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Renewable Energy Based Environmental Accounting of Heat, Power and Steel Production

Sha Sha*, Magdalena Losowska, Markku Hurme

Aalto University,
P.O.Box 16100, 00076 Aalto, Finland. sha.sha@aalto.fi

The aim of the work is to present embodied solar energy (emergy) based environmental accounting for renewable energy based heat, power and steel recycling processes. For the purpose a biomass based combined heat and power (CHP) power plant process is first evaluated. Secondly a steel recycling process is analyzed to calculate the embodied energy consumption of recycled steel with two electrical energy alternatives. The presented approach can be used for analyzing the resource consumption of processes and utilized as an energy focused sustainability index.

1. Introduction

The CO_2 emission abatement requires reducing the use of fossil energy and raw material sources. The future prospect is a fully sustainable economy, which is totally based on renewable energy and raw materials. For this purpose renewable energy oriented environmental accounting methods are needed. This method can be based on the embodied energy (emergy) principle, which expresses all resources, such as raw materials, energy and services, on a single basis; solar energy. Earlier the method has been applied on power and steel processes utilizing non-renewable production methods with fossil based materials. Here the renewable options are analyzed.

Two case studies are presented in this paper to demonstrate the method for fully renewable economy: In the first one embodied renewable energy analysis of a biomass based CHP process producing steam and electricity is done. In the second case study a steel recycling process is analyzed. Wood residues were used to generate electricity & steam and the steel is produced from scrap. Renewable energy contents (transformities) are counted for the electricity, steam and recycled steel produced on renewable basis.

2. Emergy Principle

The environmental and economic efficiency of an industrial process can be evaluated by variety of techniques, such as life cycle assessment, exergy analysis etc. (Brown and Herendeen, 1996). Emergy analysis is energy based environmental accounting method that expresses all process inputs (such as energy, natural resources, human services and society feedback) and outputs (products etc.) in solar energy equivalents. Emergy is defined as solar

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energy used directly and indirectly to generate a service or product (Odum, 1996). Solar transformity is the unit to describe the solar energy required to create a unit of product. The transformity is expressed as solar emjoules per J, kg or € of product (seJ/J, seJ/kg, seJ/€). Therefore transformity is the inverse value of the system energy effectiveness.

In earlier papers (e.g. Wang et al., 2005) the transformities of electricity, steam and recycled steel have been calculated based on fossil raw materials, such as coal and oil. In making studies of renewable economy, these values are not applicable and need to be recalculated.

3. CHP Case Study

Co-production of heat and power (CHP) is an integrated process of electricity and heat production in a power plant. The total energy efficiency 85-90 % based on fuels utilization can be achieved while in an independent power plant the electricity efficiency is approximately 35-40%. Because of the better efficiency with the CHP production, the CO_2 emissions per heat and electricity unit produced are reduced. To further reduce the fossil based CO_2 emissions, biomass fuels are an attractive alternative, since renewable fuels such as biomass and wood residues are defined as CO_2 neutral.

In this case study two biomass fueled CHP power plant alternatives are compared. The power plant information is based on Finnish CHP plants (Kirjavainen et al., 2004) and flowsheet simulation. The fuel input is 71.7 MW wood chips or residue in 40 % moisture. 10 bar steam and electricity is produced in a back-pressure turbine. Biomass transportation fuel is biodiesel. Transportation distance is 75 km.

For case A the power plant pressure is 62 bar, the electricity production efficiency 12% and heat production efficiency 77%. For case B the pressure is 93 bar, the electricity production efficiency 14% and heat production efficiency 75%. The total investment cost for case A is 23.9 M€ and for case B 32.5 M€. The investment is divided over 20 y. The other values of the alternatives are presented in Table 1. The aim of the analysis is to evaluate the effect of power plant pressure on the consumption of renewable resources (i.e. emergy value) of the steam and electricity. The system diagram is presented as Figure 1.

Since the CHP plants produce two products a problem arises, how to divide the transformities between the steam and electricity. Previous studies (e.g. Wang et al., 2005) simply divided emergy amounts equally between the electricity and heat produced. Since the heat amount was much less than electricity, this resulted in much higher transformity values for steam than for electricity. This is not logical, since electricity is thermodynamically higher value energy than heat energy. Our calculation adopts the combined and independent efficiencies concept of two co-products to get the amount of emergy for each product. The divided emergy ratio between electricity and steam in CHP process is calculated by Equation 1.

$$\frac{Em_e}{Em_s} = \frac{\eta_{CHPe} / \eta_e}{\eta_{CHPs} / \eta_s} \quad (1)$$

Em_e is electricity emergy content. Em_s is steam emergy content.

η_{CHPe} is efficiency of electricity production in CHP process, case A 12 %, case B 14 %
η_{CHPs} is efficiency of steam production in CHP process, case A 77 %, case B 75 %
η_e is electricity efficiency in non CHP process (34 %)
η_s is steam efficiency in non CHP process (89%).

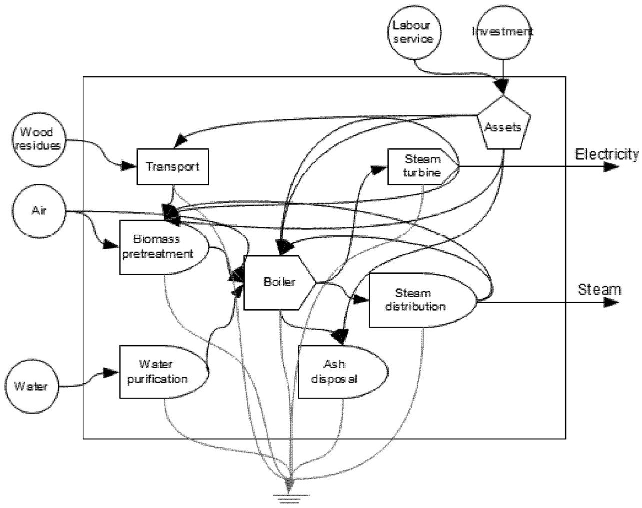

Fig. 1. Biomass CHP emergy system diagram.

Table 1: Emergy analysis of biomass CHP process alternatives

	No.	Item	Value/year	Solar transf. (seJ/unit)	Solar emergy (seJ)
Material	1	Biomass (pine)	1.94E+08 kg_{wet}	9.96E+10	1.93E+19
	2	Water	6.50E+06 kg	6.64E+08	4.30E+15
	3	Oxygen (in air)	1.96E+05 kg	5,16E+10	1.01E+16
	4 A	CHP investment cost	1.20E+06 €	1.43E+12	1.72E+18
	4 B	CHP investment cost	1.63E+06 €	1.43E+12	2.33E+18
Energy	5 A	Electricity	1.59E+13 J	4.39E+04	6.98E+17
	5 B	Electricity	1.59E+13 J	4.24E+04	6.49E+17
	6 A,B	Thermal energy	6.53E+13 J	1.60E+04	1.05E+18
Service	7	Labor	2.00E+06 €	1.43E+12	2.86E+18
	8	Biomass transport	1.94E+08 kg_{wet}	5.36E+10	1.04E+19
	9	Ash disposal cost	1.19E+05 €	1.43E+12	1.70E+17
Output	10 A	Electricity	2.39E+14 J	***4.39E+04***	1.05E+19
	10 B	Electricity	2.95E+14 J	***4.24E+04***	1.20E+19
	11 A	Steam	1.59E+15 J	***1.62E+04***	2.58E+19
	11 B	Steam	1.55E+15 J	***1.57E+04***	2.48E+19

The total emergy content was divided between electricity and steam by Equation 1 in ratio 35.2 / 86.5 = 0.407 in case A and in ratio 41.2 / 84.3 = 0.489 in case B. The calculated ratio shows the distribution of total emergy input into the two products based on the independent and combined efficiencies principle. After this the transformities of electricity and steam were calculated by dividing their energy contents by the emergy contents. The emergy of ash was considered through waste disposal cost. The input values and results of calculation are presented in Table 1. The row 1 'biomass' includes biomass growing and chipping. The row 8 'biomass transport' includes biomass forwarding and transportation by biofuel as given by Hagström (2006). The other transformity values are based on Odum (1996) and Peng et al. (2008).
By comparing the cases in Table 1, it can be seen that both electricity and steam transformities are nearly equal but slight smaller in case B. The embodied energy (emergy) efficiency in these two cases is same but case B can produce more electricity and less heat than case A. The main contributors to the emergy are the biomass (53%) and biomass transportation (28%). Based on this analysis the higher investment on the higher pressure power plant (case B) pays out in the emergy sense.

4. Steel Recycling

Steel is a fully recyclable material used in large extents. Therefore the steel recycling process has potentially a great influence on conservation of natural resources. Recycling steel scrap uses typically the Electric Arc Furnace (EAF) technology (Anon., 2008). Production performed in the EAF considerably reduces the amount of energy demand as well as the emissions compared to the virgin material based route.
In the following calculation, the main emergy contributors to steel recycling are studied. The effect of using renewable vs. fossil based electricity is also studied on the emergy of recycled steel. This also gives an indicator on the energy sustainability of the alternatives.
Table 2 presents the emergy analysis of a 100 t capacity EAF furnace with an annual production of 870,000 t of molten steel. 1.132 t of scrap is needed to produce 1 t of steel. During the melting phase oxygen added is blown into the electric arc furnace to purify the steel. Graphite electrodes heat charged material up to approximately 1,800°C. Ferroalloys are added to the steel to provide the required chemical composition and properties. Addition of fluxes guarantees that the melting material is well insulated. Refractories ensure required conditions inside the furnace like high durability against a mechanical wear-out (Anon., 2008). The emergy diagram of the system is shown in Figure 2.
In case A the electricity is renewable (i.e. the biomass CHP power plant of the previous case study). In case B the electricity is supplied by a coal CHP power plant. In both cases the thermal energy is natural gas based. The scrap transportation is done by using biodiesel.
The results in Table 2 show that the bio-based electricity reduces about 25 % of the emergy of steel recycling. The main emergy contributors in the renewable electricity based recycling (A) are the thermal energy (21 %), electricity (20 %) and refractories (18 %). In fossil electricity case (B) electricity is the main contributor (37 %).

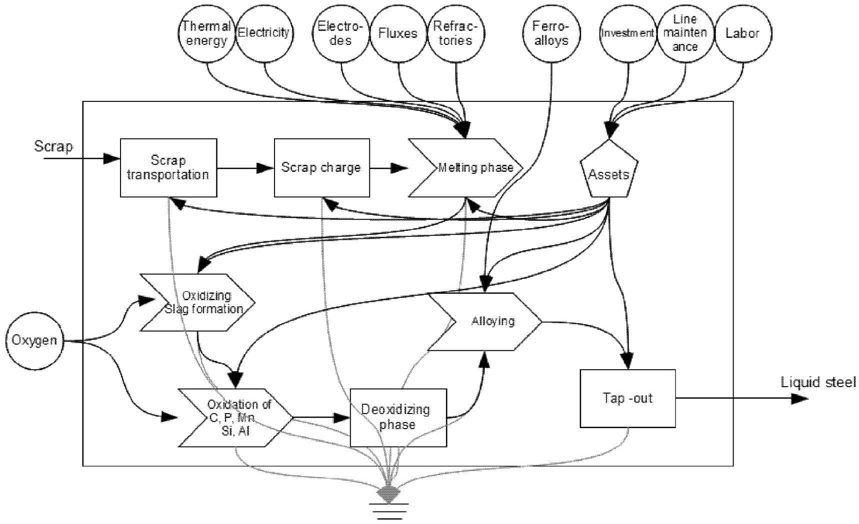

Figure. 2. Steel recycling emergy system diagram.

Table 2. Emergy analysis of a steel recycling process with two energy alternatives

	No.	Item	Value/y	Solar transf. (seJ/unit)	Solar emergy (seJ)
Material	1	Scrap	9.85E+08 kg	0	0
	2	Oxygen	1.74E+07 kg	4.47E+11	7.78E+18
	3	Ferroalloys	1.27E+07 €	1.43E+12	1.82E+19
	4	Fluxes	3.74E+07 kg	9.80E+11	3.67E+19
	5	Electrodes	1.74E+06 kg	1.78E+12	3.10E+18
	6	Refractories	4.35E+06 kg	9.90E+12	4.31E+19
	7	Investment cost	1.46E+07 €	1.43E+12	2.09E+19
Energy	8 A	Electricity	1.06E+15 J	4.39E+04	4.67E+19
	8 B	Electricity	1.06E+15 J	1.10E+05	1.17E+20
	9	Thermal energy	1.16E+15 J	4.35E+04	5.03E+19
Service	10	Labor	7.98E+06 €	1.43E+12	1.14E+19
	11	Scrap transport	3.67E+06 €	1.43E+12	5.25E+18
Output	12 A	Steel	8.70E+08 kg	***2.74E+11***	2.38E+20
	12 B	Steel	8.70E+08 kg	***3.61E+11***	3.14E+20

By comparing the transformity of steel recycling (2.74E11 seJ/kg by renewable electricity and 3.61E11 seJ/kg by fossil based electricity) to that needed of producing steel from minerals (about 4.2E12 seJ/kg), it can be seen that the steel recycling is in both cases more emergy effective alternative than producing new steel.

5. Conclusions

In this study, the energy based environmental accounting using the embodied solar energy approach (emergy) was carried out for two biomass fired CHP plant alternatives and a steel recycling mill utilizing either renewable or fossil based electricity. The method used expresses all items such as the investment, raw materials, labor, services etc. in energy units. By using this unified basis for both investment and operation related terms it allows the evaluation to be made on a single basis, which is the energy required expressed as solar energy Joules. By the emergy method renewable energy based evaluations can be made for process investment and operating alternatives. The lower the specific emergy (the transformity) of the products, the less resources are demanded from nature and society to produce the goods or services. Therefore the emergy analysis describes the energy based sustainability of the system. The main contributors affecting on the sustainability can be tracked down by the analysis and engineering methods directed to improve the aspects most hampering the sustainability. Because of its background the method can be also used to optimize sustainable economy and manufacturing routes, where the solar energy is considered as a limiting resource. The method however requires to be reworked for a fully renewable economy, since the existing transformity values are typically fossil energy based. As a method the emergy approach is totally energy sustainability focused expressing everything as solar energy units. Therefore it does not describe the emissions creating environmental pollution, which in turn affect the biosphere. Therefore a separate analysis for other environmental effects is needed to complement the emergy method. By its nature the emergy method allows CO_2 emissions to be calculated easily however.

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