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ENERGY, EXERGY AND EMERGY ANALYSIS OF A RENEWABLE ENERGY SYSTEM BASED ON BIOMASS PRODUCTION

Karolina Hovelius

Dept. of Agriculture Engineering, Swedish University of Agricultural Sciences, Box 7033, SE-750 07 Uppsala, Sweden

Tel +46-18-671000 Fax +46-18-673529, Email: Karolina.Hovelius@lt.slu.se, WWW: http://www.slu.se

Göran Wall

Exergy Studies, Solhemsgatan 46, SE-431 44 Mölndal, Sweden

Tel./Fax: +46-31-877579, Email: gw@exergy.se, WWW: http://exergy.se

Abstract Advantages and disadvantages of energy, exergy and emergy analysis is clarified, by analyzing different cultivation systems. Salix, winter wheat, and winter rape cultivations are analyzed, which shows that the Salix cultivation has the highest energy, exergy, and emergy return.

1 Introduction

Cultivation of energy crops on agricultural land will probably be an important part of energy supply in the future when: (1) agriculture has a problem with overproduction of food, and (2) burning of fossil fuels must be replaced by renewable resources. The efficiency in collecting solar energy into biomass in relation to the total input of non renewable resources then becomes an important factor, which we call the exchange. The total resource use over time is also important to consider [1]. Energy, exergy, and EMERGY analyses are applied to Salix, winter wheat, and winter rape cultivations in order to clarify some of the differences between these methods. Energy and exergy have their origins in thermodynamics, whereas EMERGY origins from systems ecology.

2 Methods

2.1 Energy analysis

The energy content in an end product does not univocal correspond to the energy used in production. To draw up an energy budget, it is necessary to accounted for all different inflows of energy in the process. In 1974, a conference was held by the International Federation of Institutes for Advanced Studies [2] at which this type of budgeting was denoted **energy analysis**, and Gibbs free energy was chosen as a unit of measure. Little has been added to this method, and analyses are usually limited to just energy.

There are basically three different methods used to perform an energy analysis; process, statistical, and input-output analyses [3]. The latter is based on an input-output table as a matrix representation of an economy. Each industry is represented by a row and column in the matrix. The main advantage of this method is that it can quickly provide a comprehensive analysis of an entire economy. The main disadvantages arise from the use of financial statistics and from the degree of aggregation in the table. A more detailed input-output table may be detained when using more detailed statistics analysis. This method is called statistical analysis, which is basically a longhand version of input-output analysis. The method has two advantages over the input-output method: (1) it can achieve a more detailed analysis and, (2) it can usually be executed directly in physical units, thus avoiding errors due to preferential pricing, price fluctuations, etc. However, its disadvantage compared with the input-output method is that the computations usually have to be done manually. Here we use process analysis, which focuses on a particular process or sequence of processes for making a specific final commodity and evaluates the total energy use by summing the contributions from all individual inputs, in a more or less detailed description of the production chain.

In the process analysis, we first establish the network of processes to make Salix, winter wheat, and winter rape. Then we define the required material and equipment flows and finally we assign a gross energy requirement to each input and perform the calculations (Excel).

2.2 Exergy analysis

Exergy could easily be incorporated into the process analysis to form an **exergy analysis**, see *figure 1*. [4]

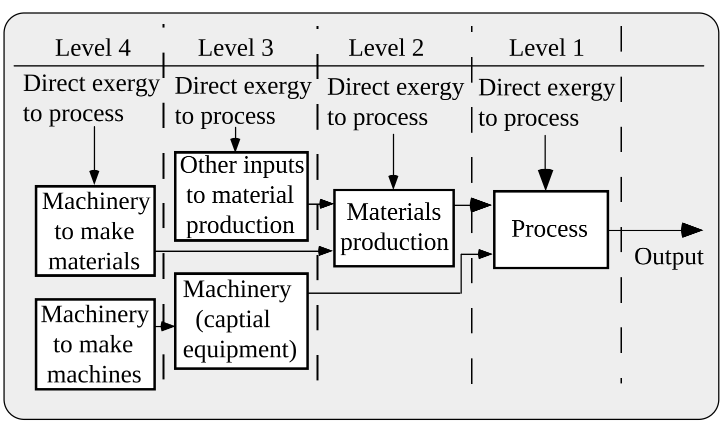
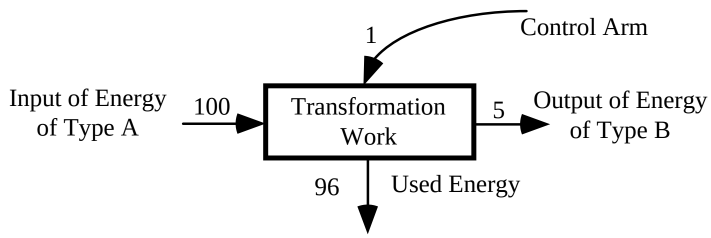


Figure 1 The levels of process analysis.

2.3 EMERGY analysis

EMERGY, written in capitals according to Odum, [5] originates in energy and memory, and defines the energy needed to generate a product [6], e.g., the solar EMERGY (sej) is the total amount of solar energy transformed into a specific output, see *figure 2*. The energy transformation ratio is a product's EMERGY divided by its energy. Most transformation processes have additional inputs of a control nature, but if these are a by-product of the energy flow from upstream or downstream they can be ignored in the calculation because they are not from an independent energy source [7]. In a chain process it is obvious that EMERGY increases in every step, e.g. in the tropical hierarchy [5].

In *figure 3* the agricultural energy system is illustrated by symbols [5]. Energy flows are indicated by pathways that may indicate interactions, show material cycles or carry information. The EMERGY flows through the system, while some of the energy disappears in the bottom. This diagram may also define the relations that are used for systems simulation.



$$\text{Energy Transformation Ratio} = \frac{A}{B} = \frac{100}{5} = 20$$

Figure 2 The energy transformation ratio.

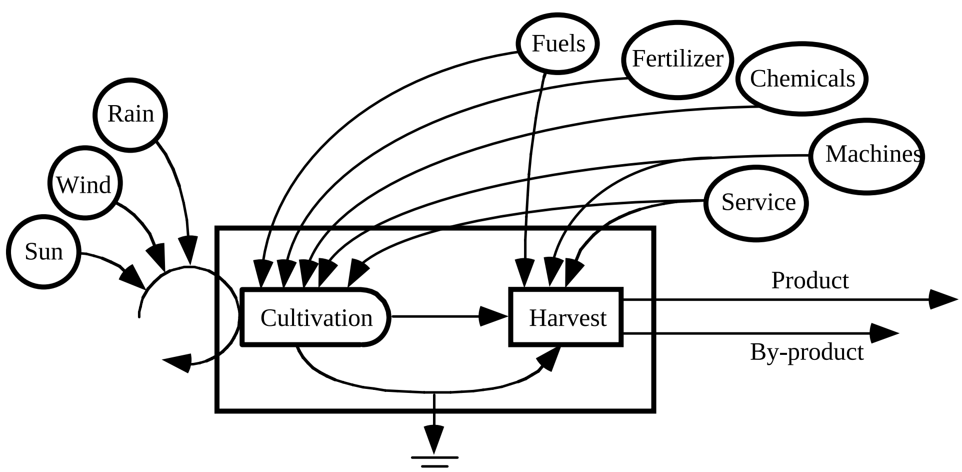


Figure 3 Energy analysis of agriculture.

The EMERGY Investment Ratio (EIR) is the ratio between the EMERGY invested from society (economy, services and other resources) and the EMERGY invested from the environment. This ratio measures the intensity of the economic development and the loading of the environment. The Net EMERGY Yield Ratio (NEYR) is a ratio that shows the ratio between the EMERGY yield and the EMERGY invested from society. The EMERGY yield ratio of each system output is a measure of its net contribution to society beyond its own operation [5].

3 Salix, winter wheat, and winter rape cultivations

System boundaries are set at the field border, thus all operations on the field during cultivation are taken into consideration and include every step needed for Salix, winter wheat, or winter rape cultivations. Thus, preparations, such as drying are not considered, and neither are transportation of the harvest from the field or storing of the products.

For Salix, all steps are included from preparation of the soil and planting of the Salix plant in year 1, to restoring of the field after 25 years. When winter wheat and winter rape are analyzed, all steps during one year, from stubble to stubble, have been taken into consideration.

Salix (willow) has a life cycle of 25 years including preparation, six cutting cycles, and restoration of the field. Preparation includes stubble harrowing, ploughing, harrowing, and planting. Salix may be harvested in the winter every 4-6 years for about 25 years, i.e. about 6 harvests. Preparation and restoration are energy demanding processes. The final product is chips.

Winter wheat for energy production is cultivated as for food production. Growing winter wheat starts in the autumn by preparing the soil for cultivation, thereafter comes initially stubble harrowing, ploughing, and harrowing, later seed-drilling and rolling, followed by fertilizing and pesticide control, and then finally harvesting. The cultivation of rape is analogous and includes all steps from stubble to stubble during one year. The final products are grains.

3.1 Energy analysis

From a process analysis, in which we first establish the network of processes required to make the commodity, in this case Salix, winter wheat, and winter rape cultivation. Then we define the material and equipment flows that are required in the production process, and finally we assign a gross energy requirement to each input and perform the necessary arithmetic, in this case by use of spread sheets (Excel).

The total energy input for Salix is 1.21×10^5 MJ/ha during 25 years, of which nitrogen accounts for 70% and fuels 20%. The total yield is 4.15×10^5 kg/ha, with 50% DM and an energy content of 8.12 MJ/kg the output becomes 3.37×10^6 MJ/ha, which gives an energy ratio (output/input) of 28.

The energy use for winter wheat is 15.1×10^3 MJ/ha, where nitrogen accounts for 46%, diesel 19% and seed 18%. The yield is 8.3×10^3 kg/ha, with energy content of 14.9 MJ/kg at 85% DM this is 122×10^3 MJ/ha, which gives an energy ratio of 8.1.

The energy use for rape cultivation is 14.6×10^3 MJ/ha; nitrogen 64% and diesel 20%. The total yield is 3.2×10^3 kg/ha, or with 25.8 MJ/kg (83% DM) 82.6×10^3 MJ and an energy ratio of 5.7.

3.2 Exergy analysis

The exergy factors used are 1 for electricity and 0.95 for fossil fuels, such as oil and natural gas. The chemical exergy in the organic matter has been calculated according to

Szargut et al. [8]. Thus, exergy of Salix with 50% DM is 10.6×10^3 kJ/kg, and the total exergy output becomes 4.40×10^6 MJ/ha per 25 years. The exergy input is 114×10^3 MJ/ha and 25 years, which gives an exergy ratio of 39.

The winter wheat uses 14.8×10^3 MJ/ha; nitrogen 45%, seed 20% and fuels 18%. The chemical exergy with 88.7% DM becomes 17.6×10^3 kJ/kg [8]. The yield is 7.9×10^3 kg/ha or 138×10^3 MJ/ha, which gives an exergy ratio of 9.3.

The chemical exergy for winter rape with 83% DM is 28.7×10^3 kJ/kg. The total yield at 83% DM is 3.2×10^3 kg/ha or 91.7×10^3 MJ/ha. The input is 13.9×10^3 MJ/ha; nitrogen 67% and diesel 21%, which gives an exergy ratio of 6.6.

3.3 EMERGY analysis

The EMERGY analysis begins with drawing an energy system diagram where all flows for the process are indicated, see *figure 3*. All the EMERGY flows and their transformities for the cultivation are calculated. The transformities for the direct environmental inputs, i.e. sun, wind, and rain, are calculated from each other, and only the largest are considered, since they will contain EMERGY for all the other environmental inputs as well. The system boundaries are at the field border, and costs for society are therefore not included.

The total EMERGY use for Salix is 2.16×10^{16} sej/ha per 25 years, where direct environment accounts for 41%, nitrogen 36%, and fuels 7%. Since the total Salix yield is 415×10^3 kg/ha, the transformity for Salix becomes 5.20×10^{10} sej/kg with 50% DM and 1.04×10^{11} sej/kg DM. The EIR becomes 2.23 and NEYR 1.45, thus the investment of society is about twice that of the environment.

For winter wheat the total EMERGY use is 2.68×10^{15} sej/ha, nitrogen 24%, machinery 21%, direct environment 13%, phosphorus 13%, and labor 11%, and with a yield of 7.0×10^3 kg DM/ha, the transformity becomes 3.85×10^{11} sej/kg DM, the EIR 11.5 and the NEYR 1.09.

The total EMERGY use for winter rape is 2.73×10^{15} sej/ha, nitrogen 31%, machinery 21%, direct environment, 13% phosphorus 10%, and labor 10%. The yield is 2.7×10^3 kg DM/ha, which gives the transformity 1.03×10^{12} sej/kg DM, the EIR 11.8, and the NEYR 1.08.

3.4 Sensitivity analysis

If the use of machinery in the winter wheat cultivation is halved, then energy and exergy exchange increase by about 5%, transformity and EIR decrease by 12% and 14%, whereas NEYR increases by about 1%.

If the use of fuels for winter wheat cultivation is halved, the energy and exergy exchange increase by approximately 11%, transformity and EIR decrease by 3% and the NEYR remains unchanged.

3.5 Result

The result of the analysis is shown in *figure 4*, the exchange should be as high as possible.

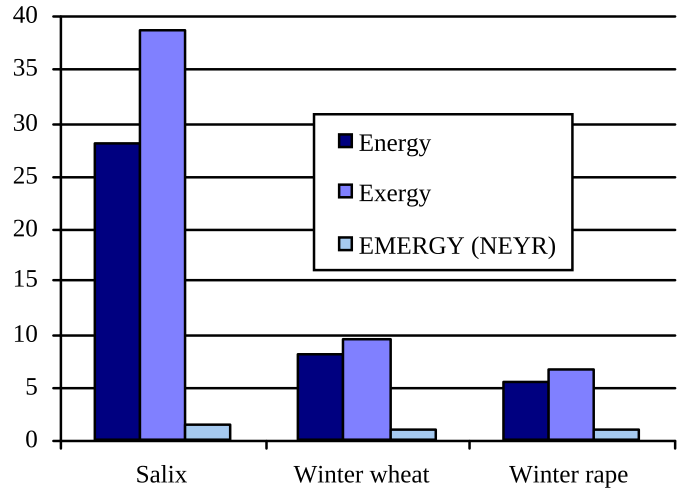


Figure 4 Energy, exergy, and EMERGY exchange of Salix, winter wheat, and winter rape.

The NEYR should be as large as possible, here it is 1.45 for Salix, 1.09 for winter wheat, and 1.08 for winter rape cultivation, which means that the EMERGY yield is 45% larger than the EMERGY input from society for Salix, but just 9% and 8% for winter wheat and winter rape.

Figure 5 shows the contribution in percent from the three methods on the analyzed Salix. The energy and the exergy methods gives similar result, but in the EMERGY analysis chemicals, phosphorus, cuttings, and labor are more important, and the use of nitrogen, fuels, and machinery less important.

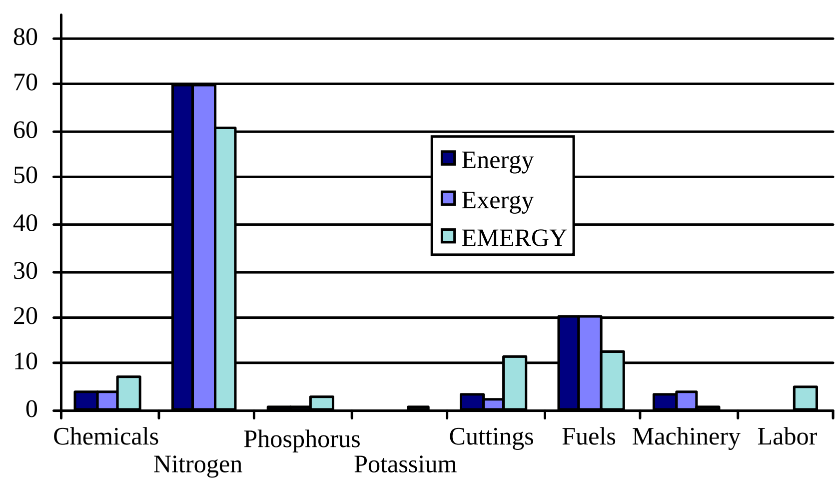


Figure 5 Percentage contribution of used resources for the cultivation.

For winter wheat cultivation, see *figure 6*, the energy analysis values the use of nitrogen highest, followed fuels, seed and machinery, and similar for exergy. The EMERGY analysis gives highest priority to used nitrogen, followed by machines. EMERGY gives a higher value to phosphorus and labor.

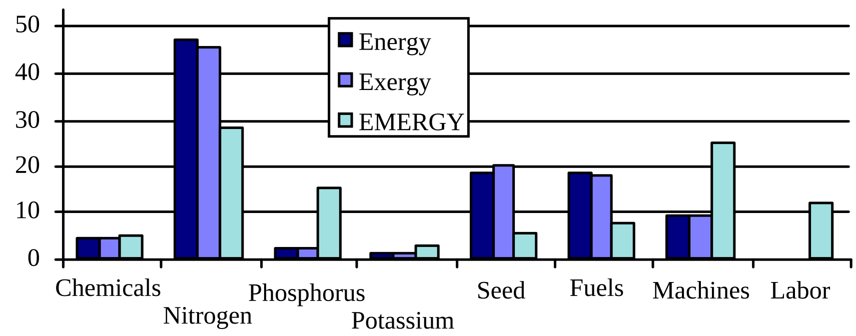


Figure 6 Percentage contribution of resources used for the winter wheat cultivation.

The winter rape is similar to the winter wheat, see *figure 7*.

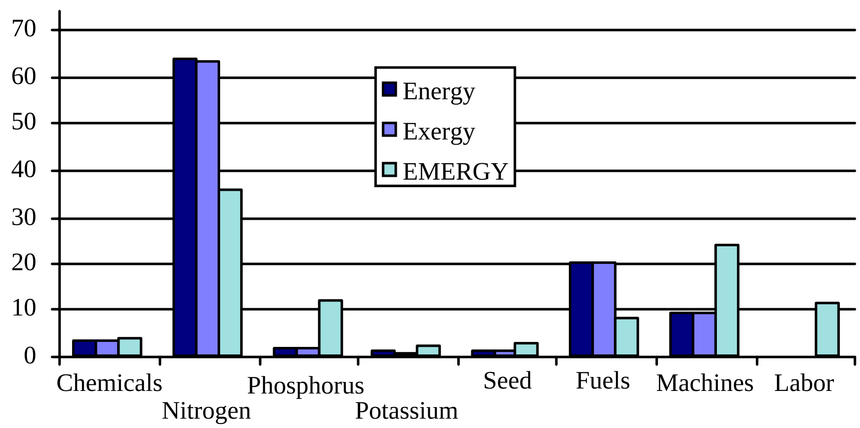


Figure 7 Percentage contribution of used resources for the winter rape cultivation.

4 Conclusions

Energy, exergy and EMERGY analyses are obviously useful methods when studying cultivation of energy crops. The energy analysis gives an energy exchange of 28 times for the Salix cultivation, for winter wheat 8.1, and for winter rape 5.7. Thus, all the studied cultivations have a higher energy output than input. The exergy analysis gives 39 for Salix, 9.3 for winter wheat, and 6.6 for winter rape, thus, a higher exchange than in the energy analysis. Mainly due to differences in the value of Salix chips, wheat, and rape seed.

The result of the EMERGY analysis differs considerably from the others. The EIR is 2.23 and NEYR is 1.10 for Salix, 11.5 and 0.66 for winter wheat, and 11.8 and 0.66 for winter rape respectively.

Further research using the exergy concept in the biomass area is needed, and particularly where biomass are converted into, for example, district heating or other exergy carrying products, such as biofuels. It is also important to study and optimize a whole farm from an exergy perspective, where a distinction between renewable and non renewable resources should be considered.

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