ENERGY AND EXERGY ANALYSES OF BIOENERGY CROPS AND RAPESEED OIL METHYL ESTER PRODUCTION

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ABSTRACT

Energy crops are a non-fossil fuel that can provide solid, liquid and gaseous fuels which may be stored and transported. In Sweden winter wheat, rapeseed and Salix are crops which are very suitable for energy use, since they suit the climatic conditions and are grown using well-established technology. However, it is important that the production of bioenergy supplies more energy than that required for production. Besides this, it is important to know how the energy quality, exergy, is affected during production and by using both energy and exergy analysis it is possible to determine not only the quantity of the energy used, but also its quality.

The objective for this study was to analyse the rapeseed oil methyl ester (RME) production chain and the cultivation of winter wheat, summer turnip rape, winter rape and Salix with respect to their energy use and exergy consumption. The objective was also to identify the stages in the production chain that accounted for the largest energy use and exergy consumption and to see how the production chain would be affected by introducing different production strategies.

The energy and exergy analyses were performed using process analysis methodology. Energy and exergy ratios and net outputs were calculated and the links in the production chain accounting for the largest energy use and exergy consumption were identified. Different production strategies were studied in order to make the production process more energy and exergy effective.

The study showed that the cultivation of winter wheat, rapeseed and Salix yielded more energy and exergy than they required during production. The whole RME production chain also had larger energy and exergy outputs than inputs. The study further showed that fertilisers accounted for a large part of the total energy use and exergy consumption. However, this energy use and exergy consumption due to use of fertilisers could be markedly decreased by using alternative fertilisers, such as furnace ash, different types of sludges and human urine, in cultivation.

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LIST OF PAPERS

This Licentiate thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Hovelius, K. 1999. Energy- and exergy analysis of a Swedish winter wheat-, turnip rape seed- and Salix cultivation. Conference paper submitted for presentation.

II Hovelius, K. & Hansson, P-A. 1998. Energy- and exergy analysis of rape seed oil methyl ester (RME) production under Swedish conditions. Accepted for publication in Biomass and Bioenergy, in press.

III Hovelius, K. & Hansson, P-A. 1998. On optimisation of energy and exergy efficiency in rape seed oil methyl ester (RME) production. Presented at 13th International Congress on Agricultural Engineering, February 2-6, 1998, Rabat, Marocco. Publ. Bartali, E. H. Daoudi, M. [Eds.], Vol. 4, ISBN 9981-1887-4-3, pp. 85-92.

IV Hovelius, K. & Hansson, P-A. 1999. Exergy analysis of fertilising strategies in Salix cultivation. Submitted for publication.

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1 INTRODUCTION

1.1 Background

Energy crops will play an important part in the energy supply of the future because they are a non-fossil fuel (Hall et al., 1992.). The carbon dioxide levels in the atmosphere will also decrease by substituting fossil fuels with biomass fuel sources (Börjesson, et al., 1997). Furthermore, biomass is unique among the types of renewable energy currently available in its ability to provide solid, liquid and gaseous fuels which can be stored and transported (Hall and Scrase, 1998).

Winter wheat, rapeseed, turnip rapeseed and Salix are bioenergy crops with great potential in Sweden since they suit the climatic conditions and are cultivated using tried and tested procedures and equipment. During the 1990s there has been an increased interest in liquid biofuels replacing diesel and petrol in Swedish vehicles (Johansson, 1996; Arnäs et al. 1997; Blümer, 1997), and today winter wheat and rapeseed are bioenergy crops which are very suitable for production of liquid biofuels. Winter wheat may be fermented into ethanol which can be used both as a mixture in ordinary petrol or as an alternative fuel in a converted petrol engine (Arnäs et al. 1997). Winter wheat may, however, also be used directly as a combustion fuel in pellet furnaces. Rapeseed and turnip rapeseed may be pressed and esterfied into rapeseed oil methyl ester which can be used in ordinary diesel engines (Mittelbach et al., 1983; Cvengros & Povazanec, 1996). Raw rapeseed oil may be used as fuel e.g. in Elsbett engines (Bernesson, 1998). Rapeseed and turnip rapeseed may also be used in environmentally friendly hydraulic oil, detergents and cleaning compounds, soaps, etc. (Bernesson, 1998). Salix is a bioenergy crop well suited for combustion, primarily in district heating plants but also in small-scale combustion plants (Ledin, 1996). Salix may also be used to produce not only methanol, but also ethanol which may be produced due to enzymatic hydrolysis (Elam et al., 1994; Palmqvist et al., 1996; Tarantili et al., 1996).

In Sweden, the total use of biofuels currently accounts for 18% of the total energy supply of 1750 PJ (Nutek, 1997). However, of this, 35.6% is accounted for by the waste soda lye used in the pulp industry and 17.2% is accounted for by other waste products from pulp and sawmill industry. The total use of wood fuels accounted for 16.1% and from this only approximately 0.4 PJ origins from Salix (Nutek, 1997). Today, only a minor proportion originates from rapeseed and wheat, and then mainly as liquid fuels.

Different studies have been carried out in an attempt to forecast the future possible bioenergy production in Sweden. For example, Andersson (1990) states that Swedish Salix production may be as high as 72 PJ in the Year 2015. Börjesson et al. (1997) present four different scenarios for the production of biomass for energy purposes in Sweden around 2015, a low scenario where only 50 PJ comes from agricultural land, a medium scenario where 97 PJ are assumed to come from agricultural land, a high scenario where 202 PJ comes from agricultural land, and a scenario where they assume that crop fertilisation is optimised, where as many as 212 PJ are estimated to originate from agricultural land.

Besides this, the Swedish Environmental Protection Agency (1997) assumes that 553 000 hectare will be used to produce 97 PJ bioenergy in Sweden by the Year 2021.

It is especially important that crops meant for energy use have a positive energy ratio and that the net energy output is as large as possible since heat, electricity or liquid fuel substitutes are the end product in bioenergy production. Thus, it is essential that an energy production process supplies more energy than it consumes during manufacture. Besides this, it is important to know how the quality of energy, its exergy, is affected. By using both energy and exergy analysis methods it is possible to determine not only the quantity of the energy used and the bioenergy produced, but also to evaluate its quality.

Energy analysis derives from the First Law of Thermodynamics, which states that energy cannot be produced or destroyed but only converted between different types of energy (IFIAS, 1974). On the other hand exergy, often called energy quality, is based on the Second Law of Thermodynamics, which states that the total entropy of a system which goes from one state to another always must increase. Thus, the Second Law of Thermodynamics sets limits for how energy may be converted (Wall, 1986; Szargut et al., 1988; McGovern, 1990a). In other words, while energy can only be converted between different types, exergy is consumed in every transformation.

Szargut et al. (1988) have provided the following comparison of the main characteristics of exergy and energy:

Energy	Exergy
1. Is subject to the Law of Conservation.	1. Is exempt from the Law of Conservation.
2. Is a function of the state of the matter under consideration.	2. Is a function of the state of the matter under consideration and of the matter in the environment.
3. May be calculated on the basis of any assumed state of reference.	3. The state of reference is imposed by the environment, which may vary.
4. Increases with rise of temperature.	4. For isobaric processes reaches a minimum at the temperature of the environment; at lower temperatures it increases as the temperature drops.
5. In the case of ideal gas, does not depend on the pressure.	5. Always depends on the pressure.
6. For an ideal vacuum equals to zero.	6. For an ideal vacuum is positive.

Earlier exergy analyses of bioenergy systems implied a different perspective than an ordinary energy analysis when explaining systems including biomass production (Hovelius and Wall, 1998). For example, Nilsson (1997) reports that the exergetic efficiency of the boiler in a district heating plant using straw as a combustion fuel is much lower than the energetic efficiency. Further, Hellström (1997) has shown that there are important differences in the results depending on whether energy or exergy analysis methodology is used when analysing a waste water treatment plant and that the flow of heat may be overestimated if only an energy analysis is performed.

No exergy analyses of winter wheat, rapeseed or Salix cultivations or RME production were found in the literature, nor were there any improvement analyses for cultivations where exergy analysis methodology was used. However, some energy analyses have been produced for winter wheat, rapeseed and Salix cultivation (Pick et al., 1989; Börjesson, 1996) and RME production (Ruiz-Altisent, 1994; Celcius, 1994). Furthermore, some earlier studies have shown that in the whole bioenergy production chain, cultivation accounts for a large part of the total energy use (Johansson, 1996; Arnäs et al., 1997; Kaltschmitt et al., 1997).

1.2 General objectives

The objective with this study was to analyse the energy use and the exergy consumption for the RME production chain and for winter wheat, summer turnip rape, winter rape and Salix, cultivated for energy use. A further objective was to study how the efficiency of the cultivation could be increased by using different cultivation strategies. Suitable strategies for improving the energy and exergy efficiency were identified by analysing the energy and exergy "hot spots" during RME production and energy crop production.

When different strategies for possible improvement in the energy and exergy efficiency were developed, studies were then carried out to analyse the effects of following through with these improvements. This was done by using suitable optimisation techniques on the cultivation strategies for winter rape and Salix. s, Finally, differences between the energy and exergy analysis methodology were compared and evaluated on the basis of the results obtained in the study.

2 METHODOLOGY

2.1 System studied

In this study, both direct and indirect energy (and exergy) used in production chains were included. In the cultivation procedure, the direct energy use and exergy consumption consisted only of diesel use. The indirect energy use (and exergy) included energy (and exergy) used in earlier processes, such as production of seed, fertilisers, chemicals etc. However, energy use and exergy consumption for production of machinery and buildings used on farm, and energy and exergy embodied in manpower were not included in the study.

In *Paper I* where winter wheat, summer turnip rape and Salix production were studied, the system boundaries were set around the farm. In *Papers II* and *III*, the first system boundary was set at the farm and the second system boundary was set after the RME distribution. The first system boundary in *Paper IV* was for artificial fertilisers before the fertiliser production plant, for urban organic waste at the end of the sewage plant and for ashes after the combustion plant. The second system boundary in *Paper IV* was at the Salix field. The system boundaries in the whole study are shown in Figure 2.1.

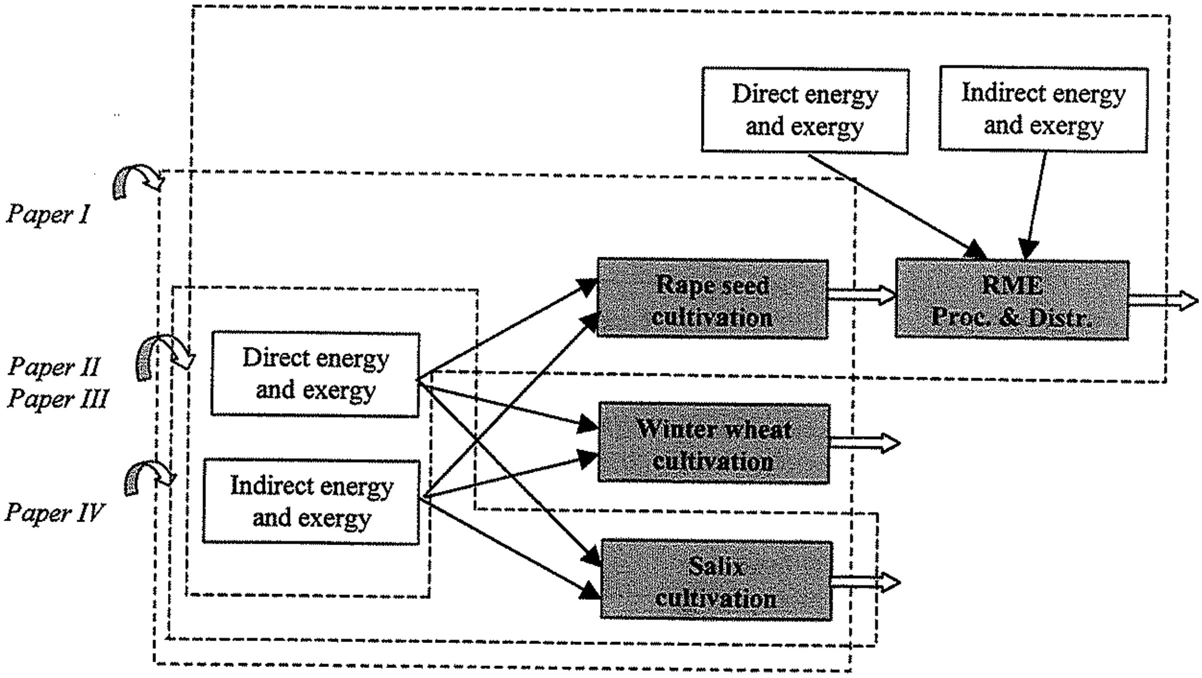


Figure 2.1. System boundaries in the different investigations.

2.2 Energy Analysis

The energy content in a product does not correspond to the energy used during production. To draw up an energy budget, it is necessary to account for all different inflows of energy in the process. In 1974, a conference was held by the International Federation of Institutes for Advanced Studies (IFIAS, 1974; IFIAS, 1975) at which this type of budgeting was termed *energy analysis*. 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 (Chapman & Roberts, 1983). The *input-output analysis* is based on an input-output table as a matrix representation of an economy. A row and column in the matrix represent each industry. 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 obtained 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 the *process analysis* methodology is used, 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. Figure 2.2 describes the different "levels" in process analysis. The first level includes only the fuel used in the last stage of manufacture. The second level adds the fuels used for manufacturing and transporting the materials used in the process, while in the third level fuels used for manufacturing of machines used in process are included.

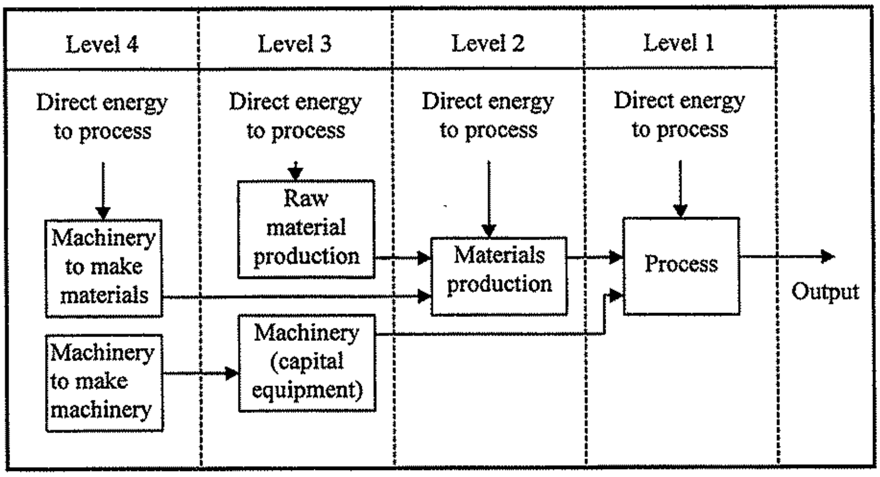


Figure 2.2. In process analysis, energy is traced backwards from the product to the primary sources. Level 1 usually accounts for less than 50% of the total energy use, while Levels 1 and 2 together usually account for more than 90% of the total energy use and it is rarely necessary to go to Level 3 or 4 (IFIAS, 1974).

2.3 Exergy Analysis

As stated previously, exergy analysis is based on the Second Law of Thermodynamics, which places distinct restrictions on energy transformations. The two most important conditions are (1) heat cannot be transformed into work with 100% efficiency, and (2) heat spontaneously flows from a body of higher temperature to one of lower temperature. The Second Law of Thermodynamics defines quality differences between different types of energy and this quality differences restricts energy conversions, e.g. mechanical work is converted readily to heat but the reverse is not true (Hall et al., 1992).

Exergy may be defined as: the amount of work obtained when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the abovementioned components of nature (Szargut, 1980). Exergy may also be defined as "work or ability for work" while energy is "motion or ability for motion" (Wall, 1986). Further, exergy is the minimum amount of work to be supplied if a material or form of energy has to be produced from the inert reference system (van Gool, 1998). The exergy [E] can be expressed with the following general equation:

$$E = U - U_{eq} + p_0(V - V_{eq}) - T_0(S - S_{eq}) + \sum n_i(\mu_{ieq} - \mu_{i0}) \quad (1)$$

Where eq denotes equilibrium with the environment. U, V, S and n_i denote the extensive parameters of the system (internal energy, volume, entropy and the number of moles of different chemical elements). T_0, p_0, and μ_{i0} denote intensive parameters of the environment (temperature, pressure and the chemical potential of the component i in its standard state, i.e. in equilibrium with the environment).

The exergy factor, also called the exergy quality factor, is the ratio between the exergy [E] and the energy [Q] (Wall, 1986). Thus, the exergy factor for heat may be described with Eq. (2).

$$\frac{E}{Q} = \left| 1 - \frac{T_0}{T - T_0} \ln \frac{T}{T_0} \right| \quad (2)$$

where T_0 is the surrounding temperature and T is the temperature of studied system, both in Kelvin.

Resources other than the energy resource also contain exergy (Wall, 1986; Szargut et al., 1988; van Gool, 1998). The chemical exergy [E_{ch}] of a material is a measure of the minimum amount of exergy that is needed to affect and uphold the chemical structure in a certain surrounding. If pressure and temperature are constant the chemical exergy in material can be calculated from (Wall, 1986):

$$E_{ch} = n\left[\mu^0 - \mu_0^0 + RT_0 \ln \frac{c}{c_0} \right] \quad (3)$$

where μ^0 is the chemical potential for the element relative to its reference state and $\mu_0{}^0$ is the chemical potential for the element in the surroundings relative to its reference state. R is the universal gas constant, T_0 is the temperature of the surroundings, c is the concentration of the element and c_0 is the concentration of the same element in the surroundings.

According to Szargut et al. (1988) the chemical exergy of liquid technical fuel containing a very small amount of ash is:

$$E_{ch} = \beta(C + L_w z_w) + E_{chw} z_w \quad (4)$$

Where:

$$\beta = \frac{1.041 + 0.216(z_{H_2} / z_c) - 0.250(z_{O_2} / z_C)(1 + 0.788(z_{H_2} / z_C)) + 0.045(z_{N_2} / z_C)}{1 - 0.304(z_{O_2} / z_C)} \quad (5)$$

C is the net calorific value, L_W denotes the enthalpy of phase change for water, which is 2 440 kJ/kg, and z the mass fraction of hydrogen (H), coal (C), nitrogen (N), and oxygen (O). E_{chw} is the chemical exergy in water, which is 50 kJ/kg.

Equation (6) describes the chemical exergy of solid technical fuels.

$$E_{ch} = \beta(C + L_w z_w) + z_S(E_{chS} - C_S) + E_{cha} z_a + E_{chw} z_w \quad (6)$$

where z_S and z_a are the mass fractions of sulphur and ash, respectively, and E_{chS} and E_{cha} are the standard chemical exergies of sulphur and of ash in joules per kilogram. The chemical exergy of ash can usually be neglected (Szargut et al., 1988). The difference in the second term of Eq. (6) can, according to Szargut et al. (1988), be calculated from the standard values:

$$E_{chS} - C_S = \frac{607300 - 296830}{32.064} = 9683\ kJ / kg\ S \quad (7)$$

Exergy could easily be incorporated into the process analysis to form an exergy analysis which is done in this study. The only difference from the energy analysis is that besides energy quantity, energy quality is also taken into account in the exergy analysis.

3 DESCRIPTION OF PAPERS

3.1 Paper I

In *Paper I* cultivations of winter wheat, summer turnip rape and Salix were studied with respect to their energy and exergy efficiency. The objectives were to analyse the energy use and the exergy consumption during cultivation and to identify the energy and exergy “hot spots” in the cultivation chain.

The energy and exergy analyses were performed on a farm in Eastern Sweden according to process analysis methodology. Both direct and indirect energy use and exergy consumption were included in the calculations. The system boundaries in the study were set around the farm.

3.2 Paper II:

The study in *Paper I* showed that cultivation of winter wheat, summer turnip rape and Salix were favourable from an energy and exergy point of view. To establish a good strategy to make bioenergy production more effective it is, however, important to find out how much of the total energy use and exergy consumption the cultivation accounts for in the whole lifecycle of bioenergy production.

In *Paper II* the rapeseed oil methyl ester (RME) production chain was analysed with respect to its energy and exergy efficiency. The objective of the study was to analyse the RME production chain and to quantify the net yields of energy and exergy and their respective degree of efficiency. The objective was also to analyse how large a part of the total energy use and exergy consumption in the RME production chain that the cultivation accounted for. The effects of changes in some parameters were studied in order to find production strategies that increased the exergy efficiency without decreasing the energy efficiency. A further objective was to quantify, discuss and explain differences between results from the energy and the exergy analysis of the RME production chain.

The study was performed by using process analysis methodology on winter rape cultivated in southern Sweden. The rapeseed was then hot pressed and the RME was esterfied in a large-scale plant. In the study, both direct and indirect energy used and the exergy consumed for RME production were included.

3.3 Paper III:

The study in *Paper II* showed that winter rape cultivation accounted for a large part of both the total energy use and exergy consumption in the RME production chain. In addition, the study in *Paper I* showed that production of artificial fertilisers accounted for more than 50% of the total energy use and exergy consumption respectively in rapeseed cultivation. Therefore it was deemed important to study in which way the fertiliser strategy for rapeseed cultivation could be changed in order to minimise the total energy use and exergy consumption in the RME production chain.

In *Paper III* the possibilities were studied of using non-linear optimisation methods in order to obtain nitrogen application rates optimising energy and exergy efficiency in the RME production chain. The objective of the study was to investigate the optimal nitrogen application rate when producing RME as an alternative engine fuel and to analyse how the energy and exergy efficiencies for RME production were affected when the nitrogen application rate was varied. In the analysis, it was further studied how the results would be affected if the energy use and exergy consumption in nitrogen production w increased or decreased. The way in which the results would change if nitrogen production was a smaller or greater part of total energy use and exergy consumption was also studied.

The spring rapeseed was cultivated in southern Sweden and the rapeseed oil was hot pressed and esterfied to RME in a large-scale plant. The optimisation was based on both energy and exergy analysis. The nitrogen/yield function used for optimisation was based on field experiments conducted in Southern Sweden between 1983 and 1994ref?.

3.4 Paper IV:

The study in *Paper III* showed that the nitrogen application rate has important effects on the energy and exergy efficiency in RME production and that changes in fertilising strategy have major effects on the results. It is likely that fertilising strategies will also have a large effect on the entire Salix chip production chain since cultivation accounts for the largest overall part of this total chain.

The objective of the study in *Paper IV* was, from an exergy efficiency point of view, to study different strategies to fulfil the nutrient demand of a Swedish Salix cultivation using both artificial and alternative fertilisers. The purpose was also to find strategies that minimised exergy consumption for the use of fertilisers, where exergy consumption due to production, loading and unloading, transportation and spreading at field were included.

In the study ,eight different fertilisation products were included (five organic waste products, one ash product and two artificial fertilisers). Two different scenarios were studied. In Scenario 1, exergy consumed during production of the artificial fertilisers, transportation, handling and spreading of all fertilisers was included in the study. In Scenario 2, exergy consumption due to alternative handling of the waste products (usually dumping on landfills) was also accounted for in the study. The model used for optimisation was general and it was based on mixed linear programming, including both continuous and binary variables.

4 RESULTS

4.1 Bioenergy production

The calculations in *Paper I* and *Paper II* showed that the energy ratio was 32 for the Salix cultivation, 9.1 for winter wheat production, 4.3 for summer turnip rape and 7.5 for winter rapeseed. The exergy ratios for Salix, winter wheat, summer turnip rape, and winter rapeseed production were 34.9, 9.8, 5.0, and 8.6 respectively. For the whole RME production chain, the energy ratio was 2.4 and the exergy ratio was 3.0, see Fig. 4.1a.

The net energy output for winter wheat production was 83.5 GJ/ha and the net exergy output was 96.5 GJ/ha. For Salix, the net energy output was found to be 3 680 GJ/ha, while the net exergy output was 4 400 GJ/ha. Summer turnip rape and winter rapeseed production had net energy outputs of 31.7 GJ/ha and 67.2 GJ/ha respectively, while the respective net exergy outputs were 40.6 GJ/ha and 78.2 GJ/ha. The whole RME production chain had a net energy output of 25.6 GJ/ha while the net exergy output was 34.4 GJ/ha, see Fig. 4.1b.

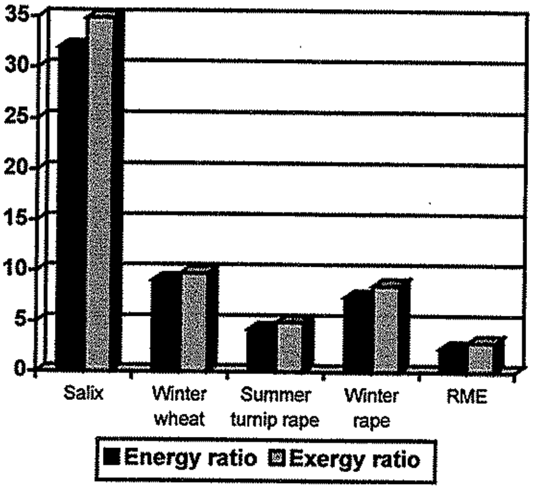


Figure 4.1a Energy and exergy ratios in Salix, winter wheat, summer turnip rape, winter rape cultivation and RME production chain.

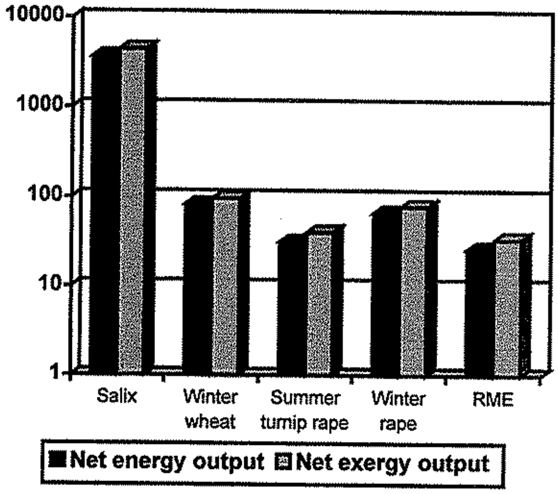


Figure 4.1b Net energy and exergy output, expressed in GJ/ha, in winter wheat, summer turnip rape, winter rape cultivation and RME production chain.

The study (*Papers I* and *II*) further showed that production of fertiliser used in bioenergy crop production accounted for a large part of the total energy use or exergy consumption and that cultivation accounted for more than 43% of the total energy use and 46% of the total exergy consumed in the whole RME production chain. The study also showed that even if the whole RME production chain was taken into account, production of fertilisers used in cultivation accounted for more than 18% of the total energy use and almost 19% of the total exergy consumed.

Figure 4.2 shows the results from sensitivity analyses performed on Salix, winter wheat and winter rape cultivation and on RME production. As seen, the yield from the cultivations has a great influence on the exergy ratio. Furthermore, the study showed that if the exergy consumed for production of fertilisers were to be increased or decreased it would influence the exergy ratio greatly.

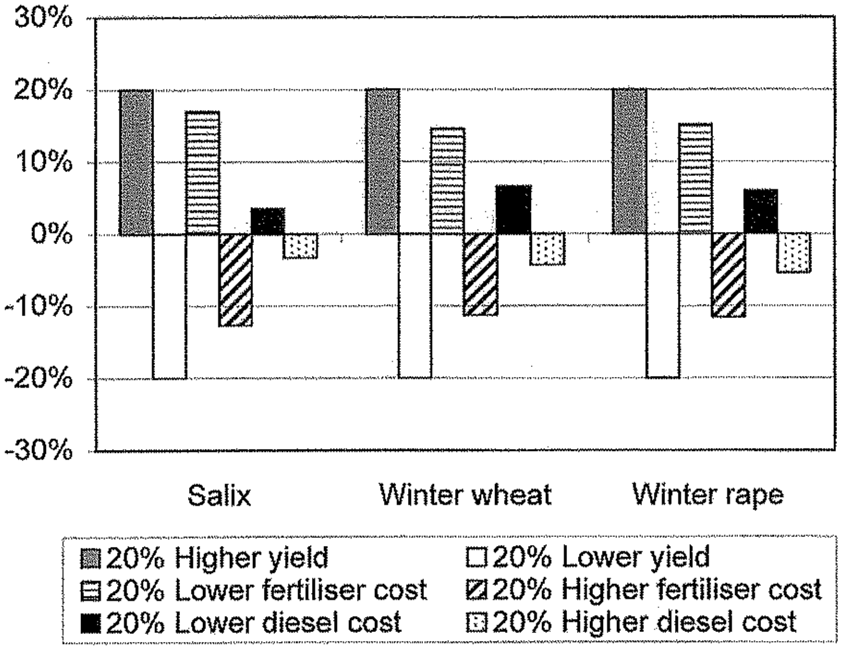


Figure 4.2. Sensitivity analyses of Salix, winter wheat, winter rape cultivation and RME production chain. Changes as a percentage of exergy ratios depending on different production conditions during cultivation.

In *Paper II* the sensitivity analysis showed that if the distribution distance for RME were to be doubled, the energy and exergy ratios would increase by 9.3 and 9.8 % respectively. If instead the distribution distance were to be decreased by 50%, the energy ratio would increase by 5.3 %, while the exergy ratio would increase by 5.5 %.

The sensitivity analysis in *Paper II* showed that the exergy ratio for RME production would increase to 4.0 if the rapeseed was dried with district heat instead of oil. Furthermore, the analysis showed that the exergy ratio would increase to 3.9 if district heating was used instead of steam to heat rapeseed before pressing. The exergy ratio would, however, decrease to 3.5 if steam, was replaced with oil instead. The energy ratio would not be affected by this replacement in energy source.

4.2 Different fertilising strategies

The study (*Paper I*) showed that a large part of both the total energy used and exergy consumed in biomass production originated in the production of fertiliser. Therefore, Salix and winter rape cultivations were studied further in an attempt to improve the energy and exergy ratios in the cultivations by changing fertiliser strategy.

The calculations in *Paper III* showed that depending on whether the output/input ratios or the energy/exergy profits were optimised in rapeseed cultivations there were important variations in results concerning which the optimal application rate. It was shown that the highest energy and exergy ratios for the RME production chain were reached at very low nitrogen fertilisation rates. The highest energy and exergy profits were, on the other hand, reached at rather high nitrogen rates. However, the results depended on the yield function, which is rather insecure, so the trend from the results should be emphasised rather than the exact figures.

In *Paper IV* it was shown that biogas sludge combined with furnace ash and NPK 21-3-10 was the most exergy optimal fertilising strategy in Scenarios 1 and 2 if it was assumed that only furnace ash and artificial fertilisers were to be used in Years 3 and 4. Compared with using only artificial fertilisers, the total exergy consumption would decrease by 7 062 and 7 540 MJ/ha, respectively, in Scenarios 1 and 2.

Figure 4.3 shows the differences between exergy consumption for manufacturing, loading and unloading, transport and spreading in five different analyses from *Paper IV*. Analysis A showed that if it was assumed that all fertilisers could be spread in all years, the optimal solution was to use 95.24 tonnes of biogas sludge combined with 0.699 tonnes of furnace ash per hectare and cutting cycle. The total exergy consumed in analysis A was 14 157 MJ lower per ha compared with if only artificial fertilisers were used. In analysis B it was assumed that biogas sludge was not available and the optimal solution here, if all fertilisers could be used in all years, was to use 114.57 tonnes of human urine and 0.41 tonnes of furnace ash per hectare and cutting cycle. Analysis C showed that the optimal strategy if neither biogas sludge nor human urine was usable was to use 236.65 tonnes of septic sludge, 1.52 tonnes of furnace ash and 0.87 tonnes of N28 per hectare and cutting cycle if all fertilisers could be used in all years. In analysis D it was assumed that only artificial fertilisers were available and here 1.55 tonnes of NPK 21-3-10 per hectare and cutting cycle were used.

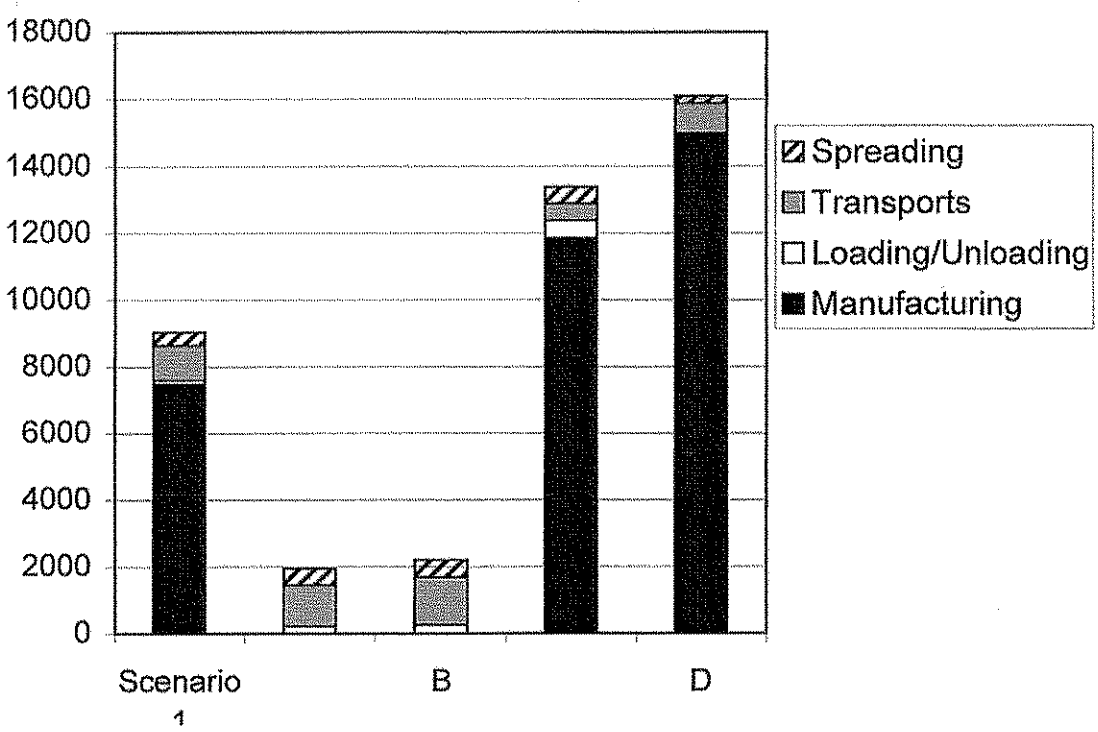


Figure 4.3. Exergy consumption due to manufacturing, loading/unloading, transportation and spreading in the different analyses.

5 GENERAL DISCUSSION

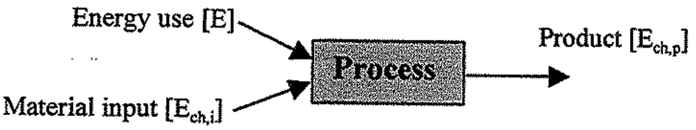
5.1 Methodology

The major differences between the energy and exergy analyses is that energy only includes the quantity of energy used while the exergy analysis also takes the quality of this energy into account. In the exergy analysis, in contrast to the energy analysis, the chemical exergy in materials used is also included in the study. This results in the exergy analysis providing new viewpoints on the study performed. Below, some particular differences between the energy and exergy analyses, as identified in this study, will be discussed further.

Various types of energy display different qualities. In the energy analysis, however, these different qualities are not taken into account, e.g. low temperature heat is valued in the same way as, for example, high temperature heat or electricity. This is not the case in exergy analysis, where energy is valued depending on its ability to perform work. The differences in methodology thus provide different results concerning choice of strategy to improve the system. For example, in *Paper II* the exergy analysis showed that the RME production chain could be improved by using an energy source with a lower exergy quality factor when the rapeseed and the rapeseed oil was heated. This change would, however, not effect the energy efficiency in the RME production chain.

In *Papers I-IV* it was shown that the exergy consumption was higher than the energy use in production of all the artificial fertilisers studied. For nitrogen production this depended to some extent on the chemical exergy in the materials used in production, but mostly on the fact that the district heating produced as a by-product in nitrogen production had a lower exergy content than the energy content. In fact the exergy content in district heating is only about 30% of that in electricity, for example (Wall, 1986). In production of phosphorus and potassium fertilisers the differences in energy and exergy analyses depend partly on energy use but mostly on the chemical exergy in materials used in the process, see Section 5.1.2 for further information concerning chemical exergy in materials.

In the exergy analysis both exergy consumed in production processes due to energy use and due to materials used were included. The chemical exergy in a material is the least possible amount of exergy that has to be consumed to create and maintain the chemical structure of the material in certain surroundings. The way in which the chemical exergy in a material influences the analysis is explained in Fig. 5.1 and Eq. 5.



$$E_{ch,p} = \left(E + E_{ch,i}\right) * \eta \qquad (5)$$

Figure 5.1. Chemical exergy in a material, where $E_{ch,p}$ is the chemical exergy in the product, E is the exergy in energy used, $E_{ch,i}$ is the chemical exergy in materials used, and η is the degree of efficiency in the process.

In this study (*Papers I-IV*) process analysis methodology was used to perform the energy and exergy analyses. In this type of analysis, the process under investigation is followed from the finished product backwards to resources used, including all steps in the process. This implies that the study can easily be made transparent and that it is easy to track the data used.

The study in *Paper III* showed that very different results were obtained depending on whether the energy (exergy) ratios or the net energy (exergy) outputs were optimised. When the energy and exergy ratios were optimised it was assumed that the resources set the limits while when the net energy and exergy outputs were optimised, the acreage set the limits.

The optimisation model used in *Paper IV* was found to be useful for the calculations. In this study, the model was used for optimisation of the exergy flow due to fertiliser strategies in a Salix cultivation, but the model was general and could be applied to any energy crop. The optimised variable in *Paper IV* was also energy use instead of exergy consumption.

5.2 Bioenergy production system

The study showed that winter wheat, summer turnip rape, winter rape and Salix are crops with an energy and exergy ratio bigger than one and positive net energy and exergy yields. The study further showed that the production of rapeseed oil methyl ester generates more energy and exergy than it requires during production. However, it is important to note that cultivation conditions may vary a lot between different regions in Sweden and that the results therefore may differ considerably. In this study, data were taken from a specific farm and may therefore not be considered general.

The system boundaries may have a great impact on the results. In this study, the system boundaries were set so that energy use and exergy consumption was analysed from a general resource perspective and no account was taken of other positive or negative effects, such as economics or amount of vacant jobs etc., that may occur by introducing a particular bioenergy production system. However, in *Paper IV* the system boundaries were extended to include alternative handling of waste products in some of the analyses and it was shown that the use of certain waste products as fertilisers would be even more efficient in these scenarios.

This study showed that production of artificial fertilisers accounts for more than 50% of the total energy use and exergy consumption, respectively, in cultivations of winter wheat, summer turnip rape, winter rape and Salix where artificial fertilisers are used to fulfil the nutrient requirements. Therefore it is important that the use of fertilisers in bioenergy crop production be studied carefully. It is also important to keep in mind that phosphorus and potassium are both non-renewable resources, so it is possible that the exergy consumption due to manufacturing of phosphorus and potassium will increase in the future when the resources have decreased.

In this study, current techniques were used except for in *Paper IV*, where in some scenarios it was assumed that new technologies allowing spreading of organic waste products even in high Salix stands were available. An increasing cultivation of energy crops, together with new regulations, will increase the need for development of energy and exergy efficient techniques for the manufacturing process. For example, new machinery in cultivation, the ban on the dumping of organic waste, use of nitrogen-fixing crops, etc.

5.3 Need for further research

This study only dealt with changes in fertilising strategies in order to make energy crop production more effective. However, in addition to this, there is a need to study how the total effectiveness would be affected by optimising other parameters in the cultivation process, for example, the machinery chain or man time used in the production chain.

Furthermore, much new information would be generated if the whole bioenergy production chain were to be studied. For example, drying of bioenergy crops could be done in several more or less exergy efficient ways. By optimising the exergy consumption due to transports lots of new information would be generated concerning where the cultivations should be located in relation to sewage treatment plants, combustion plants and refining plants.

Another very important question is how the soil is affected in the long run by the provision of, for example, heavy metals from the sludge. It would also be interesting to study other resources affected during bioenergy crop cultivation with exergy methodology, e.g. changes in humus content, effects on heavy metals in soil, etc.

6 GENERAL CONCLUSIONS

Some of the conclusions that may be drawn from this study are:

1. Winter wheat, winter rape, summer turnip rape and Salix all generate more energy and exergy than they need during cultivation. The production of rapeseed oil methyl ester also generates more energy and exergy than it needs during production.
2. Production of artificial fertilisers accounts for a large part of the total energy use and exergy consumption.
3. The efficiency of cultivation is increased if alternative fertilisers are used.
4. The exergy concept is interesting and may bring another valuable perspective to the analysis.
5. The exergy analysis has shown that the exergy efficiency in the production of rapeseed oil methyl ester may be increased without decreasing the energy efficiency.

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[1] Vittra is my German Wirehaired Pointer

[2] Hunter is Jannes Wirehaired Dachshund

[3] Gaffilur is our red cat

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	Reads	Should be
Page 6, line 9	Accepted for publication in Biomass and Bioenergy, in press.	Biomass and Bioenergy, vol. 17, pp. 279-290.
Page 9, line 24	s,	
Page 17, line 2	increase	decrease
Page 19, figure text	Exergy consumption due to manufacturing, …	Exergy consumption in MJ per hectare due to manufacturing, …
Page 25, line 22	(NUTEK)	(Naturvårdsverket)
Paper I		
Page 5, figure 2	Seed	Cuttings
Paper IV		
Page 14, table 10	Scenario 1, Scenario 2 Scenario 3, Scenario 4	Scenario 1a, Scenario 1b Scenario 2a, Scenario 2b