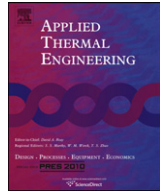


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Emergy evaluation of combined heat and power plant processes

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ABSTRACT

An energy-focused environmental accounting method based on the embodied solar energy (emergy) principle was used for evaluating biomass and coal-based combined heat and power (CHP) cogeneration processes. The emergy method expresses all the resources needed (fuel, investment, labor etc.) as solar energy equivalents. The method looks at sustainability from the point of view of the biosphere. In fact, emergy aims to be a 'memory' of how much work the biosphere has done to provide a product.

Biomass and coal-based CHP alternatives were compared with independent production of heat & power. It was found that biomass-based cogeneration is 3.3 times more emergy-efficient than coal-based independent production; i.e. the biosphere needed to work 77% less for biomass CHP produced heat & power compared to that produced independently from coal.

Cogeneration from the same fuel was in all cases 0.3 times more emergy-efficient than independent production. In general heat and power production from biomass is 2.3 times more emergy-efficient than that from coal in a similar process. The emergy sustainability index shows a similar trend, e.g. the sustainability index of a biomass CHP plant is 15 times higher than that of a coal CHP plant.

The fuel, its transport, and the oxygen in air used for burning account for over 80% of the emergy in biomass CHP, whereas in a coal-based process the share is over 90%. The share of capital is quite small in terms of total emergy.

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1. Introduction

Sustainable development, reduction of greenhouse gas emissions, and the availability of fossil energy resources are matters of great concern. These concerns are justified, since heat and power are the essential driving forces of industrial processes and communities. Nevertheless, unsustainable technology is currently dominant in electricity and heat production. Fossil fuels supply 86% of the world's commercial energy [1]. Despite concerns over biomass availability, it is claimed that biomass is more flexible and reliable as an energy source to replace fossil fuels than others, such as sunlight, wind, geothermal heat etc [2]. At the moment most electricity is produced in independent production, where heat is lost. The advantages of biomass CHP include a higher total efficiency than in conventional power plants and consequent reduction of greenhouse gas and other pollutants, provided the heat can be utilized as a by-product. From the local point of view, the application of biomass energy can contribute to sustainable development in multiple regards, not only from the environmental

aspect but also in social ways, and by enhancing the local economy due to the demand for biomass in the proximity of the power plant [3]. In general, biomass fired CHP systems are considered to have a great market potential [4]. The moisture levels of pine wood chips can be reduced by water heat from process, which is satisfactory for using as a fuel for combustion in the energy generation process, at a higher efficiency [5]. Pine wood chips are applied as the biomass input for CHP plant in this study.

Earlier emergy based evaluations of CHP processes have used fossil-based fuels, typically coal: Caruso et al. [6] compared a number of cogeneration technologies with conventional power plant technology by using several fossil fuels. The transformities were calculated for the energy produced. Brown and Ulgiati [7] compared in detail three renewable electricity production methods (wind, geothermal, hydro) with three fossil fuel fired power plants. However, these were neither CHP processes nor biomass fired. Mirandola and Stoppato [8] evaluated five power production technologies on several levels. Technologies included oil fired thermoelectric, natural gas CHP, geo-thermoelectric, gas turbine CHP, and hydroelectric processes. Feng et al. [9] compared a conventional coal-fired process with two designs of waste incineration CHP plants. Al-Sulaiman et al. [10] studied an integrated organic rankine cycle (ORC) with a biomass combustor for

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combined cooling, heating, and power production as a trigeneration system by exergy assessment. Wang et al. [11] used the emergy approach to analyze an eco-industrial park with three alternative types of coal-fired CHP power plant. The park with coal-fired integrated gasification combined cycle plant was found to be more sustainable than the coal-fired pressurized fluidized bed combustion combined cycle or the pulverized coal-fired CHP plant. Wang et al. [12] also studied two alternative energy arrangements at the Shuozhou Eco-industrial park including a coal-fired CHP plant. Peng et al. [13] used emergy to evaluate three operation modes of the Jiufa coal-fired CHP plant in Shandong China in an eco-industrial park context. Their results show that small coal-based CHP plants have lower energy efficiency, higher environmental loading, and lower sustainability than large fossil fuel and renewable energy-based systems. Bargigli et al. [14] studied three natural gas CHP processes (gas turbine, internal combustion engine and a fuel cell hybrid system), also using emergy evaluation. No conventional CHP boiler plants were included in the analysis.

All the earlier emergy analyses of thermoelectric power plants have been carried out on plants utilizing non-renewable production methods i.e. fossil fuels. Therefore the aim of this study is to make an emergy evaluation of biomass-based CHP processes and compare the results with fossil (coal)-based cogeneration.

2. Emergy principle

The environmental and economic efficiency of an industrial process can be evaluated by a variety of techniques, for example life cycle assessment, exergy analysis etc [15,16]. Emergy analysis is an energy-based environmental accounting method that expresses all the process inputs (such as energy, natural resources, services) and outputs (products) in solar energy equivalents. Emergy is defined as the solar energy used directly and indirectly to generate a service or product [17]. The solar energy unit used is the ultimate unified measure of material, energy and social resource consumption. Emergy is in fact a measure (a 'memory') of how much work the biosphere has done to provide a product. Therefore emergy analysis is a method for assessing the performance of the plant on the larger time and space scales of the biosphere; i.e. sustainability [18].

Solar transformity is the unit used to describe the solar energy required to create a unit of product. The transformity is expressed as solar energy Joules per Joule, kg or € of product (seJ/J, seJ/kg, seJ/€). Therefore transformity is the inverse value of the energy effectiveness of the system. A lower transformity means that less energy is needed to produce a given capacity of product. Transformity can be calculated with Equation (1):

$$Tr = \frac{Em}{E} \quad (1)$$

Emergy analysis is done based on a system diagram, such as the one in Fig. 4. The steps of making the analysis include [17,18]:

1. defining the system boundary.
2. listing all the external sources and internal units.
3. linking all the items according to process flows, relationships and interactions.
4. calculating the mass and energy balance of the whole process.
5. detecting whether the system is a multiproduct system.
6. creating an emergy evaluation table and calculating the transformity of the final product.

Several emergy indices have been defined in order to express the advantages and disadvantages of process alternatives. The total emergy input is the sum of renewable part R , non-renewable part N ,

and feedback from society F . Yield (Y) is the emergy of the products of the output. Five indicators are commonly used for emergy analysis to evaluate the environmental impacts and sustainability of different systems [19–21]:

- The fraction (percentage) renewable $PR = R/(R + N + F)$ gives the system's degree of renewability. The higher the value of this index, the more renewable-based the process.
- The emergy yield ratio $EYR = Y/F$. The ratio of yield to society feedback is a measure of how much a process will contribute to the economy, also indicating how dependent the process is on the purchased inputs. The higher the value of this index, the larger amount of products is obtained per unit of economy feedback.
- The environment loading ratio $ELR = (F + N)/R$ is an indicator of the loading placed on the environment. A high ELR means non-renewables and society feedback are used a lot compared to renewables, which causes higher environmental impacts.
- The emergy investment ratio $EIR = F/(R + N)$ is the ratio of emergy feedback from outside a system to the indigenous emergy input. A low EIR implies that the process is an economical user of the emergy that is invested.
- The emergy sustainability index $ESI = EYR/ELR$ is the ratio of the emergy yield ratio to the environmental loading ratio. To be sustainable in the long run, the process should have a high yield ratio EYR and a low environmental loading ratio ELR , i.e. the ESI value should be high.

3. Combined heat and power plants

CHP is a process of heat and power cogeneration, which is designed to meet the needs of energy users for both. A back-pressure or extraction steam turbine is used to produce both electricity and steam or hot water. CHP plants are integrated with industry or the local community, since the heat is typically used as steam at industrial sites and the hot water for the heating purposes of industry and communities. Cogeneration is also attractive in "eco-industrial" parks, which aim to benefit from the mass and energy integration between various plants [12]. The scale of CHP plants is limited by the heat demand of local consumers, since the long-distance transport of heat is usually not attractive. Typical power to heat ratios in CHP are about 0.4 in small CHP plants (<40 MW heat production) and ≥ 0.7 on a larger scale (40–100 MW heat production) [22].

Many kinds of raw materials could be used as the fuel for CHP, such as coal, natural gas, biomass, waste etc. A total energy efficiency of as much as 80–90% can be achieved whereas in an independent power plant the electricity efficiency is approximately 35–40% [23]. Because of the superior total efficiency in CHP production, the CO_2 emissions per heat and electricity unit produced are reduced. To further reduce fossil-based CO_2 emissions, biomass fuels are an attractive alternative, since renewable fuels such as wood chips or bio-based residues are CO_2 neutral, apart from the fossil fuels needed for fertilizing, harvesting, chipping and transport.

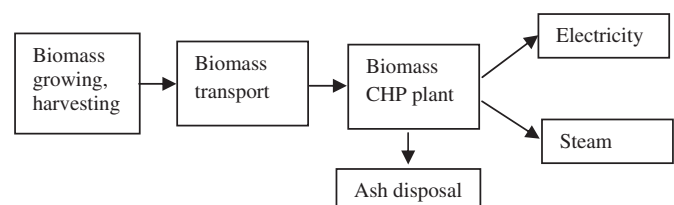


Fig. 1. Steps considered in bio-CHP process energy evaluation.

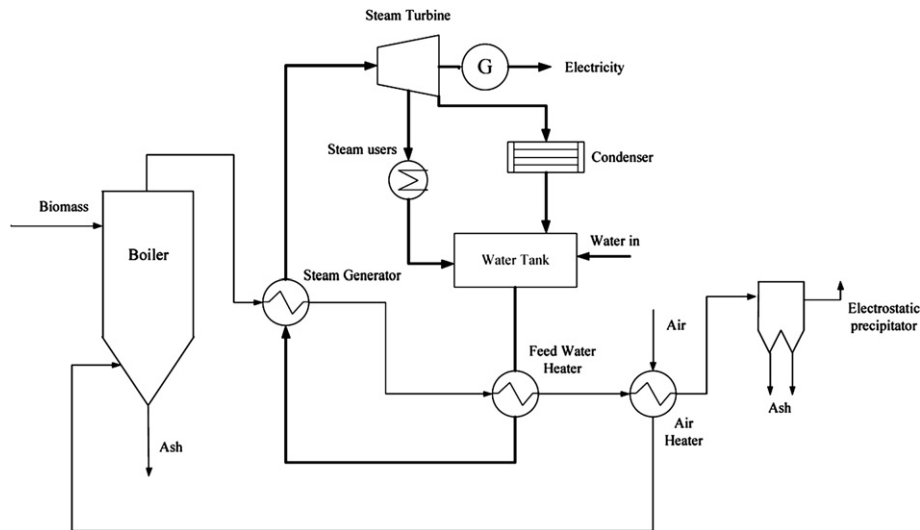


Fig. 2. Process diagram of biomass CHP power plant.

However, CHP has two obvious shortcomings. One problem is that the initial investment and maintenance cost for CHP plants is higher, because the technology has been more expensive and complex [24]. Energy savings eventually pay back the investment, but more money still has to be spent upfront to begin with. Another problem is that smaller-scale CHP plants tend to produce electricity more expensively than larger scale ones because of the economies of scale. This is the case especially in the case of biomass CHP, which needs to optimize the balance between the biomass transport distance and the size of the plant. The typical size of biomass CHP plants is ten times smaller (from 1 to 100 MW) than coal-fired plants, because of the availability and transport cost of biomass. On the other hand, the CHP size is always limited by the heat demand of the local customers.

CHP power plants are popular, especially in Northern Europe. Finland is the country with both the highest number of CHP plants and the highest electric and thermal capacity installed. Denmark and Sweden with a smaller number of installed plants reach a similar total capacity with medium and large-scale plants. In Austria, although there are many biomass-based CHP plants, the total electric capacity is lower [25].

4. Emery evaluation of bio-CHP process

4.1. Biomass CHP process case

An emery analysis was done for two cases of biomass CHP power plants (62 and 93 bar pressure), which resemble existing Finnish CHP plants [26]. The aim of the analysis was to compare biomass and coal-fired CHP processes and also independent heat & power production emery consumption. In addition, the effect of biomass power plant pressure on the consumption of resources, i.e. the transformity of the energy produced, is studied too.

The steps from forest to electricity and steam produced have been included in the analysis as presented in Fig. 1. The wood biomass is harvested in the forest and chipped. The average

Table 1

Calculated efficiencies of biomass CHP processes.

	Steam	Electricity efficiency	Steam efficiency	Total efficiency
Case A	62 bar, 510 °C	18.9%	47.1%	66.0%
Case B	93 bar, 515 °C	19.8%	49.3%	69.1%

transportation distance of the biomass is assumed to be 75 km, which corresponds to an approx. 100 km² area of biomass collection. The biomass transport is done by trucks using biodiesel as fuel.

The power plant fuel input is 71.7 MW (LHV), which corresponds to 1.94E+08 kg/a wood chips at 40% moisture (LHV_{dry} = 19.3 MJ/kg). The operating time is 8000 h/a. The plant has a bubbling fluidized bed boiler. Two cases of boiler pressures have been studied: 62 bar 510 °C (case A) and 93 bar 515 °C (case B). The 10 bar steam is extracted from a condensing turbine. The power to heat ratio is 0.4 and the air excess ratio is 1.2. The water loss in the process was assumed to be 2% of the feed water rate. The soot-blowing steam demand was assumed to be 3% of the high-pressure steam generated. The power demand of the process is 38 kWh/t dry solids [26]. The ash content of the wood (pine) is 0.74%. The labor requirement is estimated at 4 persons per shift. There are 6 shift groups in total and one manager on the day shift. Salary and social expenses are estimated at € 80000 per person annually [27]. The process diagram of the biomass CHP process is shown in Fig. 2.

The heat and energy balances for the CHP plants used by industry were simulated with a flowsheeting program to calculate the process efficiency. The results are shown in Table 1. The total efficiency is around 65–70%. A larger efficiency (about 90%) can be reached in cases that do not produce steam but district heat (i.e. hot water) [22].

4.2. Biomass CHP investment cost analysis

The plant construction phase is also commonly included in emery evaluations. One way to evaluate this is to count the emery consumption of the plant investment items based on their weight

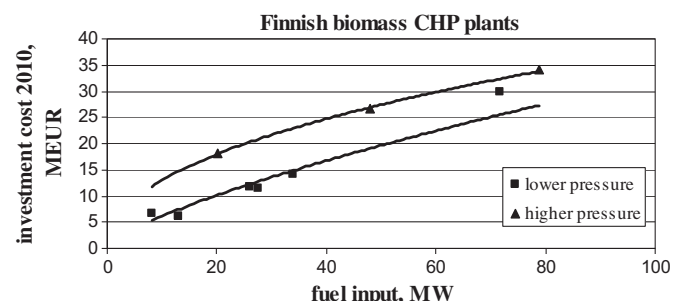


Fig. 3. Finnish biomass CHP investment cost at 2010 price level vs. fuel MW.

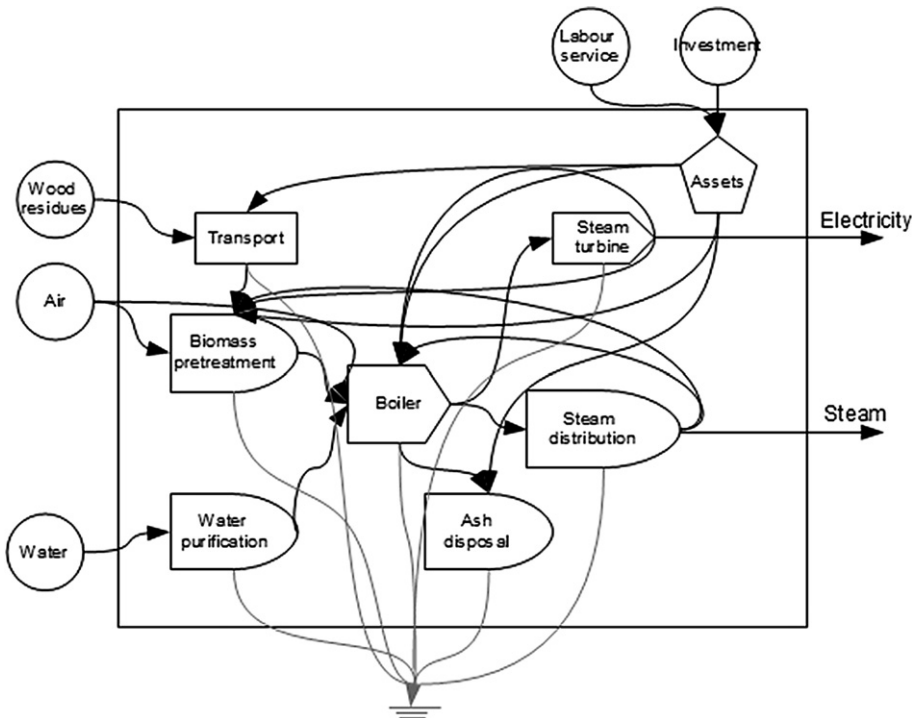


Fig. 4. Biomass CHP energy system diagram.

and the transformity of materials, as was done by Brown and Ulgiati [7]. Another way is to use the investment cost and use the transformity of the se/€ unit [12,20]. The transformity of money is based on the ratio of the total energy in the national economy to the gross national product [17]. Since the investment costs of the CHP plants can be estimated, the latter approach was chosen.

The cost estimation of the biomass CHP investment is based on data concerning Finnish small-scale CHP plant investments [22] using the plant cost index to update the costs. The steam pressure is one parameter affecting the investment cost. Fig. 3 presents the fitted cost curves for high and low pressure plants. Higher pressure CHPs operate at 80–93 bar steam pressure. Lower pressure processes have approx. 60 bar steam pressure, except for the two smallest, which are rotating grate combustion processes with a steam engine at approx. 25 bar. The larger plants mostly use bubbling fluidized bed technology, apart from two circulating fluidized bed plants.

The investment cost for a 71.7 MW_{fuel} power plant from the graphs shown in Fig. 3 is 25.0 M€ for case A (62 bar, 510 °C) and 32.5 M€ for case B (93 bar, 515 °C). The investment cost is given later in the emergy calculation, divided over 20 years with 5% interest.

4.3. Transformity in co-production

When comparing products or processes by the emergy approach, transformity is a measure of efficiency from the viewpoint of the biosphere, since it represents the work done by nature and society to generate a product or service. Since CHP plants produce two products, a problem arises, namely whether the total energy needs to be divided between heat and power. In the emergy approach it is incorrect to apportion the input energy between co-products if the products are *inseparable*, i.e. they cannot be produced independently in the process. In the case of inseparable co-products, all the

Table 2
Emergy analysis of biomass CHP process alternatives (71.7 MW_{fuel}) Case A 62 bar 510 °C, case B 93 bar 515 °C.

	No	Item	Unit	Value/year	Solar transf. (sej/unit)	Ref	Solar emergy (sej)	% of emergy case A	% of emergy case B
Material	1	Biomass	kg	1.94E + 08	9.96E + 10	[28]	1.93E + 19	40.04%	39.34%
	2 A	Water	g	1.24E + 10	6.64E + 05	[12]	8.25E + 15	0.02%	–
	2 B	Water	g	1.26E + 10	6.64E + 05	[12]	8.37E + 15	–	0.02%
Energy	3	Oxygen (in air)	g	2.05E + 11	5.16E + 07	[12]	1.06E + 19	21.90%	21.52%
	4 A	Investment cost	€	2.01E + 06	1.43E + 12	[35]	2.87E + 18	5.94%	–
Service	4 B	Investment cost	€	2.61E + 06	1.43E + 12	[35]	3.73E + 18	–	7.59%
	5 A	Electricity	J	1.59E + 13	8.17E + 04	b	1.30E + 18	2.69%	–
	5 B	Electricity	J	1.59E + 13	8.05E + 04	b	1.28E + 18	–	2.61%
	6 A	Thermal energy	J	2.92E + 13	3.12E + 04	b	9.10E + 17	1.89%	–
	6 B	Thermal energy	J	3.05E + 13	3.03E + 04	b	9.25E + 17	–	1.88%
	7	Labor	€	2.00E + 06	1.43E + 12	[35]	2.86E + 18	5.93%	5.82%
Output	8	Biomass transport	kg	1.17E + 08	8.93E + 10	[28]	1.04E + 19	21.56%	21.18%
	9	Ash disposal cost	€	1.44E + 04	1.43E + 12	[35]	2.06E + 16	0.04%	0.04%
	10 A	Electricity	J	3.91E + 14	3.54E + 04	a	4.83E + 19	–	–
	11 A	Steam	J	9.73E + 14	–	–	–	–	–
	10 B	Electricity	J	4.10E + 14	3.44E + 04	a	4.91E + 19	–	–
	11 B	Steam	J	1.02E + 15	–	–	–	–	–

Ref. notes: (a) calculated, (b) independent production values.

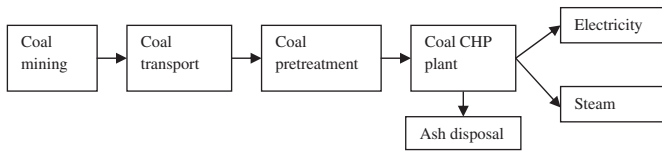


Fig. 5. Steps considered in coal CHP process energy evaluation.

Table 3

Calculated efficiencies of coal CHP process (71.7 MW, 93 bar, 515 °C).

	Electricity efficiency	Steam efficiency	Total efficiency
Coal CHP	18.7%	46.5%	65.2%

co-products have the same emery, which is the same as the total emery input [18,28]. Therefore the total emery is doubled in the co-production of two inseparable products. For semi-independent products, which can be produced independently of each other in the process, splitting can however be done [1].

The background of this thinking is that emery is a 'memory' of all the resources used by the biosphere in the previous steps leading to the product. Both products required the same amount of past work of the biosphere [18]. Emery is not a thermodynamic state function like energy or exergy. The inseparable co-product stream transformities cannot be directly used for comparing the emery efficiency of process alternatives. For this reason Bastiaoni and Marchettini [19] introduced two transformity definitions for the evaluation of co-production systems: joint transformity Tr_j and the weighted average of transformities Tr_{ave} .

Joint transformity Tr_j is defined as the solar emery required for the co-production divided by the sum of the energy content of the products (Equation (2)). The weighted average of transformities Tr_{ave} comes from the weighted ratio of two products with the same quantities as in the co-production case obtained by independent production (Equation (3)). Co-production is more efficient if the joint transformity Tr_j is smaller than the weighted average of transformities Tr_{ave} [19].

$$Tr_j = \frac{Em_{es}}{E_e + E_s} \quad (2)$$

$$Tr_{ave} = \frac{E_e}{E_e + E_s} Tr_e + \frac{E_s}{E_e + E_s} Tr_s = \frac{Em_e + Em_s}{E_e + E_s} \quad (3)$$

4.4. Calculation of transformity of biomass CHP cases

A system diagram (Fig. 4) was formed for the biomass CHP processes. Case A operates at 62 bar pressure and case B at 93 bar,

both 71.7 MW fuel power. Based on this and the heat and material balances an emery table was formed (Table 2). The transformity values of the input were taken or modified from literature as referred to in Table 2.

The 'biomass' in row 1 includes biomass growing and chipping [28]. The 'biomass transport' in row 8 includes biomass forwarding and transportation in trucks using biodiesel fuel. The value of biomass transport transformity was obtained as the average of three kinds of biomass resources: industrial wood cutting, logging residues from final felling, and logging residues from thinning. Motor fuel, capital investment, machines and human services were the cost items counted in biomass transportation [28]. The emery of ash was considered through the waste disposal cost [29]. The transformity of the heat and power used by the plant was taken from the independent production values calculated later.

The joint transformity calculated for heat and power production is $3.54E + 04$ seJ/J for case A (62 bar) and $3.44E + 04$ seJ/J for case B (93 bar), as presented in Table 2. Case B can produce more electricity and heat than case A, because of the higher operating pressure. The power to heat ratios are the same in both cases. The main contributors to the emery are the biomass (40%), oxygen (air) consumed in burning (22%), and biomass transportation (21%). Based on this analysis the higher investment in the higher pressure power plant pays off in the emery sense, since the joint transformity is slight smaller in case B.

5. Emery evaluation of coal-based CHP process

To compare the solar emery use per unit of power and heat produced from renewable and non-renewable raw materials, the same scale (71.7 MW_{fuel}) coal-based CHP process was studied. The calculation principle and the operating values were the same as for the biofuel CHP. Again the aim was to consider all steps in the evaluation as shown in Fig. 5.

Coal is transported by rail inland and by ship overseas. Here the emery of transportation is calculated as the weighted average of five major European coal importing/exporting countries. Their average transport distance is 6300 km by ship and 1800 km by train [30,31]. The transformities of railroad and ship transportation are $3.47E + 10$ seJ/t-km and $7.99E + 10$ seJ/t-km respectively with diesel fuel consumption [32]. The investment cost was calculated according to the coal-based CHP investment data presented by Pilavachi et al. [24].

The simulated efficiencies are presented in Table 3. By comparing the results of Tables 1 and 3, it can be seen that for the same operating conditions, the total efficiency of coal-based CHP (65%) is somewhat lower than that of biomass-based CHP (69%) at the same pressure of 93 bar.

Table 4

Emery analysis of coal CHP process (71.7 MW_{fuel}, 93 bar, 515 °C).

	No.	Item	Unit	Value/year	Solar transf. (seJ/unit)	Ref. no.	Solar emery (seJ)	% of emery
Material	1	Coal	J	2.06E + 15	3.92E + 04	[24]	8.09E + 19	53.29%
	2	Water	g	1.28E + 10	6.64E + 05	[12]	8.50E + 15	0.01%
	3	Oxygen (in air)	g	2.60E + 11	5.16E + 07	[12]	1.34E + 19	8.83%
	4	Limestone	g	5.50E + 08	1.00E + 09	[12]	5.50E + 17	0.36%
	5	Investment cost	€	1.93E + 06	1.43E + 12	[35]	2.75E + 18	1.81%
Energy	6	Electricity	J	9.93E + 12	2.72E + 05	b	2.70E + 18	1.78%
	7	Thermal energy	J	3.84E + 13	9.49E + 04	b	3.64E + 18	2.40%
Service	8	Labor	€	2.00E + 06	1.43E + 12	[35]	2.86E + 18	1.88%
	9	Transport	kg	7.94E + 07	5.65E + 11	[32,33,35]	4.48E + 19	29.54%
	10	Ash disposal cost	€	1.01E + 05	1.43E + 12	[32]	1.45E + 17	0.10%
Output	11	Electricity	J	3.86E + 14	1.13E + 05	a	1.52E + 20	
	12	Steam	J	9.59E + 14				

Ref. notes: (a) calculated, (b) independent production values.

Table 5
Energy analysis of coal CHP process for larger scale (150 MW_{fuel}, 93 bar, 515 °C).

	No.	Item	Unit	Value/year	Solar transf. (sej/unit)	Ref.No.	Solar energy (sej)	% of emergy
Material	1	Coal	J	4.32E + 15	3.92E + 04	[24]	1.69E + 20	53.323%
	2	Water	g	2.68E + 10	6.64E + 05	[12]	1.78E + 16	0.01%
	3	Oxygen (in air)	g	5.44E + 11	5.16E + 07	[12]	2.80E + 19	8.82%
	4	Limestone	g	1.15E + 09	1.00E + 09	[12]	1.15E + 18	0.36%
Energy	4	Investment cost	€	3.73E + 06	1.43E + 12	[35]	5.33E + 18	1.68%
	5	Electricity	J	2.08E + 13	2.68E + 05	b	5.57E + 18	1.75%
	6	Thermal energy	J	8.03E + 13	9.34E + 04	b	7.50E + 18	2.36%
Service	7	Labor	€	4.80E + 06	1.43E + 12	[35]	6.86E + 18	2.16%
	8	Transport	kg	1.66E + 08	5.65E + 11	[32,33,35]	9.39E + 19	29.53%
	9	Ash disposal cost	€	2.12E + 05	1.43E + 12	[35]	3.03E + 17	0.10%
Output	10	Electricity	J	8.07E + 14	1.13E + 05	a	3.18E + 20	
	11	Steam	J	2.01E + 15				

Ref. notes: (a) calculated, (b) independent production values.

The emergy evaluation is presented in Table 4. The main contributors to emergy are coal (53%), transportation (30%), and oxygen input (9%). The calculated transformity of coal heat & power is 2.3 times higher than biomass-based (Table 2). This means that the biosphere needed to work 2.3 times more to produce a unit of energy by coal CHP than by the biomass CHP route at this size. Furthermore, the formation of coal is a non-renewable process.

Coal-fired CHP plants are commonly larger than biomass-based CHP plants, because the logistics are not a limiting factor as they are for biomass-based plants. Therefore a 150 MW_{fuel} coal CHP was calculated for comparison. The investment cost was scaled up with a capacity exponent of 0.90 based on the cost data in literature [24]. The calculated investment costs per kW_e and total capital cost for the coal CHP processes were 1395 €/kW_e and 21.7 M€ for 71.7 MW_{fuel}, 1291 €/kW_e and 41.9 M€ for 150 MW_{fuel} capacity. Also, the number of personnel was increased from 6 to 10 persons per shift. The emergy evaluation values are shown in Table 5.

The results in Table 5 show that the transformity of energy produced in both scales of coal-fired power plant are the same, because over 90% of the emergy load comes from coal, its transport and oxygen in air for burning. These are variable costs. The share of investment is only very small (<2%). In addition, the investment capacity exponent is large (0.90) giving a minor capacity benefit for the larger size [24].

6. Results and discussion

To allow comparison by means of the joint and weighted average of transformities (Equations (2) and (3)), the independent production transformities for heat and power were calculated for the same heat & power capacities and operating conditions as in the CHP cases (Table 6). Investment costs were 10% less for independent power production compared to the CHP process, and 20% less for independent steam production [33]. Next, the weighted average transformities and joint transformities were calculated according to Equations (2) and (3). The results are presented in Table 7.

Table 6
Transformities and efficiencies of independently produced heat and power.

	Steam	Electricity transformity sej/J	Steam transformity sej/J	Electricity efficiency	Steam efficiency
Biomass A 71.7 MW 510 °C	62 bar,	8.17E + 4	3.12E + 4	30.1%	83.5%
Biomass B 71.7 MW 515 °C	93 bar,	8.05E + 4	3.03E + 4	31.3%	83.5%
Coal 71.7 MW 515 °C	93 bar,	2.72E + 5	9.49E + 4	28.1%	80.6%
Coal 150 MW 515 °C	93 bar,	2.68E + 5	9.34E + 4	28.1%	80.6%

Table 7 shows that in all the cases cogeneration is more emergy-efficient than independent production, since the joint transformity is less than the weighted average of transformities calculated from the independent production. The weighted average of transformities of independent production is approx. 30% larger than the joint transformity. Therefore the biosphere needed to work about 0.3 times more for the independently produced heat and power compared to the cogenerated.

In independent production the transformity of biomass-generated electricity and heat is approx. 30% of the transformity of coal-generated electricity and heat. The same applies also to the heat and power generated in biomass CHP compared to coal-based CHP. Therefore the biosphere needed to work about 2.3 times more for the coal-generated heat & power compared to biomass-generated both in cogeneration and in independent production.

Finally, it can be seen from Table 7 that heat and power independently produced from coal has 77% smaller transformity than CHP produced from biomass. Therefore the biosphere needs to work 3.3 times more for independently produced coal-based heat & power than for CHP produced from biomass.

Table 8 presents the emergy indices calculated for the biomass and coal-based CHP processes. It was assumed that biomass fuel is fully renewable. Oxygen in the air and water are also renewable inputs. Coal and limestone are non-renewable. Investment, energy inputs, labor, biomass transportation, and ash disposal were considered as society feedback.

The two biomass CHP cases are quite similar in indicator results as are the coal CHP cases. The fraction renewable (PR) in the biomass cases is 6 times higher than in the coal cases. The yield ratios (EYR) are almost the same in all cases as their society feedbacks are quite the same. The environmental loadings (ELR) are very high (more than 10) for the coal CHPs, because of the non-renewable coal fuel. The renewable energy systems have very low environmental loading ratios (less than 1.0). The emergy investment ratios (EIR) are all approx. 0.6, meaning that the processes do not depend highly on the feedback from society. The environmental sustainability index (ESI) represents long-term sustainability; the higher the ESI the more sustainable the process. The biomass CHP

Table 7
Weighted average transformities and joint transformities.

	Biomass 62 bar, 510 °C	Biomass 93 bar, 515 °C	Coal (71.7 MW _f) 93 bar, 515 °C	Coal (150 MW _f) 93 bar, 515 °C
Weighted transformity (independent production) ksej/J	45.7	45.0	147	143
Joint transformity (CHP production) ksej/J	35.4	34.4	113	113

Table 8
Energy indices for biomass and coal-based CHP processes.

	Biomass, 71.7 MW 62 bar, 510 °C	Biomass, 71.7 MW 93 bar, 515 °C	Coal, 71.7 MW 93 bar, 515 °C	Coal, 150 MW 93 bar, 515 °C
PR	0.62	0.61	0.090	0.090
EYR	2.63	2.56	2.67	2.67
ELR	0.62	0.64	10.32	10.29
EIR	0.62	0.64	0.60	0.60
ESI	4.27	3.98	0.26	0.26

plants at 62 bar have the highest ESI value of 4.27, followed by the biomass CHP plants at 93 bar with an ESI value of 3.98. Both the coal CHP processes show ESI values of less than 0.3.

7. Conclusions

In this study, a solar energy based environmental accounting analysis was carried out for two biomass and two coal-fired CHP plant alternatives. This study is one of the main focuses in the area of energy and thermal engineering has been on improving the design and operation of energy systems, enhancement and integration of renewable applications [34]

The emergy method can be used for analyzing power plants from the large-scale and long-term sustainability point of view, since the emergy expresses how much work the biosphere has done to provide a product or service. The emergy approach proved to be an efficient method for analyzing power plants. However, one shortcoming was the inability to calculate transformities for heat and power separately in cogeneration. Nevertheless, a comparison between cogeneration and independent heat and power generation was possible through joint and average transformities.

In the comparison of CHP and independent production, it was found that biomass CHP was 3.3 times more emergy-efficient than coal-based independent production. Therefore the biosphere needed to work 77% less for biomass CHP compared to independent coal-based production of heat and power.

For the same fuel, cogeneration was 0.3 times more emergy-efficient than independent production in all the cases studied. Therefore the biosphere needed to work about 20–25% less for cogenerated heat and power than independently produced heat and power for the same fuel.

Heat and power production from biomass is 2.3 times more emergy-efficient than production from coal by the same production method. The biosphere needed to work about 70% less for biomass-generated heat and power compared to coal-generated, both in CHP and in independent production.

Fuel, its transportation, and oxygen in the air used for burning account for >80% of the total emergy in biomass-based production and >90% in coal-based. The share of investment is 7–8% of emergy in biomass-based CHP production.

Calculated emergy indices indicated that the biomass CHP process had a higher renewable percentage (0.6) and emergy sustainability index (4.0 – 4.3) than the coal CHP process (PR = 0.090, ESI = 0.26). Environmental loading ratios in the coal CHP plants were about 15 times higher than in the biomass case. Therefore, biomass fired plants were much more sustainable from the emergy point of view.

Emergy analysis can also be used to indicate more detailed process design selections. It was studied whether a higher steam generation pressure is more emergy-efficient in the relatively small-scale biomass CHPs. When looking at the transformities, the result was that a higher boiler pressure is about 3% better from the emergy perspective. Therefore the higher heat and power production 'paid off' the higher boiler investment in the emergy sense in this case study.

Nomenclature

E	is the rate of the stream (as energy, mass etc.)
E_e	is energy content of electricity (equal in CHP and independent production)
E_s	is the energy content of steam (equal in CHP and independent production)
E_m	is the total emergy of the stream
$E_{m_{es}}$	is the total emergy needed for cogeneration
E_{m_e}	is the emergy of electricity in independent production
E_{m_s}	is the emergy of steam in independent production
EIR	is the emergy investment ratio $F/(R + N)$
ELR	is the environmental loading ratio $(F + N)/R$
ESI	is the emergy sustainability index EYR/ELR
EYR	is the emergy yield ratio Y/F
F	is the feedback from society
N	is the non-renewable input part
PR	is the percentage renewable $R/(R + N + F)$
R	is the renewable input part
Tr	is the transformity
Tr_j	is the joint transformity in CHP
Tr_{ave}	is the average of transformities in independent production
Tr_e	is the transformity of electricity in independent production
Tr_s	is the transformity of steam in independent production
Y	is the yield

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