.

In this study a commercially available ORC system was investigated. According to the manufacture's recommendations refrigerant R134a (tetrafluoroethane) (for temperatures <90°C) or R245fa (pentafluoropropane) (for temperatures 80-120°C) should be used as a working fluid. Only the turbine is supplied from the manufacturer, whereas all other components, such as: the evaporator, condenser, pump and heating source (boiler) have to be delivered from other suppliers.

The ORC system model is presented in Fig 2. In this study R245fa was used as working fluid and a biomass boiler was used as a heat source for the ORC cycle, although other heat sources may be used. The system consists of three separate loops. Water is heated in the boiler 6 and supplied to the heat exchanger 1. Here water heats the refrigerant R245fa, which evaporates. Cooled water is then supplied to the boiler 6. Pump 5 is used to circulate hot water in the loop. High pressure and temperature R245fa vapour is delivered to the turbine 2, where it expands. Exhaust vapour after turbine 2 is condensed in the heat exchanger 3. Then the liquid is pumped to the heat exchanger 1 repeating the cycle. Heating system water is heated from 50°C to 70°C in the heat exchanger 3 and supplied to the heating system 7 using circulation pump 8.

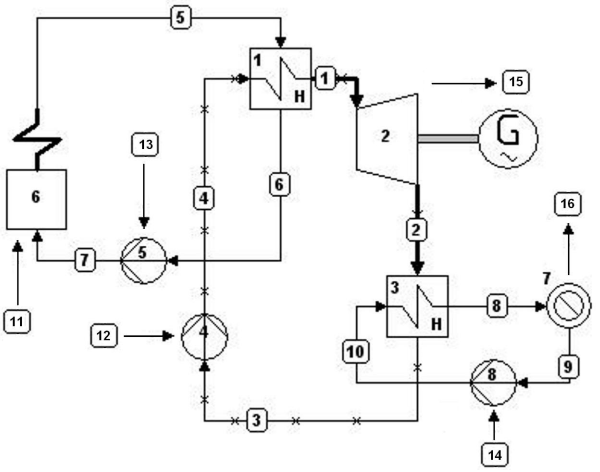

Fig 2. Micro ORC CHP system model

Performance data, taken from manufacture's data sheet, and simulation data are presented in table 2. ORC without superheating was modelled based on the maximum turbine inlet temperature and heating system supply temperature.

Table 2. ORC system performance and simulation data

Parameter	Performance	Model
Fuel energy, kW	117-176	137
Electrical output, kW	5-12	10
Thermal output, kW	-	114
Electrical efficiency, %	8-11	7.3
Total efficiency, %	-	90.5
Turbine inlet temp., °C	120-80	120
Working fluid	R245fa	R245fa
Heating system temp, °C		50°/70°

Lower efficiency in the model was obtained because of the high temperature required for the heating system. The reduction of heating system temperature in the heat exchanger 3 increases efficiency of the ORC to 12-13%.

3. SPECO methodology

The Specific Exergy Costing (SPECO) approach is a systematic methodology for calculating exergy related costs in thermal systems (Lazzaretto and Tsatsaronis 2006).

SPECO method consists of three steps:

- identification of exergy streams;
- definition of products and fuels;
- construction of cost equations.

The first step was carried out using Cycle-Tempo software. Energy and exergy streams in the particular model were calculated. Total exergy was used in this study, because the use of separate forms of exergy, such as: thermal, mechanical or chemical, only marginally improves calculation accuracy (Lazzaretto and Tsatsaronis 2006).

The next step is very important as incorrect definition of *fuel* and *product* may lead to false results. The *Fuel-Product* concept is very useful and is often used conducting exergy efficiency analysis. According to its definition, the *product* is the desired result produced by the system (Bejan *et al.* 1996). The *fuel* represents the resources used to generate the product (Bejan *et al.* 1996). For example for the simple turbine *fuel* is the difference of input exergy stream (fluid) and output exergy stream (fluid), and the *product* is the shaft power output. Using these definitions *fuels* and *products* were defined for each component of the system.

The last step, the construction of the cost equations consists of two parts. First the exergy cost equation for each component of the system is composed. General form of this equation for the *k-th* component is:

$$\sum_e \left(c_e \dot{E}_e\right)_k + c_{w,k}\dot{W}_k = c_{q,k}\dot{E}_{q,k} + \\ + \sum_i \left(c_i \dot{E}_i\right)_k + \dot{Z}_k \qquad (1)$$

Here c_e, c_i, c_q, c_w are the average costs per unit of exergy (EUR/kJ); $\dot{E}_e, \dot{E}_i, \dot{E}_q, \dot{W}_q$ are the exergy streams (kW) and $\dot{Z}_k$ are the sum of capital investments and operating and maintenance expenses (EUR/s).

Cost streams $\dot{C}$ (EUR/s) associated with the corresponding exergy streams are calculated using equation:

$$\dot{C}_e = c_e \dot{E}_e \\ \dot{C}_i = c_i \dot{E}_i \qquad (2)$$

However there are more streams than components, therefore auxiliary equations have to be formulated. *F* and *P* principles are used to compose auxiliary equations. According to the *F* principle, the specific cost (cost per exergy unit) associated with the removal of exergy from the *fuel* stream is equal to the average specific cost at which the removed exergy is supplied to the same stream in upstream components (Lazzaretto and Tsatsaronis 2006). In this way one auxiliary equation is composed per each removal of exergy. The *P* principle states that each exergy unit is supplied to any stream associated with the *product* at the same average cost. Thus *F* and *P* principles together provide the required number of equations in order to find the specific costs of the streams.

In order to find cost flow rates and average costs per unit exergy, system of linear equations was constructed. Matrix formulation was used to solve the system of equation:

$$A \times X = B \tag{3}$$

where A is the matrix of coefficients constructed from main and auxiliary equations, X is the unknown vector of cost flow rates ($\dot{C}$) and B is the vector of capital cost flow rates ($-\dot{Z}$) (Lazzaretto and Tsatsaronis 2006).

Auxiliary equations for gas turbine CHP system

The micro GT CHP system consists of seven main components (Fig 1), thus 7 equations (using equation 1) for each component are formulated. The total number of streams is 15, therefore 8 auxiliary equations have to be constructed based on F or P principles.

Two equations are constructed associated with the exergy streams supplied with the material to the system from outside.

For fuel supplied to the system:

$$\dot{C}_{10} = \dot{C}_{fuel} \tag{4}$$

where $\dot{C}_{fuel}$ is cost stream (EUR/s) associated with the fuel exergy.

Air supply to the system:

$$\dot{C}_{11} = \dot{C}_{air} \tag{5}$$

where $\dot{C}_{air}$ is cost stream associated with the air exergy.

Electricity is generated by turbine 3 and generator, and consumed internally by the pump 7. The average cost per unit of electricity generated is equal to the average cost per unit of electricity consumed:

$$\frac{\dot{C}_{13}}{\dot{E}_{13}} = \frac{\dot{C}_{14}}{\dot{E}_{14}} \tag{6}$$

Since two products are generated in the turbine 3, using P principle the auxiliary equation is composed for the compressor 1:

$$\frac{\dot{C}_{13}}{\dot{E}_{13}} = \frac{\dot{C}_{12}}{\dot{E}_{12}} \tag{7}$$

Finally the remaining four auxiliary equations are composed using F principle.

The auxiliary equation for the turbine 3:

$$\frac{\dot{C}_{3}}{\dot{E}_{3}} = \frac{\dot{C}_{4}}{\dot{E}_{4}} \tag{8}$$

The auxiliary equation for the heat exchanger 4:

$$\frac{\dot{C}_{3}}{\dot{E}_{3}} = \frac{\dot{C}_{4}}{\dot{E}_{4}} \tag{9}$$

The auxiliary equation for the heat exchanger 5:

$$\frac{\dot{C}_{5}}{\dot{E}_{5}} = \frac{\dot{C}_{9}}{\dot{E}_{9}} \tag{10}$$

The auxiliary equation for the heating system 6:

$$\frac{\dot{C}_{6}}{\dot{E}_{6}} = \frac{\dot{C}_{7}}{\dot{E}_{7}} \tag{11}$$

Auxiliary equations for ORC CHP system

The same method of constructing main and auxiliary equations was applied for the ORC system (Fig 2). The ORC system consists of 8 components; therefore 8 main equations are formulated for each component. The number of streams is 16, and therefore 8 auxiliary equations are formulated based on the principles described above.

For fuel supplied to the system (boiler 6):

$$\dot{C}_{11} = \dot{C}_{fuel} \tag{12}$$

Three auxiliary equations are used to define electricity supply for pumps 4, 5 and 8.

$$\begin{gathered} \frac{\dot{C}_{15}}{\dot{E}_{15}} = \frac{\dot{C}_{12}}{\dot{E}_{12}} \\ \frac{\dot{C}_{15}}{\dot{E}_{15}} = \frac{\dot{C}_{13}}{\dot{E}_{13}} \\ \frac{\dot{C}_{15}}{\dot{E}_{15}} = \frac{\dot{C}_{14}}{\dot{E}_{14}} \end{gathered} \tag{13}$$

The auxiliary equation for the turbine 2 is:

$$\frac{\dot{C}_{6}}{\dot{E}_{6}} = \frac{\dot{C}_{7}}{\dot{E}_{7}} \tag{14}$$

The auxiliary equation for the heat exchanger 1:

$$\frac{\dot{C}_{5}}{\dot{E}_{5}} = \frac{\dot{C}_{6}}{\dot{E}_{6}} \tag{15}$$

The auxiliary equation for the heat exchanger 3:

$$\frac{\dot{C}_2}{\dot{E}_2} = \frac{\dot{C}_3}{\dot{E}_3} \tag{16}$$

The auxiliary equation for the heating system 7:

$$\frac{\dot{C}_8}{\dot{E}_8} = \frac{\dot{C}_9}{\dot{E}_9} \tag{17}$$

Hence, systems of linear equations were constructed and solved using Matlab.

4. Calculation of fuel and capital costs

Exergoeconomic calculation of the system is based on the capital costs of components. Sometimes it is difficult to obtain exact costs of equipment, in which case the cost functions are used to estimate an average cost of the component (Bejan *et al.* 1996; Silveira and Tuna 2003; Galanti and Massardo 2010).

The total cost of the GT unit was provided by the manufacture. Capital costs of micro GT system components were estimated based on the cost functions provided by Galanti and Massardo (Galanti and Massardo 2010). The cost of each component: compressor, turbine, combustion chamber, recuperator and generator were corrected proportionally with regard to the total unit cost. Other costs of pump and heat exchanger were taken from the manufactures' quotes. The total cost of the micro GT system is 128 kEUR.

The ORC turbine is delivered unassembled, therefore all additional components, such as heat exchangers, pumps, boiler have to be purchased separately. Costs of ORC system components were taken from the manufactures' quotes. The total cost of the ORC CHP system is 60 kEUR.

It was assumed that estimated operation time of CHP is 15 years; interest rate on the capital – 15%; time of operation of plant – 7000 hours/year.

Natural gas as fuel was used for micro GT CHP system. The energy price 0.04 EUR/kWh of natural gas for domestic consumers in UK in 2009 was taken from EU Energy Portal (www.energy.eu).

Biomass fuel price was recalculated based on the data provided in the report (E4Tech 2010). It was assumed that the cost of wood chips was 0.0276 EUR/kWh.

5. Exergoeconomic evaluation

First exergy analysis was carried out. Exergy streams were calculated using the Cycle-Tempo software. From these data the exergy of the *product* and *fuel* of the component was calculated. Exergy efficiency of the component was calculated using the equation:

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} = 1 - \frac{\dot{E}_D - \dot{E}_L}{\dot{E}_F} \tag{18}$$

Here $\dot{E}_P$ is the exergy of the *product* of the component, $\dot{E}_F$ is the exergy of the *fuel* of the component, $\dot{E}_D$ is exergy destruction rate of the component and $\dot{E}_L$ is exergy loss rate of the component. In this study it was assumed that $\dot{E}_L = 0$.

In order to find which components are responsible for the exergy destruction in the system an exergy destruction ratio was calculated using the equation:

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{D,tot}} \tag{19}$$

Using the SPECO method cost rates of exergy streams ($\dot{C}$) were calculated. From the cost rates associated with exergy stream cost rates associated with the *fuel* ($\dot{C}_F$) and the *product* ($\dot{C}_P$) were calculated. Average cost per exergy unit of fuel and product for the component *k* was defined using the equation:

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}_{F,k}} \qquad c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}_{P,k}} \tag{20}$$

In order to conduct exergoeconomic analysis exergoeconomic variables of the component *k*, such as: cost rate of exergy destruction $\dot{C}_{D,k}$, relative cost difference r_k and exergoeconomic factor f_k have to be calculated.

Cost rate of exergy destruction $\dot{C}_{D,k}$ were calculated using the equation (Bejan *et al.* 1996):

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \tag{21}$$

Here $c_{F,k}$ is unit cost of *fuel* and $\dot{E}_{D,k}$ is exergy destruction rate.

Relative cost difference r_k indicates the relative increase in the average cost per exergy unit between fuel and product of the component (Bejan *et al.* 1996). It was calculated using the equation:

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{P,k}} \tag{22}$$

Here $c_{F,k}$ is unit cost of *fuel* and $c_{P,k}$ is unit cost of *product*.

Exergoeconomic factor f_k combines non-exergy costs (capital investment and operating and maintenance costs) with exergy destruction costs. For the k^{th} component it was calculated using the equation (Bejan *et al.* 1996):

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \qquad (23)$$

Gas Turbine CHP

Exergy efficiency and exergy destruction ratio of the micro GT CHP system are presented in Fig 3.

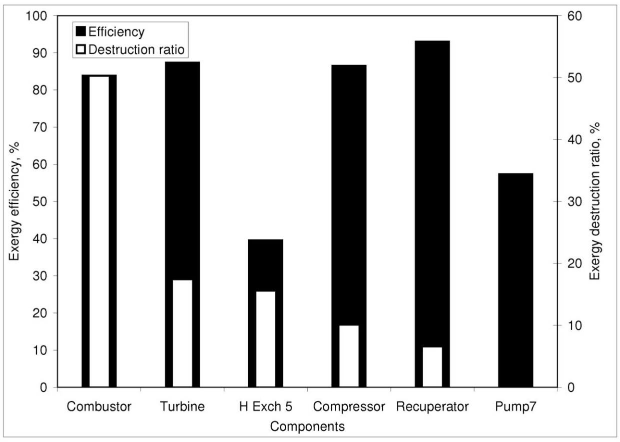

Fig 3. Exergy destruction and efficiency of the GT CHP system

Exergy efficiency (black column) of the combustor, turbine, compressor and recuperator are relatively high (>80%). However the largest exergy destruction ratio (white column) is found in the combustion chamber. The combustion chamber is responsible for the destruction of almost 50% of total exergy destroyed in the system. Exergy destruction ratio in other components is considerably lower compared with the combustion chamber.

Exergy efficiency of the heat exchanger 5 is low (<40%) and exergy destruction ratio is higher than that of recuperator. This is due to the large temperature difference in the heat exchanger, where high temperature gas (around 270°C) is used to heat low temperature heating water (50°-70°C). The efficiency of the heat exchanger can be improved by changing the temperature regime in the system.

Exergoecononomic variables: exergoeconomic factor f_k, relative cost difference r_k and the sum of capital cost flow rate and exergy destruction rate $\dot{Z}_k + \dot{C}_{D,k}$ of micro GT CHP system are presented in Fig 4.

Largest relative cost difference (black) is observed in the heat exchanger 5 (1.54) and pump 7 (1.49). It means that the exergy cost increase is large in these components. However the sum of destruction and capital cost rate in the pump 7 is very low. It infers that the pump contribution to the total cost formation in the system is insignificant. The sum of exergy destruction and capital cost rate for the heat exchanger 5 is about 3 EUR/h. This component contributes largely to the formation of the product cost.

The small exergoeconomic factors (grey) for the combustion chamber, heat exchanger 5 and compressor, indicates that exergy destruction rate is much higher than capital cost flow rate; therefore component efficiency can be improved even increasing capital investments. This is particularly relevant for the compressor. Improving compressor's efficiency would reduce exergy destruction cost.

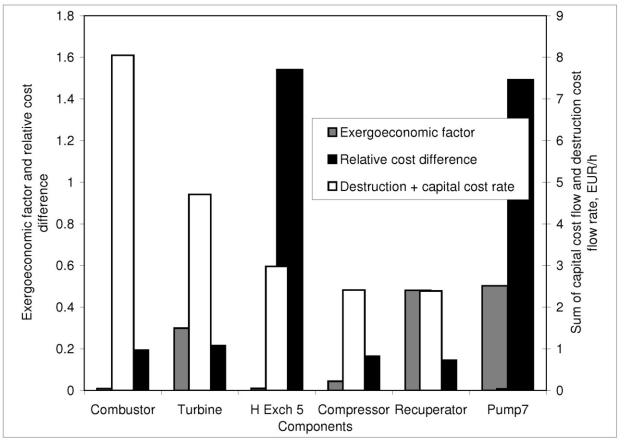

Fig 4. Exergoeconomic variables of the GT CHP system

The highest value of exergy destruction cost rate is observed in the combustion chamber. The exergoeconomic factor is very low, suggesting that capital investment into more efficient design would reduce the exergy destruction in the combustor. However this will not necessarily improve the performance, as the combustion process is inherently related to the large exergy destruction due to the internal energy exchange in the system (Chavannavar and Canton 2006).

The third largest contributor to exergy destruction cost is the heat exchanger 5. A low exergoeconomic factor and large relative cost difference indicates that the performance of this component can be improved. One of the possible solutions might be the more effective utilisation of high temperature exhaust gas.

Organic Rankine Cycle (ORC) CHP

Exergy efficiency and exergy destruction ratio of ORC CHP system are presented in Fig 5.

Largest exergy destruction is observed in the boiler. The boiler is responsible for more than 90% of all exergy destruction in the system. The exergy destruction in the other components, such as: heat exchanger 1 and 3 and turbine is insignificant.

Exergoecononomic variables: exergoeconomic factor f_k, relative cost difference r_k and the sum of capital cost flow rate and exergy destruction rate $\dot{Z}_k + \dot{C}_{D,k}$ of ORC CHP system are presented in Fig 6.

As anticipated the largest relative cost difference is observed in the boiler. The low exergoeconomic factor suggests that destruction cost rate is much higher than investment (capital) cost rate. However improvement in the boiler efficiency would not reduce exergy destruction considerably. The combustion process is the largest contributor to the exergy destruction. Replacing the boiler with another low grade energy source (for example waste heat from industrial process) would reduce exergy destruction in this component and improve the overall ORC performance.

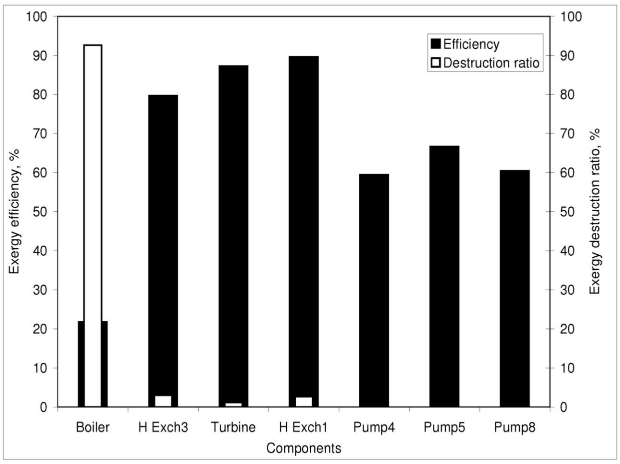

Fig 5. Exergy destruction and efficiency of ORC CHP system

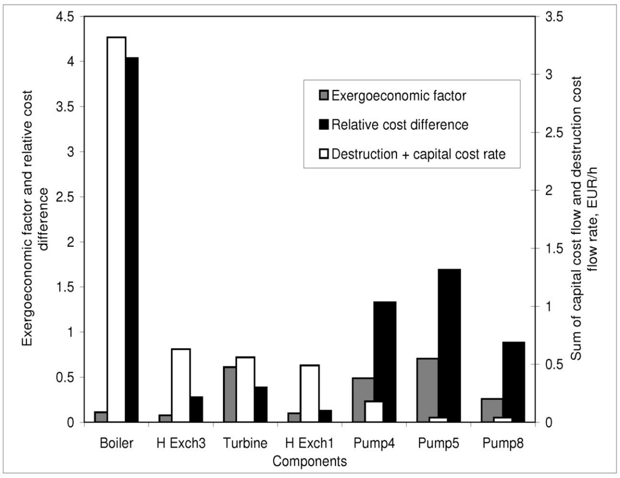

Fig 6. Exergoeconomic variables of ORC CHP system

The exergoeconomic factor and relative cost difference of two heat exchangers 1 and 3 are low. The exergy destruction cost rate is larger than the capital cost rate. Reduction of pressure losses in the exchangers would decrease the exergy destruction cost and improve system performance. The role of the pumps in the exergy destruction cost formation is insignificant.

6. Comparison of GT and ORC systems

The main objective of CHP systems is to generate electricity and produce heat. The cost formation process in the GT and ORC systems takes place differently. The costs of the final products are presented in Table 3.

Fuel exergy cost in the GT system is higher than in ORC system. During the energy conversion process fuel exergy is converted to mechanical work (electricity) and heat. Exergy destruction takes place in all components. In addition only a small part of exergy is wasted (stack 8 in Fig 1). The cost of the wasted heat is added equally to the stream 13 (electricity) and stream 15 (heating).

Table 3. Exergy costs of products, EUR/kWh

Exergy cost, EUR/kWh	Micro GT	Micro ORC
Fuel exergy cost	0.038	0.025
Electrical exergy cost	0.107	0.207
Heat exergy cost	0.230	0.195

The wasted heat in the boiler in the ORC system is accounted by the boiler energy efficiency.

Although the investment for the GT system is higher than for the ORC system, power and heat generation is more efficient in terms of exergy and consequently the exergy cost of electrical exergy is lower. The increase of heat exergy cost is related to exergy destruction in the heat exchanger 5. Decreasing the exergy destruction rate in this component would reduce the heat exergy cost.

In the ORC system the boiler is responsible for the largest exergy destruction. The exergy destruction cost increases considerably when the biomass fuel is burned in the boiler. Combustion affects the cost of the final products. The cost of electrical exergy is slightly higher than the cost of heat exergy because of the very low electrical exergy (10 kW) generated in the turbine. Heat exergy generated in the cycle is 15.54 kW, therefore the specific cost of heat exergy is lower.

7. Conclusions

Exergy and exergoeconomic analysis of micro gas turbine CHP system and micro Organic Rankine Cycle CHP system has been presented.

Calculated exergy cost of electricity is 0.107 EUR/kWh in a micro GT system and 0.207 EUR/kWh in an ORC system.

The performance of micro GT CHP system is better than micro ORC system. The main disadvantage of using ORC cycle with biomass combustion is large exergy destruction in the boiler. However the ORC system is more flexible than the micro GT system as a variety of fuels may be used as well as high temperature waste from industrial processes.

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References

Bejan, A.; Tsatsaronis, G.; Moran, M. 1996. *Thermal Design and Optimization*. A Wiley-Interscience Publication: New York, p 542.

Chavannavar, P. S.; Canton, J. A. 2006. Destruction of availability (exergy) due to combustion process: a parametric study. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power And Energy* 220, 655-669.

Cortés, E.; Rivera, W. 2010. Exergetic and exergoeconomic optimization of a cogeneration pulp and paper mill plant including the use of a heat transformer. *Energy* 35, (3), 1289-1299.

D'Accadia, D.; Fichera, A.; Sasso, M.; Vidiri, M. 2002. Determining the optimal configuration of a heat exchanger (with a two-phase refrigerant) using exergoeconomics. *Applied Energy* 71, (3), 191-203.

Drescher, U.; Bruggemann, D. 2007. Fluid selection for the Organic Rankine Cycle (ORC) in biomass power and heat plants. *Applied Thermal Engineering* 27, 223-228.

E4Tech *Biomass prices in the heat and electricity sectors in the UK. URN 10D/546*; 2010; p 33.

Evans, R. B.; Tribus, M. 1962. *.A contribution to the theory of thermoeconomics*; UCLA Department of Energy: report No 62-63: Los Angeles, CA.

Galanti, L.; Massardo, A. F. 2010. Thermoeconomic Analysis of Micro Gas Turbine Design in the Range 25-500 kW$_e$. In *Proceedings of ASME Turbo Expo 2010: Power for Land, Sea and Air*, June 14-18, Glasgow, UK, 2010.

Hammond, G. P.; Ondo-Akwe, S. S. 2007. Thermodynamic and related analysis of natural gas combined cycle power plants with and without carbon sequestration. *International Journal of Energy Research* (31), 1180-1201.

Jin, Z. L.; Dong, Q. W.; Liu, M. S. 2008. Exergoeconomic analysis of heat exchanger networks for optimum minimum approach temperature. *Chemical Engineering and Technology* 31, (2), 265-269.

Kaushik, S. C.; Abhyankar, Y. P.; Bose, S.; Mohan, S. 2001. Exergoeconomic evaluation of a solar thermal power plant. *International Journal of Solar Energy* 21, (4), 293-314.

Kazim, A. 2005. Exergoeconomic analysis of a PEM fuel cell at various operating conditions. *Energy Conversion and Management* 46, (7-8), 1073-1081.

Lazzaretto, A.; Tsatsaronis, G. 2006. SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems. *Energy* 31, 1257-1289.

Obernberger, I.; Thonhofer, P.; Reisenhofer, E. 2002. Description and evaluation of the new 1000 kW$_{el}$ Organic Rankine Cycle process integrated in the biomass CHP plant in Lienz, Austria *Euroheat & Power* 10.

Oktay, Z.; Dincer, I. 2009. Exergoeconomic analysis of the Gonen geothermal district heating system for buildings. *Energy and Buildings* 41, (2), 154-163.

Orhan, M. F.; Dincer, I.; Rosen, M. A. 2010. Exergoeconomic analysis of a thermochemical copper-chlorine cycle for hydrogen production using specific exergy cost (SPECO) method. *Thermochimica Acta* 497, (1-2), 60-66.

Ozgener, O.; Hepbasli, A. 2005. Exergoeconomic analysis of a solar assisted ground-source heat pump greenhouse heating system. *Applied Thermal Engineering* 25, (10), 1459-1471.

Silveira, J. L.; Tuna, C. E. 2003. Thermoeconomic analysis method for optimization of combined heat and power systems. Part I. *Progress in Energy and Combustion Science* 29, 479-485.

Sciubba, E.; Wall, G. 2007. A brief Commented History of Exergy From the Beginnings to 2004. *International Journal of Thermodynamics* 10, (1), 1-26.

Tsatsaronis, G. 1984. Combination of Exergetic and Economic Analysis in Energy-Conversion Processes. In *Energy Economics and Management in Industry*, Proceedings of the European Congress, Pergamon Press, Oxford, England: Algarve, Portugal, April 2-5, Vol. 1, pp 151-157.

Tsatsaronis, G.; Lin, L. 1990. On exergy costing in exergoeconomics. In *Computer-aided energy systems analysis*, Tsatsaronis, G.; Bajura, R. A.; Kenney, W. F.; Reistad, G. M. Eds. ASME: New York, Vol. 21, pp 1-11.

Tsatsaronis, G. 1993. Thermoeconomic Analysis and Optimization of Energy Systems. *Progress in Energy and Combustion Science* 19, 227-257.

Tsatsaronis, G.; Pisa, J. 1994. Exegoeconomic Evaluation and Optimization of Energy Systems - Application to the CGAM Problem. *Energy* 19, (3), 287-321.

Tsatsaronis, G. 1996. Exergoeconomics: Is It Only a New Name? *Chemical Engineering and Technology* 19, 163-169.

Valero, A.; Lozano, M. A.; Serra, L.; Tsatsaronis, G.; Pisa, J.; Frangopoulus, C.; Spakovsky, M. R. V. 1994,.CGAM Problem: Definition and Conventional Solution. *Energy* 19, (3), 279-286.