The Solar Transformity of Power and Heat in Combined Heat and Power Production

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ABSTRACT

Power and heat are the primary energies for the industry and communities. Combined heat and power (CHP) is a process of heat and power cogeneration, which is designed to meet the needs of both users. In previous studies of emergy analysis on CHP, the transformity was simply calculated by dividing the total emergy input by the amount of production. The result always showed that transformity of electricity is lower than the transformity of steam, which is not logical since electricity is thermodynamically higher value energy than heat. Neither can it illustrate that the co-production process is more efficient than an independent one because the efficiency of co-production is calculated by considering the available energy of the two products together and comparing it with the available energy of the electricity only in another plant. According to emergy analysis rules, the emergy is thought to be the energy history that cannot be separated for inseparable co-production. However, if the product can be produced separately in the system, the emergy could be split. In principle power and heat can be produced independently in CHP plants. We could argue that CHP can be considered as a separated production. The possibilities in splitting the emergy by different alternatives are discussed. A biomass-based CHP plant is analyzed as a case study for emergy division by exergy and maximum production. The results provided reasonable transformities of electricity and heat in CHP plant.

INTRODUCTION

Heat and power are the primary energy inputs for industries and human daily life, which affect the economic and social activities of humanity. Combined heat and power (CHP) generation process has been considered worldwide as the major alternative to traditional power systems in terms of significant energy saving and environmental friendly point of view (Dentice d’Accadia et al. 2003). The secondary energy from electricity production can be used for industrial process steam requirement and local district heating for buildings (Korhonen, 2002).

Sustainability aspects of energy production are important these days. One way to assess sustainability is emergy analysis. Emergy analysis can be used as a sustainability evaluation method which quantitatively illustrates not only energy flows but also economic and environmental values. This environmental accounting method, introduced by Odum (1996), sorts out all the relative contributions of energy, services and materials to final product in the form of solar equivalent energy, called emergy. Emergy analyses require accurate estimation of the transformity of main products from every process (Ulgiati et al. 2011).

Multi-product Analysis

The application of emergy analysis on multi-product systems has been studied to overcome the problem of double counting or split mistakes. Multi-product systems can be classified into two
categories: co-production and split products. The energy can be assigned to each product in a split system according to the available energy carried by each pathway; this cannot be done in a co-production situation (Brown and Herendeen, 1996). Based on previous studies (Cao and Feng, 2007; Bastianoni et al. 2009) splits and co-products are handled differently.

Inseparable Production

According to the second rule of by-product calculation, the total energy driving a process is assigned to each of the by-products (Brown and Herendeen, 1996). Cao and Peng (2007) pointed out that it is easy to make mistakes in emergy analyses of multi-product systems. They maintained that it is wrong to assign the whole input emergy to each product of inseparable multi-product systems because the emergy value is an energy ‘memory’ of resources. In addition, the most important procedure for emergy analysis of multi-product system is distinguishing the category of it. Bastianoni and Marchettini (2000) introduced two transformity definitions for co-production, Ñ joint transformity and the weighted average of transformity. The aim of it is to illustrate the different efficiency aspects between combined and independent processes.

Joint transformity $T_{rj}$ is defined as the solar emergy required for the co-production divided by the sum of the available energy of the products (Eq. 1). The weighted average of transformities $T_{rave}$ comes from the weighted ratio of two products with the same quantities as in the co-production case obtained through independent production (Eq. 2). Co-production is more efficient if the joint transformity: $T_{rj}$ is smaller than the weighted average of transformities, $T_{rave}$ (Bastianoni and Marchettini, 2000).

\[
T_{rj} = \frac{Em}{E_{se} + E_{sc}} \tag{1}
\]

\[
T_{rave} = \frac{E_{ei}}{E_{ei} + E_{si}} T_{re} + \frac{E_{si}}{E_{ei} + E_{si}} T_{rj} = \frac{Em_e + Em_s}{E_{ei} + E_{si}} \tag{2}
\]

- $E_{ei}$ available energy of electricity in independent production
- $E_{si}$ available energy of steam in independent production
- $E_{se}$ available energy of electricity in CHP
- $E_{sc}$ available energy of steam in CHP
- $Em$ total emergy needed for cogeneration
- $Em_e$ energy of electricity in independent production
- $Em_s$ energy of steam in independent production
- $T_{rj}$ joint transformity in CHP
- $T_{re}$ transformity of electricity in independent production
- $T_{rave}$ average of transformities in independent production
- $T_{rs}$ transformity of steam in independent production

Separable Production

The third rule related to split outputs declares that, when a pathway splits, the emergy is assigned to each ‘leg’ of the split based on its percentage of the total emergy input (Brown and Herendeen, 1996). Bastianoni et al. (2009) had studied the solar transformity of petroleum fuels. They treated the question in the process of petroleum derivatives which are splits of complex hydrocarbon mixtures. The emergy can be split based on the fraction of available energy or mass in a product; however, split in terms of available energy gave more reasonable results than in terms of mass. It gave for higher quality fuels higher emergy per unit mass. Cao and Feng (2007) pointed out that the inner structure of a multi-product system needs to be clarified to see what the processes are.
**CHP: Is it separable?**

Since the CHP plants produce two products, a problem arises, namely how and if to divide the input emergy between the steam and electricity. Although joint transformity indicates that the co-product is more efficient if joint transformity is smaller than weighted average transformity, independent transformities of heat and power from CHP process still cannot be specified separately (Bastianoni and Marchettini, 2000). Previous studies (e.g. Peng et al. 2008) simply divided emergy amounts equally between the electricity and heat produced. Wang et al. (2005) split the emergy flow in the CHP network, however the output emergy from the power plant is lower than the emergy input. Since the heat amount was much less than electricity, this resulted in much higher transformity values for steam than for electricity. Their results are not logical according to electricity is thermodynamically higher value energy than heat. This paper aims to find out if production of heat and power in CHP process can be considered as independent origin.

In practice, for CHP plants based on internal combustion engine or gas turbine, as said by Carnot heat loss is "the price to pay to nature" and thus there is no split for these plants. However, for CHP plants based on steam turbines (back-pressure cycle or condensation cycle), the energy flow is split during the operation. As shown in Figure 1, the biomass fuel is burned in a boiler to produce high pressure steam (A) that is used to power a steam turbine driven power generator. The steam is extracted from the turbine at low or medium pressure (D) and used for industrial process or district heating (EPA, 2007). Another but less efficient way to produce lower pressure steam is to use pressure reduction (C).

When running the CHP in power production mode, all the high pressure steam (A) goes to steam turbine and electricity generation (B) without any pressure reduction (C) and extraction (D). There will be no heat product since all heat goes to cooling water in the condenser (E). In opposite case, all the steam goes to steam users (C) and no electricity is produced. Therefore, power and heat in CHP process are not necessarily produced together but can be fully separated. However, in CHP power and heat are always manufactured together in practice to increase the process efficiency and fully use the heat value of fuel. Therefore the high pressure steam goes to steam turbine (B) and a middle pressure steam (D) is extracted from the turbine as the steam product. The rest of steam is condensed (E) to create electricity.

![Figure 1. The CHP process diagram.](image_url)
Different Ways of Separation

There is no standard way for apportioning the input emergy flow in CHP plants. In power plant engineering, the value of heat and power can be calculated in CHP in several ways: exergy, enthalpy, maximum production efficiency or cost (Huhtinen et al., 2008). In emergy methodology the definition of transformity is given as emergy per unit of available energy, exergy, mass, etc, expressed in solar equivalent joules per unit (seJ/J, seJ/g, seJ/$) (Brown and Ulgiati, 2004). Therefore emergy flow could be split on the basis of the enthalpy, exergy, etc.

The enthalpy loss could be seen as a loss of emergy in the split flows, since the flows are on a branch that leads to dispersion in the environment. However, emergy divided by enthalpy basis will result in the same transformity value for both power and heat. The both values equal to the joint transformity (Eq. 1). This way of transformity calculation only shows the CHP entire process efficiency is higher than the independent processes but not the differences between the products.

Exergy is the part of energy that is available for work. In CHP, it can be considered as how much the steam can make electricity if not produced as heat shown in Figure 2. Due to the higher exergy, the quality of energy in power is higher and it needs more inputs to be generated compared to an energy unit of heat. Bastianoni et al. (2007) had stated that emergy can be formulated as a function of exergy and its physical and mathematical validity is the same as exergy’s. Transformity values obtained from exergy based allocation will give the sense of process exergy efficiency. The formula of exergy based transformity calculation is shown in Eq. 3.

\[
\frac{Tr_{ce}}{Tr_{ce}} = \frac{1/(E_{ce} - E_{ce})}{1/E_{ce}}
\]

Cost also can be considered as an allocation basic since the price reflects the social consumptions of products and feedback of the system. The obtained transformities will highly depend on the location but less on process technology. This way of division mainly relies on economic foundation.
Biomass Based CHP Plant Case Study

A case study on biomass CHP plant is presented based on Finnish CHP plants (Kirjavainen et al., 2004). The fuel input is 72 MW wood chips or forest residue. The plant steam pressure is 93 bar and temperature is 515 °C. Steam product is in 10 bar to be used in industry. The processes were simulated with a flow sheet simulator in two cases: In an extraction turbine case a CHP process with an extraction turbine and the electricity is produced from flow E and steam from flow D as shown in Figure 1. Because of the limitations of steam turbine, the steam extraction percentage was studied from 15% to 85% from the high pressure steam rate. The other one is a condensing turbine case where steam is only made by reduction (C). The entire power production range was simulated for the condensing turbine case. The production flow sheet analyzed is shown in Figure 3. Energy table for the plant is shown as Table 1 (Shia and Hurme, 2012).

Pine logging residue was considered as a local renewable source. Therefore, there are no external nonrenewable energy sources needed in the analyzed boundary. The exergy and maximum efficiency split models have been applied for both cases. The annual operation time is assumed to be 8000h/y. The calculated transformity values are summarized in Table 2 and the extraction case values are shown in Figure 4.

The condensing turbine case gives the same transformity values in both the exergy and maximum production split models, 5.53E+04 sej/J for power and 2.30E+04 sej/J for heat. Based on power and heat the exergy efficiency simulation of the two processes and Eq. 3, the transformity ratio of power to heat is 2.40 and 3.28 for condensing turbine and extraction cases respectively. According to the maximum efficiency principle Eq. 4, the transformity ratio for the condensing turbine case gives the same result as in exergy split model. For the extraction case, the heat transformity varies around 2.1E+04 sej/J and power transformity varies around 4.8E+04 sej/J (see Figure 4).

Both the exergy and maximum efficiency cases give lowest transformity for heat and highest for power with the joint transformity in the middle. For the maximum production split model, the power and heat transformity values are increasing along with the raise of power to heat ratio, but they always keep the same ratio 2.3. In exergy split model, power and heat transformities keep constant.

The exergy split model results follow the thermodynamic theory. The transformity value indicates that a joule of electricity produced contains two to three times of available energy process than a joule of steam in the CHP. The simulation of the two technology cases results in different transformity values. The lowest transformity values are in extraction turbine case (Table 2). In condensing turbine case where the steam is produced by a pressure reduction, especially the heat transformity is much higher than in the extraction case. The energy based split model gives a same transformity for both heat and power. This is however not realistic since power has a larger available energy and it requires more energy for its production.
Table 1. Consumption of emery in biomass CHP process. (Sha and Hurme, 2012).

<table>
<thead>
<tr>
<th>No.</th>
<th>Item</th>
<th>Unit</th>
<th>Value/year</th>
<th>Transformity (seJ/unit)</th>
<th>Emergy (seJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Biomass</td>
<td>kg</td>
<td>1.94E+08</td>
<td>9.96E+10</td>
<td>1.93E+19</td>
</tr>
<tr>
<td>2</td>
<td>Water</td>
<td>g</td>
<td>1.26E+10</td>
<td>6.64E+05</td>
<td>8.37E+15</td>
</tr>
<tr>
<td>3</td>
<td>Investment cost</td>
<td>€</td>
<td>2.61E+06</td>
<td>1.43E+12</td>
<td>3.73E+18</td>
</tr>
<tr>
<td>4</td>
<td>Electricity</td>
<td>J</td>
<td>1.59E+13</td>
<td>8.05E+04</td>
<td>1.28E+18</td>
</tr>
<tr>
<td>5</td>
<td>Thermal energy</td>
<td>J</td>
<td>3.05E+13</td>
<td>3.03E+04</td>
<td>9.25E+17</td>
</tr>
<tr>
<td>6</td>
<td>Labor</td>
<td>€</td>
<td>2.00E+06</td>
<td>1.43E+12</td>
<td>2.86E+18</td>
</tr>
<tr>
<td>7</td>
<td>Biomass transport</td>
<td>kg</td>
<td>1.17E+08</td>
<td>8.93E+10</td>
<td>1.04E+19</td>
</tr>
<tr>
<td>8</td>
<td>Ash disposal cost</td>
<td>€</td>
<td>1.44E+04</td>
<td>1.43E+12</td>
<td>2.06E+16</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.85E+19</td>
</tr>
</tbody>
</table>

Note: The calculation of table refers to (Sha and Hurme, 2012).

Table 2. Transformities for power and heat derived from the different split models.

<table>
<thead>
<tr>
<th>Transformity</th>
<th>Exergy</th>
<th>Max efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power, seJ/J (1)</td>
<td>5.53E+04</td>
<td>5.53E+04</td>
</tr>
<tr>
<td>Heat, seJ/J (1)</td>
<td>2.30E+04</td>
<td>2.30E+04</td>
</tr>
<tr>
<td>Power, seJ/J (2)</td>
<td>5.35E+04</td>
<td></td>
</tr>
<tr>
<td>Heat, seJ/J (2)</td>
<td>1.63E+04</td>
<td>See Figure 4. (A)</td>
</tr>
</tbody>
</table>

1: Condensing turbine case with steam by pressure reduction
2: Extraction turbine case

Figure 4. The solar transformity of heat and power in CHP plant in extraction turbine case. A: split in term of maximum production; B: split in terms of exergy.
CONCLUSION

In this study the transformity calculation of power and heat derived from CHP was carried out. The paper discussed two aspects. The first one is whether the emergy flow can be split or should the co-products be treat as inseparable for CHP. It was found that the production is separable, since heat and power can be produced also independently in CHP. The second question is how to divide the emergy in a proper way. Four split methods have been discussed here and two split ways have been calculated by using data from Finnish biomass based CHP plants as a case study. Both condensing and extraction turbine alternatives were studied. Results showed that power transformity is 2.4 times the heat transformity based on exergy and maximum efficiency split models in the condensing turbine case. In the extraction turbine case, the power transformity is 3.3 times the heat transformity based on exergy split and 2.3 times higher in terms of maximum efficiency split. The lowest transformities are in the extraction turbine case 5.3E+04 and 1.63E+04 sej/J for power and heat, respectively.

The split solution avoids problems of double counting the sum of emergy input to the products. Emergy was split based on exergy rather than energy for the reason that using an exergy split higher quality of the product and lower energy efficiency results into higher emergy per unit joule.

Emergy evaluation has received criticism on the calculation of the transformities, since the calculated transformity values are used in the future research works. Therefore reasonable and reliable transformities are required. A modest contribution to strengthen the emergy analysis methodology is done, providing the transformity calculation from engineering point of view for the sustainability evaluation of emergy systems with more than one product.

REFERENCES

Odum H. T., 1996, Environmental accounting: emergy and environmental decision making, J. Wiley (Eds.), New York, USA.

