# ENERGY-, EXERGY- AND EMERGY ANALYSIS OF BIOMASS PRODUCTION

Karolina Hovelius

Institutionen för lantbruksteknik

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Department of Agricultural Engineering

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## SUMMARY

An important aspect that must be evaluated concerning biofuels is their efficiency in converting solar energy into biomass. This evaluation is important in reaching the right decisions about which crops are to be preferred in any specific situation. Another important factor is whether or not the cultivation is profitable from an energy point of view, i. e. if we get as much energy out of the cultivation, such as salix chips, as we invest in it, e. g. as fuels, nutrients, etc. This type of evaluation may be done from different viewpoints and in this report three different methods have been used, energy-, exergy-, and EMERGY analyses.

The energy and the exergy methods are both based upon the laws of thermodynamics. The energy analysis has its roots in the first law of thermodynamics and therefore only concerns the amount of energy put into a product throughout the manufacturing but not how physical valuable the used energy was. The exergy analysis is based upon both the first and the second laws of thermodynamics, which results in not only the amount of energy used but also the energy quality is taken into consideration.

EMERGY analysis, in contrast, is based upon H T Odum's theory and has its roots in systems ecology and the maximum power principle. EMERGY is a record of previously consumed available energy that is a property of the smaller amount of available energy in the transformed product. The transformities are the "keys" in the EMERGY analysis. They describe the amount of energy, expressed in one and same unit, that has been used to create a flow or resource.

In this report, results from analyzing salix-, winter wheat-, and winter rape cultivations from energy, exergy, and EMERGY perspectives are presented. The exchange in terms of energy for this Salix cultivation is 28 times, but if instead an exergy analysis is done the exchange for exactly the same process is 36 times. The energy analysis gives an energy exchange of 8.1 for winter wheat cultivation, and 5.7 for winter rape cultivation. Corresponding exchanges for the exergy analysis are 9.3 for winter wheat and 6.6 for winter rape.

The EMERGY analysis gives a transformity for salix of 1.04E+11 sej/kg DM, for winter wheat 3.85E+11 sej/kg DM, and for winter rape 1.03E+12 sej/kg DM. Thus, the EMERGY need is bigger for rape cultivation than for winter wheat and salix cultivation. The NEYR is the ratio between the EMERGY yield and the EMERGY invested from society (economy, services and other resources), and it is 1.10 for this salix cultivation, and 0.66 for both the winter wheat and the winter rape cultivations. The EIR is the ratio between the EMERGY invested from society and the EMERGY invested from the environment, and it is 2.23 for this salix cultivation, 11.5 for the winter wheat cultivation, and 11.8 for the winter wheat cultivation.

INDEX

## 1 INTRODUCTION

Cultivation of different energy crops on agricultural land will probably be an important part of our energy supply in the future. Some reasons for this are: (1) Swedish agriculture has a problem with overproduction of food, and (2) burning of fossil fuels increases the greenhouse effect by discharging carbon dioxide to the atmosphere. Additionally, fossil fuels are nonrenewable resources.

To grow crops for energy production the farmers find a use for their land and at the same time the environment is not damaged by burning fossil fuels.

An important aspect that must be evaluated concerning cultivations is its efficiency in collecting solar energy and converting it into biomass. This has not been done very thoroughly in the past. This evaluation is important if the right decisions are to be made about which crops are preferred in any specific situation. Another important factor is whether or not the cultivation is profitable from an energy point of view, i. e. if we get as much energy out of the cultivation, such as salix chips, as we invest in it, e. g. as fuels, nutrients, etc.

Today, different methods are used to analyze living systems, e. g. energy, exergy, and EMERGY analyses. These methods all have differing origins and are based on different theories, which make it difficult, or sometimes impossible, to compare their results.

To make an analysis useful by giving us the answers we need, it is important that we know, and understand, the differences between the methods. It is also necessary that we are sure about which questions the used method of analysis is framed to answer.

Energy analysis may be divided into two different origins: thermodynamics and systems ecology. The first law of thermodynamics describes energy as that which cannot be created or destroyed, and the second law of thermodynamics describes the ways in which energy may be transformed. Energy analysis, which is the most common method, originates from the first law of thermodynamics (Johansson & Lönnroth, 1975; Chapman & Roberts, 1983). Exergy analysis, on the other hand, is based on a combination of the first and the second laws of thermodynamics (Szargut et al, 1988; Wall, 1986).

EMERGY analysis, in contrast, is based upon H T Odum's theory, which has its roots in systems ecology (Odum, 1983; Odum, 1996).

In this report, results of analyzing salix-, winter wheat-, and winter rape cultivations from energy, exergy, and EMERGY perspectives are presented. The results clarify some of the differences between the methods, which enables the differences between the methods to be described and explained.

# 2 METHODS

The cultivations were analyzed with three different methods, energy-, exergy- and EMERGY analysis. Energy and exergy have their origins in thermodynamics, but the EMERGY analysis has its origins in systems ecology. The different methods are described below in order to make the results easier to understand.

## 2.1 Thermodynamics

Thermodynamics is the branch of science that studies energy and its transformations. Usually, thermodynamics is associated with heat, but the subject deals not only with heat but with all forms of energy. The principles of thermodynamics are well established and provide an foundation for the understanding of physical-, chemical- and biological systems.

### *2.1.1 Definitions*

*Heat* is measured in Joules (J) and it is defined as energy that flows because of a temperature difference between two bodies. The basic unit of heat is one calorie, which is the energy required to heat 1 g of water 1°C. The specific heat of materials varies considerably and is usually much lower than that of water.

*Work* may be defined as organized motion and is measured in Joules (J). Work can be mechanical, electrical, magnetic, or of other origin.

*Energy* is the same as motion or ability to move. There are different forms of energy, e. g. potential energy, kinetic energy, pressure energy, etc. and they are all measured in Joule (J).

*Enthalpy* is the amount of energy a system releases if the system's temperature drops (assuming the pressure is constant) to 0 K. Heat content is, therefore, another word for enthalpy.

*Entropy* is a measurement of the disorder in the motion, and it is measured in Joules per Kelvin (J/K).

*Exergy* is measured in the same unit as energy and its definition is work (organized motion) or ability to perform work for a system in a specified area. Exergy is the part of the energy that can be used as an energy source, thus each process implies that exergy is consumed and it is therefore always related to the surroundings.

### *2.1.2 Laws*

The first and second laws of thermodynamics form the foundation on which the thermodynamics is based. They are both accepted as fundamental principles that have been repeatedly upheld by human observations, however there is no proof of this concept.

The *first* law of thermodynamics:

**Energy cannot be created or destroyed.
However, it can be converted into other kinds of energy.**

In other words, energy that flows into a system must be fully accounted for in other forms of energy. This results in the total energy in an closed system being constant, which is why an energy balance (where the total input is equal to the total output) can be stated for each process. Energy can, therefore, be defined as that which always is preserved in all processes.

The *second* law of thermodynamics (Clausius):

**Heat cannot spontaneously go from a lower to a higher temperature.**

or (Lord Kelvin):

**Heat cannot be converted into only work.**

By using the definition "entropy", the second law of thermodynamics may be described as; "The enthalpy increases in every closed system, thus the order decreases" or; "All spontaneous changes in an isolated system occur with an increase in entropy or disorder." Thus, the second law of thermodynamics places limits on how energy may be converted, because there are always losses in the transformations. 1 MJ of room heat in energy terms cannot be converted into 1 MJ of electricity, but 1 MJ of electricity can be converted into 1 MJ of room heat.

## 2.2 Energy Analysis

The energy analysis is based on the first law of thermodynamics, whereby "the energy content in a closed system is constant and only converted into different types".

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 (Berry, 1972). In 1974, a conference was held by the International Federation of Institutes for Advanced Studies (IFIAS) at which this type of budgeting was denoted energy analysis, and Gibb´s free energy was chosen as a unit of measure (IFIAS, 1974. For a short summary, see Kristoferson and Nilsson, 1976.). Since little has been added to this method, and usually the analysis is limited to the first law of thermodynamics, i. e. the concept of energy.

There are basically three different methods used to perform an energy analysis, e. g. process, statistical, and input-output analyses (Chapman and Roberts, 1983.). 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 tables 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. In this report, I have used "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 process analysis, we first establish the network of processes required to make the commodity, here salix, winter wheat, and winter rape cultivation. Then we define the material and equipment flows required in the production process, and finally we assign a gross energy requirement to each input and perform the necessary arithmetic, here using spread sheets (Excel).

## 2.3 Exergy analysis

### *2.3.1 Background, definition*

Exergy is defined as work (organized motion) or ability to produce work in contrast to energy which is defined as motion or ability to move. The shortest definition of exergy is useful energy, i. e. that part of the energy that can be used as an energy source. Exergy is the maximum amount of work (mechanical energy) that can be obtained from a system in a process leading to the system reaching equilibrium with its surroundings.

Exergy may be defined as:

> *Exergy is the amount of work obtainable 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 above mentioned components of nature* (Szargut, 1980).

or as:

> *... work or ability to produce work* (Wall, 1986).

The various kinds of energy display different qualities, which are mainfest in their ability to feed and drive energy processes and to be converted into other kinds of energy (Szargut, et al. 1988). Thus, exergy describes the maximum *useful energy* for the system in given surroundings.

The exergy concept combines the first and second laws of thermodynamic. The first law of thermodynamic says that energy is impossible to destroy - energy will always be preserved. What happens is that the energy is degraded when we use it to drive a process. By degrading we mean that quality is depreciated but quantity remains. This results in the exergy, in contrast to the energy, being consumed.

### *2.3.2 Energy quality and exergy carriers*

Both energy- and material flows can be considered as carriers of exergy, so-called exergy carriers. The quality of energy may be indicated by an index, see Table 2.1, giving the approximate exergy content as a percentage of the energy content. This quality index ranges from 100 for potential energy, kinetic energy, and electricity to 0 for the valueless (exergy-lacking) heat radiation from the earth. The difference between energy-, exergy-, and material flows are described in Figure 2.1.

**Table 2.1.** The quality of different forms of energy. (Modified from Wall, 1990.)

| | Form of energy | Quality index (Percentage of exergy) |
|---|---|---|
| **Extra superior** | Potential energy[1] | 100 |
| | Kinetic energy[2] | 100 |
| | Electrical energy | 100 |
| **Superior** | Nuclear energy[3] | almost 100 |
| | Sunlight | 93 |
| | Chemical energy[4] | 95 |
| | Hot steam | 60 |
| | District heating | 30 |
| **Inferior** | Waste heat | 5 |
| **Valueless** | Heat radiation from the earth | 0 |

[1] e.g. highly situated water resources
[2] e.g. waterfalls
[3] e.g. the energy in nuclear fuel
[4] e.g. oil, coal, gas or peat.

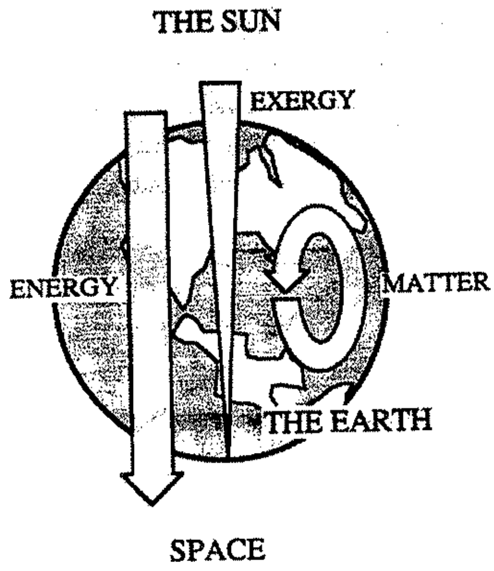



**Figure 2.1.** Flows of energy and matter on earth are driven by the contrast between the sun and space (Wall, 1977).

As mentioned earlier, not only energy containing systems have exergy. All systems that deviate from the environment have exergy. Thus, analogous to the quality of energy, the quality of a certain material can be expressed in exergy terms, see Table 2.2. The highest quality index is that for the purest forms of matter, which consists only of completely known elements, and for which the entropy is almost zero. Diluted and mixed matters have a higher entropy, and therefore they also have lower quality.

**Table 2.2.** The qualities of different materials, i. e. forms of matter. (Modified from Wall, 1986.)

| **Form of matter** | **Quality index (Percentage of exergy)** |
|---|---|
| Matter in an ordered form[1] | 100 |
| Matter as commercial goods[2] | almost 100 |
| Mixtures of elements[3] | approximately 90 |
| Rich mineral deposits[4] | 50-80 |
| Ore | approximately 50 |
| Poor mineral deposits[5] | 20-50 |
| Mineral dissolved in sea water or soil | approximately 0 |

[1] e.g. carbon in the form of diamond or living organisms
[2] e.g. iron, gold or lead
[3] e.g. steel, alloys or plastics
[4] e.g. bog iron (limonite) or sea nodules
[5] e.g. bauxite

As the exergy does not differentiate between "extra superior energy" and "matter in an ordered form", there is a clear connection between energy and matter. Accordingly, we can exchange extra superior energy for the same amount of exergy in the form of matter in an ordered form, which is exactly what we do when enriching and refining a mineral deposit into pure material. Thus, we exchange exergy in the form of energy for exergy in the form of matter (Wall, 1977).

## 2.4 EMERGY analysis

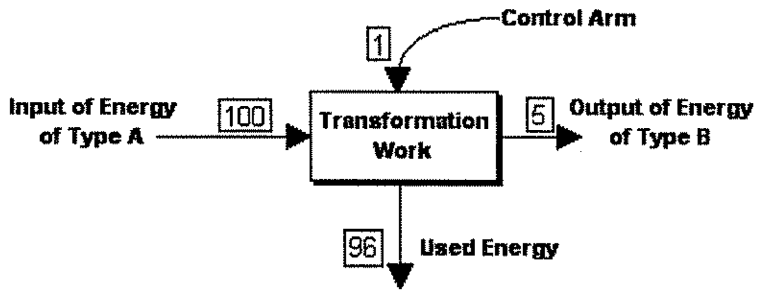
### *2.4.1 Background*

EMERGY analysis (Written in capitals according to Odum, 1996) is an important part of the American system ecologist H. T. Odum's theory. The word EMERGY originates in the words energy and memory, and it is defined as the energy of one type required in transformations to generate a flow or a storage (Odum, 1988). For example, the solar EMERGY (sej) of a flow or a storage is the total amount of solar energy required to produce that storage or flow.

> *"The universal idea among common folk was, and still is, that putting more energy into something generates more value. The concept EMERGY is scientifically defined to give a quantitative measure to this ancient principle."* (Odum, 1996)

### *2.4.2 Transformities*

The transformities are the "keys" in the EMERGY analysis. They describe the amount of energy, expressed in one and same unit, that has been used to create a flow or resource. A product's EMERGY divided by its energy is a quotient defined as its transformity. Thus, the transformity is the same as the EMERGY of one type required to make a unit of energy of another type, see Figure 2.2.




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

**Figure 2.2.** Definition of the energy transformation ratio according to Odum (1984). 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 (Odum, 1984).

At every transformation the available energy is used up to produce a smaller amount of energy of another form. Thus, the more energy transformities there are contributing to a product the higher is its transformity. This implies that EMERGY increases but energy decreases in every step in the tropical hierarchy (Odum, 1996).

In this report, only solar transformities are used, which is the solar EMERGY per unit energy (sej/J). The solar transformity for sun is, of course, 1 sej/J, and the transformities increase as the energy decreases in the higher levels of an hierarchy (Odum, 1988).

### *2.4.3 Symbols*

Odum uses energy system symbols in diagrams to describe processes in our world, see Figure 2.3. Energy flows are indicated by pathways that may indicate interactions, show material cycles or carry information. The system diagram also defines the equations that are used for systems simulation (Odum, 1996).

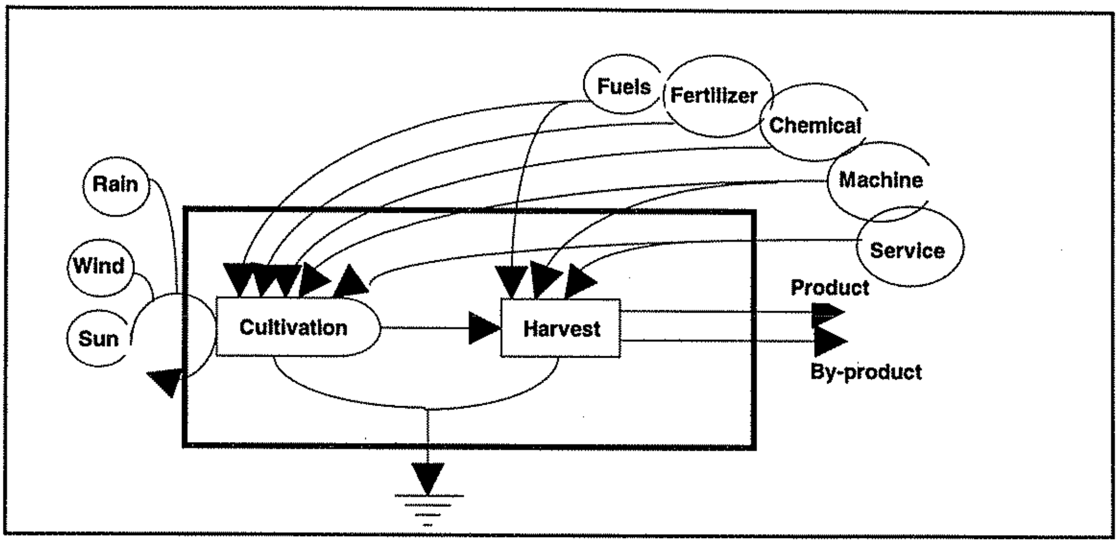



**Figure 2.3.** Energy analysis of a Swedish cultivation. All the EMERGY flows straight through the system, while some of the energy disappears in the bottom.

### *2.4.4 EMERGY Investment Ratio and Net EMERGY Yield Ratio*

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 (Odum, 1996).

The Net EMERGY Yield Ratio (NEYR) is a ratio that shows the ratio between the EMERGY yield and the EMERGY invested from society (economy, services and other resources). The EMERGY yield ratio of each system output is a measure of its net contribution to society beyond its own operation (Odum, 1996).

# 3 CULTIVATION

## 3.1 System boundaries

In the analysis, the 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. Consequently preparations, such as drying, etc. are not considered in this analysis, and neither are transportations 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.

## 3.2 Salix

Salix (willow) is one type of short rotation forest cultivated in Sweden. Its lifecycle is 25 years and it includes preparation, six cutting cycles, and restoration of the field. Preparation includes stubble harrowing, ploughing, and harrowing, thereafter the salix plant is planted. Salix may be harvested in the winter every 4-6 years until the cultivation is around 25 years, when it is time to restore the field and replant salix or any other crop. Since preparation and restoration are two energy demanding steps, it is important that these are taken into consideration when planning. For further information concerning the cultivation steps, see for example Ledin (1996).

This analysis includes all steps in the cultivation, from preparation and planting to restoring of the field after 25 years. During these 25 years the salix has been harvested six times. All activities on the field have been taken into consideration when the analysis has been made. The analysis ends when the salix is harvested as chips at the edge of the field. Since salix cultivation is a relatively new crop, most of the data are based on interviews with farmers and investigators active in the area. For more information concerning the cultivation, see Table 3.1.

**Table 3.1.** Inputs to Salix cultivation in Sweden (pers. com. Ledin, 1996).

| Year | | Addition | (per ha) | | Comments |
|---|---|---|---|---|---|
| (I) | **Preparation** | | | | |
| 1 | Weed control | Roundup | 4 | l | |
| 1 | Stubble harrow | | | | |
| 1 | Plough | | | | |
| 1 | Harrow (3 times) | | | | |
| 1 | Planting | Cuttings | 18 000 | st | |
| 1 | Weed control | Gardoprim | 2.5 | l | |
| 1 | Fertilizer | Phosphorus | 19.8 | kg | 180 kg PK 11-21 |
| | | Potassium | 37.8 | kg | 180 kg PK 11-21 |
| 1 | Weed control | | | | mechanical |
| 2 | Cutting | | | | Yield: 375 kg DM |
| ( II ) | **Cutting cycle 1** | | | | |
| 2 | Weed control | Gardoprim | 2.5 | l | |
| 2 | Weed control | | | | Mechanical |
| 2 | Fertilizer | Nitrogen | 45 | kg | 160 kg N28 |
| 3 | Fertilizer | Nitrogen | 125 | kg | 445 kg N28 |
| 4 | Fertilizer | Nitrogen | 95 | kg | 340 kg N28 |
| 5 | Harvest | | | | Yield: 27 000 kg DM |
| (III.a) | **Cutting cycle 2-6** | | | | |
| 5 | Weed control | Roundup | 4 | l | |
| 5 | Weed control | | | | Mechanical |
| 5 | Fertilizer | Nitrogen | 60 | kg | 215 kg N28 |
| 6 | Fertilizer | Nitrogen | 100 | kg | 360 kg N28 |
| 7 | Fertilizer | Nitrogen | 60 | kg | 215 kg N28 |
| 8 | Fertilizer | Nitrogen | 60 | kg | 215 kg N28 |
| 9 | Harvest | | | | Yield: 36 000 kg DM |
| | Total diesel use | Diesel | 632 | l | |
| | Total work | | 23 | h | |

## 3.3 Winter wheat

Today, there is no difference between cultivation of winter wheat for energy production and cultivation for food production. Both species and cultivation methods are the same.

Growing winter wheat starts in the autumn by preparing the soil for cultivation: Initially stubble harrowing, ploughing, and harrowing, later seed-drilling and rolling, followed by fertilizing and pesticide control, and then finally harvesting.

This analysis includes all steps during one year, from stubble to stubble, and ends when the grain is harvested and ready to be taken away from the field. The data for cultivation of winter wheat are based on marginal costings from Skåne 1995 (Malmö

Hus Läns Hushållningssällskap, 1995). For more information concerning this wheat cultivation, see Table 3.2 and Table 3.3.

**Table 3.2.** Inputs to winter wheat cultivation in Skåne. (Adapted from Malmö Hus Läns Hushållningssällskap, 1995.)

| | Addition | (per ha) | Comments |
|---|---|---|---|
| Sowing | Seed | 170 kg | |
| Fertilizer | Nitrogen | 140 kg | 107 kg NS 26-14 + 400 kg N 28 |
| | Phosphorus | 20 kg | 180 kg PK 11-21 |
| | Potassium | 38 kg | 180 kg PK 11-21 |
| Pest control | Herbicide | 1.9 l | 1 l Arelon + 0.5 l Cougar + 0.4 l Starane |
| | Insecticide | 0.25 l | Sumi-alpha |
| | Fungicide | 1,3 l | 0.8 l Tilt Top + 0.5 l Mantrac |
| | Roundup | 0.60 l | Every 5 year: 3 l Roundup |
| Liming | Lime | 143 kg | 200 kg CaO (71.47% Ca ; 28.53% O) |
| Tractor | Diesel | 66.5 l | 7 h and 9.5 l/h |
| Harvest | Diesel | 6.25 l | 0.5 h and 12.5 l/h |
| Work | | 10.6 h | Spring farming: 3.1h, sowing until harvest: 2.4h, harvest and handling: 2.1h, and service of inventories: 3h. |

**Table 3.3.** Yield from winter wheat cultivation in Skåne (Adapted from Malmö Hus Läns Hushållningssällskap, 1995).

| | Yield | DM (%) | Yield (DM) |
|---|---|---|---|
| Seed | 8 300 | 84 | 6 972 |

## 3.4 Winter Rape

As with the wheat cultivation, there are no differences between food and energy cultivation of rape seed. As for winter wheat, cultivation of winter rape starts in the autumn by preparing the soil for cultivation by stubble harrowing, ploughing and harrowing followed by seeding and rolling, fertilizing and pesticide control. Finally in late summer, the crop is harvested. This analysis of winter rape includes all steps from stubble to stubble during one year. All data for cultivation of winter rape are based on marginal costings from Skåne in 1995 (Malmö Hus Läns Hushållningssällskap, 1995). Tables 3.4 and 3.5 contain more information concerning the analyzed winter rape.

**Table 3.4**. Inputs to winter rape cultivation in Skåne, 1995 (Adapted from Malmö Hus Läns Hushållningssällskap, 1995).

| | Addition | (per ha) | Comments |
|---|---|---|---|
| Sowing | Seed | 6.5 kg | |
| Fertilizer | Nitrogen | 185 kg | 214 kg NS 26-14 + 300 kg N 28 + 300 kg calcium nitrate |
| | Phosphorus | 15 kg | 140 kg PK 11-21 |
| | Potassium | 29 kg | 140 kg PK 11-21 |
| Pest control | Herbicide | 2.0 l | Butisan |
| | Insecticide | 0.90 l | 0.2 l Decis autumn + 0.2 l Decis spring + 0.5 l Mantrac |
| | Roundup | 0.66 l | Every 5 year: 3 l Roundup Bio + 0.3 l Lissapol Bio |
| Liming | Lime | 143 kg | 200 kg CaO (71.47% Ca ; 28.53% O) |
| Tractor | Diesel | 69 l | 7.3 h and 9.5 l/h |
| Harvest | Diesel | 8.8 l | 0.7 h and 12.5 l/h |
| Work | Work | 10.1 h | Spring farming: 3.1 h, sowing until harvest: 2.4 h, harvest and handling: 1.6 h and service of inventories: 3 h. |

**Table 3.5.** Yield from winter rape cultivation in Skåne, 1995 (Adapted from Malmö Hus Läns Hushållningssällskap, 1995).

| | Yield | DM (%) | Yield (DM) |
|---|---|---|---|
| Seed | 3 200 | 83 | 2 656 |

## 4 RESULTS

### 4.1 Energy analysis

In this report the energy analysis has been made with the process analysis method, 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). Energy inputs used for manufacturing are accounted for in Appendix 2.

#### *4.1.1 Results from salix cultivation*

The energy inputs for this salix cultivation are described in Table 4.1. As can be seen nitrogen, followed by the use of fuels, is the main contributor to energy use in the cultivation. The total yield for this salix cultivation is $4.15*10^5$ kg/ha with 50% DM, and its energy content is 8.12 MJ/kg.

**Table 4.2.** Energy inputs in salix cultivation.

| | Inputs per hectare | Energy use for manufacturing | Total energy use 25 years (MJ/ha) |
|---|---|---|---|
| *Chemicals* | | | |
| Roundup | 24 l | 166 MJ/l | 3 984 |
| Gardoprim | 5 l | 131 MJ/l | 655 |
| *Fertilizers* | | | |
| Nitrogen | 1 665 kg | 50.3 MJ/kg N | 83 750 |
| Phosphorus | 15 kg | 16 MJ/kg P | 240 |
| Potassium | 40 kg | 5.0 MJ/kg K | 200 |
| *Others* | | | |
| Cuttings | 250 kg | 16 MJ/kg* | 4 000 |
| Fuels | 632 l | 37.8 MJ/l** | 23 890 |
| Machines | 44.5 kg | 90 MJ/kg | 4 005 |
| **Total** | | | **120 724** |

* Energy content in cuttings.
** Energy content in diesel.

The total energy input for this salix cultivation is $1.21*10^5$ MJ/ha and 25 years. The energy output for the same cultivation is $3.37*10^6$ MJ/ha, which gives an energy ratio (output/input) of 28.

### *4.1.2 Results from winter wheat cultivation*

The energy use for winter wheat cultivation is described in Table 4.3. In the table we see that the biggest contributor to this cultivation is the use of nitrogen followed by the use of diesel and seed. The yield from the cultivation is, as mentioned earlier, $7.0*10^3$ kg DM/ha, thus 8 300 kg/ha and its energy content is 14.9 MJ/kg at 85% DM.

**Table 4.4.** Energy inputs in winter wheat cultivation.

| | Inputs per hectare | Energy Use for manufacturing | Total Energy Use (MJ/ha) |
|---|---|---|---|
| *Chemicals* | | | |
| Herbicide | 1.9 l | 204 MJ/l | 388 |
| Insecticide | 0.25 l | 112 MJ/l | 28 |
| Fungicide | 1,3 l | 119 MJ/l | 155 |
| Roundup | 0.66 l | 166 MJ/l | 100 |
| *Fertilizers* | | | |
| Nitrogen | 140 kg | 50.3 MJ/kg N | 7 042 |
| Phosphorus | 20 kg | 16 MJ/kg P | 320 |
| Potassium | 38 kg | 5.0 MJ/kg K | 190 |
| *Others* | | | |
| Seed | 170 kg | 16.0 MJ/kg* | 2 720 |
| Lime | 143 kg | 0.17 MJ/kg | 24 |
| Fuels | 73 l | 37.8 MJ/l** | 2 759 |
| Machines | | 10 % | 1373 |
| **Total** | | | **15 099** |

* Energy content in seed plus energy use for handling.
** Energy content in diesel.

According to these assumptions, the energy use for winter wheat cultivation is $15.1*10^3$ MJ/ha. The energy output for the same cultivation is $122*10^3$ MJ/ha, which gives an energy ratio (output/input) of 8.1.

### *4.1.3 Results from winter rape cultivation*

Energy use for this winter rape cultivation is shown in Table 4.5. The analysis shows that the use of nitrogen and diesel contributes most to the total energy use for the cultivation. The total yield is $3.2*10^3$ kg/ha, thus $2.7*10^3$ kg DM/ha and its energy content is 25.8 MJ/kg (83% DM). Thus, the total energy output from this cultivation is $82.6*10^3$ MJ.

**Table 4.6.** Energy inputs in winter rape cultivation

| | Inputs per hectare | Energy use for manufacturing | Total energy use (MJ/ha) |
|---|---|---|---|
| *Chemicals* | | | |
| Herbicide | 2.0 l | 134 MJ/l | 268 |
| Insecticide | 0.90 l | 53 MJ/l | 48 |
| Roundup | 0.66 l | 166 MJ/l | 110 |
| | | | |
| *Fertilizers* | | | |
| Nitrogen | 185 kg | 50.3 MJ/kg N | 9 306 |
| Phosphorus | 15 kg | 16 MJ/kg P | 240 |
| Potassium | 29 kg | 5.0 MJ/kg K | 145 |
| | | | |
| *Others* | | | |
| Seed | 6.5 kg | 26 MJ/kg* | 169 |
| Lime | 143 kg | 0.17 MJ/kg | 24 |
| Fuels | 78 l | 37.8 MJ/l** | 2 948 |
| Machines | | 10 % | 1 326 |
| | | | |
| **Total** | | | **14 584** |

* Energy content in seed plus energy use for handling.
** Energy content in diesel.

According to Table 4.7, the energy use for rape cultivation is $14.6*10^3$ MJ/ha and the energy yield for the same cultivation is $82.6*10^3$ MJ/ha. This results in an energy ratio (output/input) of 5.7.

## 4.2 Exergy analysis

The exergy used in the cultivations has been calculated from the energy that has been used for the same cultivation. The amount of energy used has then been multiplied by the same energy's quality factor which is 1.00 for electricity, and 0.95 for chemical energy, such as oil and natural gas (see Chapter 2.2). This tells us how much exergy has been used for cultivation of salix, winter wheat and winter rape.

The specific chemical exergy , $\xi_{ch}$, in the organic matter, such as cuttings, seed, salix, etc. has been calculated from Szargut et al. (1988);

$$\xi_{ch} = (NCV + L_w z_w)\beta + \xi_{chw} z_w$$

where:

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

*NCV* is the Net Calorific Value, $L_W$ denotes the entalphy of phase change for water, which is 2 440 kJ/kg, and $z$ the mass fraction for water (w), hydrogen (H), coal (C), nitrogen (N), and oxygen (O). $\xi_{chw}$ is the chemical exergy in water, which is 50 kJ/kg.

### *4.2.1 Results from salix cultivation*

For salix that has been harvested in winter the following data have been used; $z_C = 48.4\%$, $z_o = 45.2\%$, $z_H = 6.0\%$, $z_N = 0.36\%$ and $z_w = 50\%$. $NCV = 8\ 120$ kJ/kg, $L_w = 2\ 440$ kJ/kg and $\xi_{chw} = 50$ kJ/kg (pers. comm. Ledin, 1996). Thus, according to Szargut et al. (1988) the chemical exergy for salix with 50% DM is $10.6{*}10^3$ kJ/kg. The total exergy output is, consequently, $4.40{*}10^6$ MJ/ha and 25 years.

**Table 4.8.** Exergy inputs in salix cultivation

| | Inputs per hectare | Form of energy | Exergy use for manufacturing | Total exergy use 25 years (MJ/ha) |
|---|---|---|---|---|
| *Chemicals* | | | | |
| Roundup | 24 l | Electricity | 166 MJ/l | 3 984 |
| Gardoprim | 5 l | Electricity | 131 MJ/l | 655 |
| *Fertilizers* | | | | |
| Nitrogen | 1 665 kg | Natural gas | 47.8 MJ/kg N | 79 587 |
| Phosphorus | 15 kg | Oil | 15.2 MJ/kg P | 228 |
| Potassium | 40 kg | Oil | 4.75 MJ/kg K | 190 |
| *Others* | | | | |
| Cuttings | 250 kg | | 10.6 MJ/kg* | 2 650 |
| Fuels | 632 l | | 35.9 MJ/l** | 22 689 |
| Machines | 44.5 kg | Electricity | 90 MJ/kg | 4 005 |
| **Total** | | | | **113 988** |

* Exergy content in cuttings.
** Exergy content in diesel.

The exergy input for this salix cultivation is, according to Table 4.9, $114{*}10^3$ MJ per hectare and 25 years. This gives an exergy ratio (output/input) of 39.

#### *4.2.2 Results from winter wheat cultivation*

The total exergy input for this winter wheat cultivation is 14.8*10$^3$ MJ/ha, see Table 4.10. For winter wheat, the following data have been used; $z_C$ = 43.6%, $z_o$ = 46.7%, $z_H$ = 6.0%, $z_N$ = 1.5% and $z_w$ = 11.3%. *NCV* = 15 010 kJ/kg, $L_w$ = 2 440 kJ/kg and $\xi_{chw}$ = 50 kJ/kg (Praks, 1993 a). Thus, according to Szargut et al. (1988) the chemical exergy for winter wheat with 88.7% DM is 17.6*10$^3$ kJ/kg. The total yield at 88.7% DM is 7.9*10$^3$ kg/ha, thus the total exergy output is consequently 138*10$^3$ MJ/ha and year. This assumption gives an exergy ratio (output/input) of 9.3.

**Table 4.11.** Exergy inputs in winter wheat cultivation

| | Inputs per hectare | Form of energy | Exergy use for manufacturing | Total exergy use (MJ/ha) |
|---|---|---|---|---|
| *Chemicals* | | | | |
| Herbicide | 1.9 l | Electricity | 204 MJ/l | 388 |
| Insecticide | 0.25 l | Electricity | 12 MJ/l | 3.0 |
| Fungicide | 1.3 l | Electricity | 119 MJ/l | 155 |
| Roundup | 0.66 l | Electricity | 166 MJ/l | 100 |
| *Fertilizers* | | | | |
| Nitrogen | 140 kg | Natural gas | 47.8 MJ/kg N | 6 692 |
| Phosphorus | 20 kg | Oil | 15.2 MJ/kg P | 304 |
| Potassium | 38 kg | Oil | 4.75 MJ/kg K | 181 |
| *Others* | | | | |
| Seed | 170 kg | | 17.6 MJ/kg* | 2992 |
| Lime | 143 kg | Oil + Diesel | 0.16 MJ/kg | 23 |
| Fuels | 73 l | | 35.9 MJ/l** | 2 621 |
| Machines | | | 10 % | 1 346 |
| **Total** | | | | **14 805** |

* Exergy content in seed.
** Exergy content in diesel.

#### *4.2.3 Results from winter rape cultivation*

For winter rape, the following data have been used (Calculated from: Norén, 1993, Prax, 1993 b and Malmö Hus Läns Hushållningssällskap, 1995); $z_C$ = 57.8%, $z_o$ = 20.2%, $z_H$ = 8.21%, $z_N$ = 2.76% and $z_w$ = 17%. *NCV* = 25 800 kJ/kg, $L_w$ = 2 440 kJ/kg and $\xi_{chw}$ = 50 kJ/kg. Thus, according to Szargut et al. (1988), 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, thus the total exergy output is 91.7*10$^3$ MJ/ha and year.

**Table 4.12.** Exergy inputs in winter rape cultivation

| | Inputs per hectare | Form of energy | Exergy use for manufacturing | Total exergy use (MJ/ha) |
|---|---|---|---|---|
| *Chemicals* | | | | |
| Herbicide | 2.0 l | Electricity | 134 MJ/l | 268 |
| Insecticide | 0.90 l | Electricity | 53 MJ/l | 48 |
| Roundup | 0.66 l | Electricity | 166 MJ/l | 110 |
| *Fertilizers* | | | | |
| Nitrogen | 185 kg | Natural gas | 47.8 MJ/kg N | 8 843 |
| Phosphorus | 15 kg | Oil | 15.2 MJ/kg P | 228 |
| Potassium | 29 kg | Oil | 4.75 MJ/kg K | 138 |
| *Others* | | | | |
| Seed | 6.5 kg | | 28.7 MJ/kg* | 187 |
| Lime | 143 kg | Oil + Diesel | 0.16 MJ/kg | 23 |
| Fuels | 78 l | | 35.9 MJ/l** | 2 800 |
| Machines | | | 10 % | 1 265 |
| **Total** | | | | **13 910** |

* Exergy content in seed.
** Exergy content in diesel.

According to Table 4.13, the total exergy input for this winter rape cultivation is $13.9*10^3$ MJ/ha and this gives an exergy ratio (output/input) of 6.6.

## 4.3 EMERGY analysis

The EMERGY analysis begins with drawing an energy system diagram where all flows for the process are indicated, see Figure 4.1. All the EMERGY flows and their transformities for the cultivation are illustrated in Tables 4.7, 4.8 and 4.9.

The transformities for the direct environmental inputs, i. e. sun, wind, and rain, are calculated from each other, which is why only the largest are taken into consideration in the analysis. Thus, this factor will contain EMERGY for all the other environmental inputs as well.

Depending on the system boundaries, the service cost is calculated from prices with or without taxes. In this scenario, the system boundaries are at the field border, and costs for society are therefore not taken into consideration. Thus, prices and salaries are without taxes and other society fees.

### *4.3.1 Results from salix cultivation*

According to Table 4.14, we see that the total EMERGY use for this salix cultivation is 2.85E+16 sej/ha, hear is the EMERGY input from service included. As can be seen, the biggest contributor to the cultivation is the direct environment followed by nitrogen fertilizer, service and fuels.

When the transformity for salix is stated it should be free from service costs, thus the transformity for one hectare of salix under these circumstances is 2.16E+16 sej. Since the total salix yield is $415*10^3$ kg, the transformity for salix is 5.20E+10 sej/kg with 50% DM and 1.04E+11 sej/kg DM.

**Table 4.15.** EMERGY analysis of salix cultivation

| Footnote* | | Inputs per hectare | Transformity (sej/unit) | Sun-EMERGY (sej/25 years) |
|---|---|---|---|---|
| | *Direct environment* | | | |
| 1 | Sun | 6.43E+14 J | 1.00E+00 | 6.43E+14 |
| 2 | Wind, kinetic energy | 1.77E+12 J | 1.50E+03 | 2.64E+15 |
| 3 | Rain, evapotranspiration | 4.85E+11 J | 1.82E+04 | 8.83E+15 |
| | **Total:** | | | **8.83E+15** |
| | *Chemicals* | | | |
| 4 | Roundup | 24 l | 3.32E+13 | 7.97E+14 |
| 5 | Gardoprim | 5 l | 2.64E+13 | 1.32E+14 |
| | *Fertilizers* | | | |
| 6 | Nitrogen | 1 665 kg | 4.63E+12 | 7.71E+15 |
| 7 | Phosphorus | 15 kg | 1.78E+13 | 2.67E+14 |
| 8 | Potassium | 38 kg | 1.74E+12 | 6.61E+13 |
| | *Others* | | | |
| 9 | Cuttings | 18 000 st. | 7.92E+10 | 1.43E+15 |
| 10 | Fuels | 632 l | 2.49E+12 | 1.58E+15 |
| 11 | Machinery incl. mantainance | 44 480 g | 1.98E+09 | 8.81E+13 |
| 12 | Labour | 23 h | 2.64E+13 | 6.04E+14 |
| | **Total:** | | | **2.16E+16** |
| 13 | Service | 28 847 SEK | 2.40E+11 | **6.92E+15** |
| | **Total:** | | | **2.85E+16** |

* Appendix 2 contains further data.

The EMERGY Investment Ratio for salix in this cultivaton 2.23. The Net EMERGY Yield Ratio for the same cultivation is 1.45.

### *4.3.2 Results from winter wheat cultivation*

The results from the EMERGY analysis of winter wheat cultivation are accounted for in Table 4.16, showing that the total EMERGY use for the cultivation is 4.43E+15 sej/ha.

For this cultivation, nitrogen fertilizer gives the biggest contribution followed by machinery, direct environment, phosphorus fertilizer, and labour.

The transformity for one hectare of winter wheat in this cultivation is 2.68E15 sej. Because the yield is $7.0*10^3$ kg DM/ha, the transformity for winter wheat is 3.85E+11 sej/kg DM.

**Table 4.17.** EMERGY analysis of winter wheat cultivation

| Footnote* | | Inputs per hectare | Transformity (sej/unit) | Sun-EMERGY (sej/year) |
|---|---|---|---|---|
| | *Direct environment* | | | |
| 1 | Sun | 2.57E+13 J | 1.00E+00 | 2.57E+13 |
| 2 | Wind, kinetic energy | 7.07E+10 J | 1.50E+03 | 1.06E+14 |
| 3 | Rain, evapotranspiration | 1.94E+10 J | 1.82E+04 | 3.53E+14 |
| | **Total:** | | | **3.53E+14** |
| | *Chemicals* | | | |
| 4 | Herbicide | 1.90 l | 2.60E+13 | 4.94E+13 |
| 5 | Insecticide | 0.25 l | 2.60E+13 | 6.50E+12 |
| 6 | Fungicide | 1.3 l | 2.60E+13 | 3.38E+13 |
| 7 | Roundup | 0.6 l | 3.32E+13 | 1.99E+13 |
| 8 | Lime | 143 kg | 5.56E+09 | 7.95E+11 |
| | *Fertilizers* | | | |
| 9 | Nitrogen | 140 kg | 4.63E+12 | 6.48E+14 |
| 10 | Phosphorus | 20 kg | 1.78E+13 | 3.56E+14 |
| 11 | Potassium | 38 kg | 1.74E+12 | 6.61E+13 |
| | *Others* | | | |
| 12 | Seed | 170 kg | 6.96E+11 | 1.18E+14 |
| 13 | Fuels | 73 l | 2.49E+12 | 1.82E+14 |
| 14 | Machines | 2 371 SEK | 2.40E+11 | 5.69E+14 |
| 15 | Labour | 11 h | 2.64E+13 | 2.90E+14 |
| | **Total:** | | | **2.69E+15** |
| 16 | Service | 7 249 SEK | 2.40E+11 | **1.74E+15** |
| | **Total:** | | | **4.43E+15** |

* Further data are found in appendix 2.

For this winter wheat cultivation, the EMERGY Investment Ratio is 11.5 and the Net EMERGY Yield ratio for this cultivation is 1.09.

### *4.3.3 Results from winter rape cultivation*

As seen in Table 4.18, the total EMERGY use for winter rape cultivation under these assumptions is 4.52E+15 sej/ha. The biggest contribution comes from nitrogen fertilizer followed by machinery use, direct environment, phosphorus fertilizer, and labour.

The transformity for one hectare of rape according to this assumption is 2.73E+15 sej. The yield from this cultivation is $2.7*10^3$ kg DM/ha, which gives the transformity, under these circumstances, for winter rape of 1.03E+12 sej/kg DM.

**Table 4.19.** EMERGY analysis of winter rape cultivation

| Footnote* | | Inputs per hectare | Transformity (sej/unit) | Sun-EMERGY (sej/25 years) |
|---|---|---|---|---|
| | *Environment* | | | |
| 1 | Sun | 2.57E+13 J | 1.00E+00 | 2.57E+13 |
| 2 | Wind, kinetic energy | 7.07E+10 J | 1.50E+03 | 1.06E+14 |
| 3 | Rain, evapotranspiration | 1.94E+10 J | 1.82E+04 | 3.53E+14 |
| | **Total:** | | | **3.53E+14** |
| | *Chemicals* | | | |
| 4 | Herbicide | 2.0 l | 2.60E+13 | 5.20E+13 |
| 5 | Insecticide | 0.9 l | 2.60E+13 | 2.34E+13 |
| 6 | Roundup | 0.66 l | 3.32E+13 | 2.19E+13 |
| 7 | Lime | 143 kg | 5.56E+09 | 7.95E+11 |
| | *Fertilizers* | | | |
| 9 | Nitrogen | 185 kg | 4.63E+12 | 8.57E+14 |
| 10 | Phosphorus | 15 kg | 1.78E+13 | 2.67E+14 |
| 11 | Potassium | 29 kg | 1.74E+12 | 5.05E+13 |
| | *Others* | | | |
| 12 | Seed | 6.5 kg | 1.08E+13 | 7.02E+13 |
| 13 | Fuels | 78 l | 2.49E+12 | 1.94E+14 |
| 14 | Machines | 2 371 SEK | 2.40E+11 | 5.69E+14 |
| 15 | Labour | 10 h | 2.64E+13 | 2.64E+14 |
| | **Total:** | | | **2.73E+15** |
| 16 | Service | 7 434 SEK | 2.40E+11 | **1.78E+15** |
| | **Total:** | | | **4.52E+15** |

* Further data are found in appendix 2.

The EMERGY investment ratio for winter rape under these circumstances is 11.8. The net EMERGY yield ratio according to these assumptions is 1.08.

### 4.4 Sensitivity analysis

To evaluate how sensitive the different methods are to changes in input values, two different analyses of sensitivity were made on the winter wheat cultivation. In the first case, the use of machines for winter wheat cultivation has been assumed to be only half as big as in the original case, and in the second case the use of fuels has been changed to fifty percent less than in the "normal" case.

Figure 4.1 shows, the results when the use of machinery in the winter wheat cultivation has been halved. As can be seen, both the exchange of energy and exergy have increased by more than four percent.

As further seen in Figure 4.1, the transformity has decreased by over 12 percent, and the EMERGY investment ratio (EIR), i. e., the ratio between EMERGY invested from the society and the EMERGY invested from the environment, has decreased by 14 percent. According to these assumptions, the ratio between the EMERGY yield and the EMERGY invested from the society, i. e., the net EMERGY yield ratio (NEYR), has increased by approximately one percent.

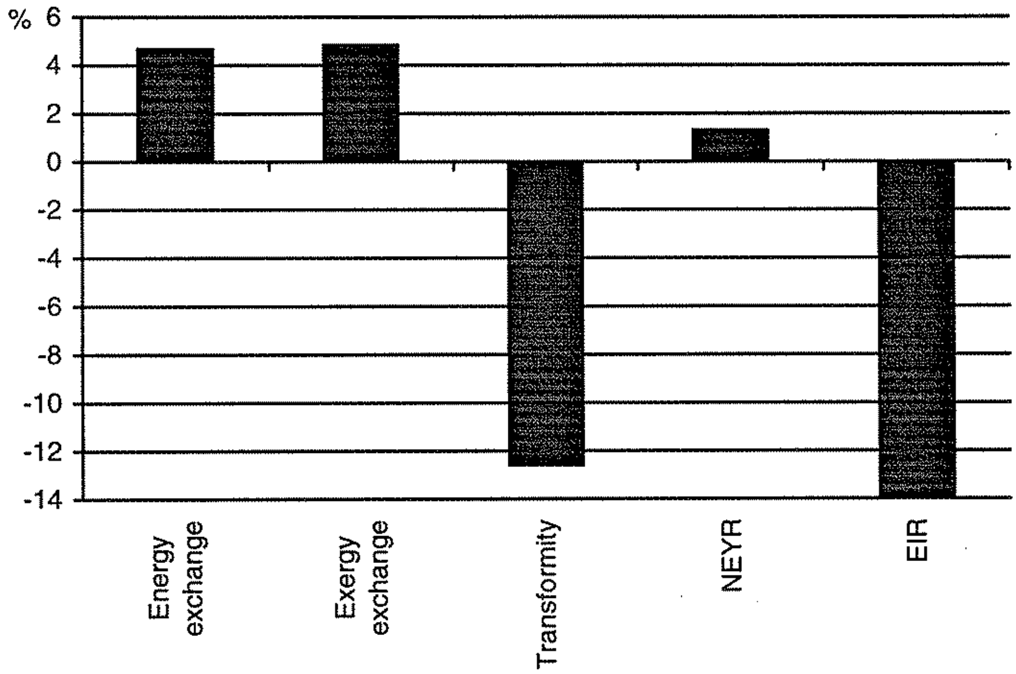



**Figure 4.2.** Percentile change in results from winter wheat cultivation when the use of machinery has been halved.

When, instead, the use of fuels for this winter wheat cultivation have been assumed to be only half as large, see Figure 4.2, both the energy-, and the exergy exchange increase by approximately 11 percent.

The transformity and the EMERGY investment ratio decrease by around three percent. The net EMERGY yield ratio is almost zero, see Figure 4.2.

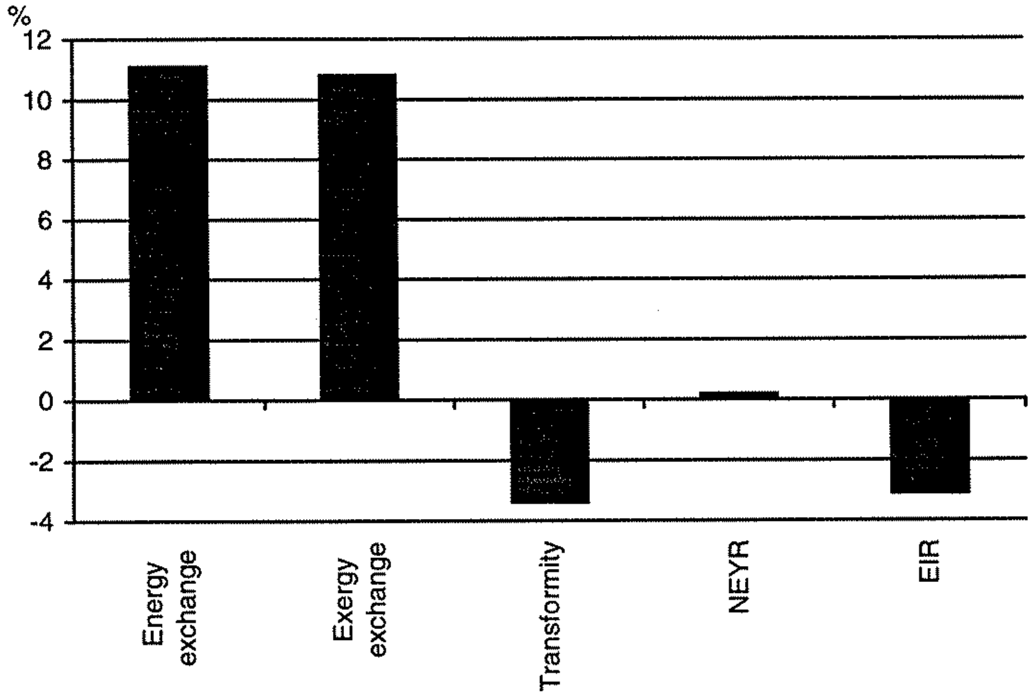



**Figure 4.3.** Percentile change in results from winter wheat cultivation when the use of fuels has been halved.

# 5 DISCUSSION

## 5.1 Differences between methods

### *5.1.1 Energy analysis*

The energy analysis only answers the question concerning the size of the energy flows in the process, it does not consider the quality of energy used. However, the energy flow can be split into fossil and renewable sources, and the analysis can be complemented with other studies in order to get a broader perspective. Another problem with the energy analysis is that it does not take into consideration whether or not the used energy has its origin in waste heat which, from a resource point of view may be assumed to be free, or if it is high quality energy, such as electricity or oil.

### *5.1.2 Exergy analysis*

In contrast to the energy analysis, the exergy analysis is based on both the first and the second laws of thermodynamics. This results in the exergy analysis not only giving answers about how large the energy flows are, but also answering questions on how high quality the used energy had. Thus, the results give us an opportunity to see if we have used high quality energy when, instead, we could have used low quality energy obtaining the same results.

High quality energy are usualy used in this macroscopic system, which is why the inputs of exergy are almost the same as the inputs of energy for this salix cultivation. In this analysis the major difference between the energy and exergy analysis with the present scenario lies in the valuation of the resource obtained, i. e. the salix chips, the winter wheat, and the winter rape.

### *5.1.3 EMERGY analysis*

The EMERGY analysis is based on the maximum power principle in contrast to the energy and the exergy analyses which are based on the laws of thermodynamics. EMERGY analysis is a measure of energy that has already been used up (degraded during transformations) to produce a storage or flow, including the energy from environment, e. g. solar radiation and rainwater. Thus EMERGY is a record of previously consumed available energy that is a property of the smaller amount of available energy in the transformed product.

The EMERGY analysis tries to value the inputs in the cultivation by expressing them in terms of how much solar energy has been used to create the source or the flow. The more solar energy that has been used, and thus the higher transformity, the more valuable (or harmful to use) is the resource. Also the service used for manufacturing is taken into consideration in the EMERGY analysis. However, this results in very large values which are difficult to understand and compare. Because we do not have to pay the environment for resources used in the production, it is assumed that the price for a product reflects only how much service that has been put into that product. Thus, it is assumed that the inputs of service in this salix cultivation can be valued from the prices of the products used in the same cultivation.

## 5.2 Different results with different methods

The energy content of a crop, i. e. the enthalpy value, is different to the exergy content, i. e., the chemical exergy content, in the same crop (see Figure 5.1). This difference results in different ratios between outputs and inputs for the cultivations. Higher value for the exergy content is obtained because the energy value does not take the upgrading of energy in the cultivation into consideration; the same differences can therefore also be seen for winter wheat and winter rape cultivation.

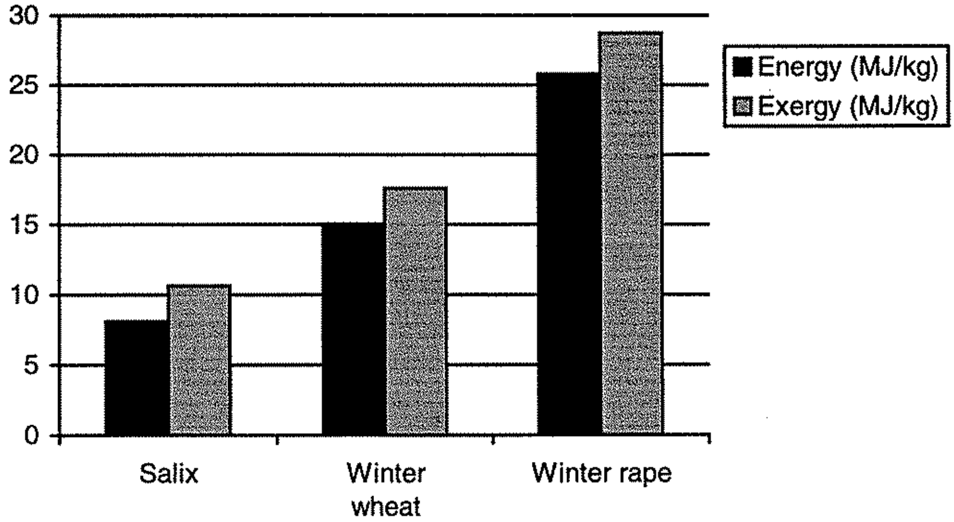



**Figure 5.1.** Energy content versus chemical exergy content in salix (50% DM), winter wheat (88.7% DM), and winter rape (83% DM).

To get an idea of whether the cultivation is profitable from an energy point of view, the exchange for the process is usually evaluated (see Figure 5.2). The exchange in energy for this salix cultivation is 28 times, but if instead an exergy analysis is performed, the exchange for exactly the same process is 39 times. The primary reason for the higher value for the exergy analysis is that the energy analysis does not take the upgrading of energy in the cultivation into consideration (see Figure 5.1). For the same reason we see that the exergy exchange is higher than the energy exchange for both the winter wheat and the winter rape cultivations.

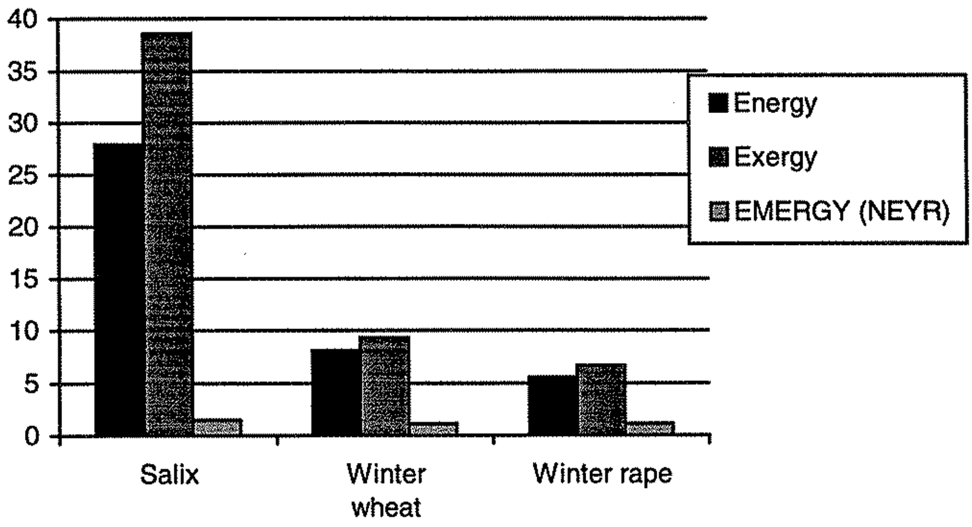



**Figure 5.2.** Energy, exergy, and EMERGY exchange of an Swedish salix, winter wheat, and winter rape cultivations. The energy, exergy, and, NEYR (Net EMERGY Yield Ratio) value should to be as large as possible.

According to the definition of EMERGY analysis, all the EMERGY that has been invested in the process is found in the final product. Thus, the EMERGY exchange is 1.00 for all processes. Useful values for evaluating the profit in EMERGY analysis results are EMERGY Investment Ratio (EIR), and Net EMERGY Yield Ratio (NEYR). These ratios value the inputs from society, e. g. diesel use, fertilizer use and labour in proportion to environmental inputs, e. g. solar radiation and rain.

The EMERGY investment ratio describes the relation between the amount of EMERGY invested by society and the amount of EMERGY invested by the environment, thus this ratio ought to be as small as possible (Odum, 1996). According to this assumption, the EIR is 2.23 for salix cultivation, 11.5 for winter rape cultivation, and 11.8 for winter rape cultivation, showing that when we cultivate salix the investment of society is twice that of the environment, etc.

The net EMERGY investment ratio shows the relation between the EMERGY yield and the EMERGY invested by society, and consequently it ought to be as large as possible (Odum, 1996). For these cultivations, the NEYR is 1.45 for the salix cultivation, 1,09 for the winter wheat cultivation, and 1,08 for the winter rape cultivation. This should be interpreted as meaning that the EMERGY yield is 45% larger than the EMERGY input from society for the salix cultivation, but the output is just 9% and 8% larger than the input for the winter wheat and the winter rape cultivations.

Figures 5.3, 5.4 and 5.5 show that the energy-, the exergy-, and the EMERGY methods value the resources used for the three cultivation systems in different ways. In Figure 5.3, the percentage contribution from the three different methods on the analyzed salix cultivation is shown. As can be seen, the energy- and the exergy analyses give almost the same answers about which resources contribute most to cultivation of salix. The EMERGY analysis values the use of chemicals, phosphorus, cuttings, and labour as more important than the energy- and the exergy analyses. On the other hand, the EMERGY analysis values the use of nitrogen, fuels, and machinery less than the energy- and the exergy methods.

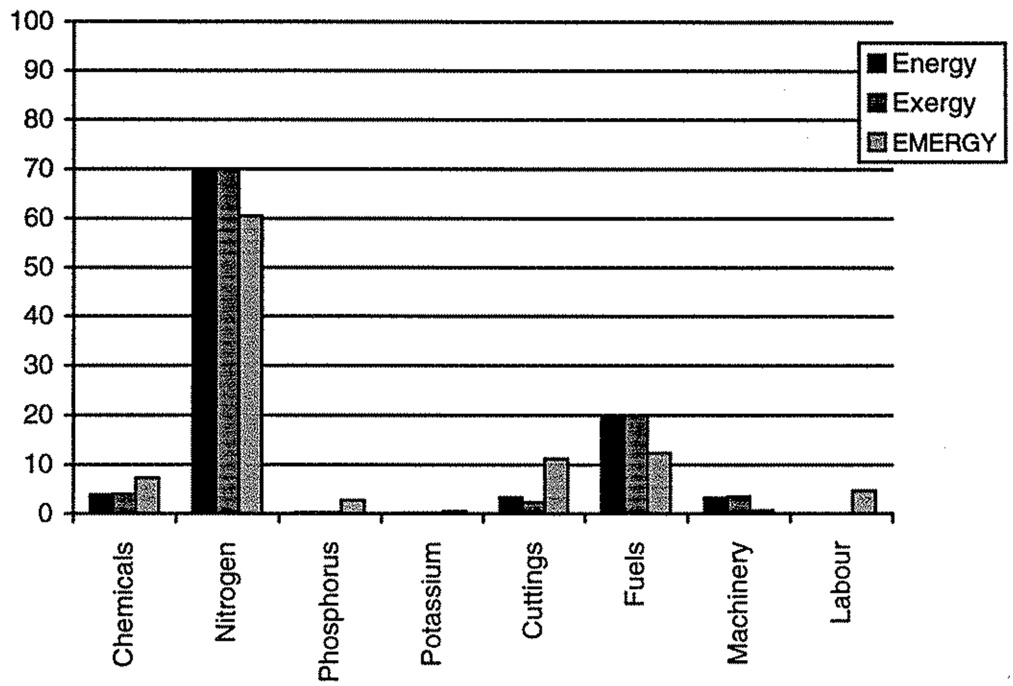



**Figure 5.3.** Percentage contribution of used resources from energy-, exergy-, and EMERGY perspective for a Swedish salix cultivation.

In Figure 5.4, the percentage contribution of resources used for winter wheat cultivation is shown. The energy analysis values the use of nitrogen highest, followed by the fuels used, seed and machinery, in that order. When an exergy analysis is made on the same cultivation, we get almost the same answers on the size of the contributions as in the energy analysis. One differences is, as seen in Figure 5.1, that the chemical exergy content in the seed is larger than equivalent energy value for the seed. This results in a different order for the contributor when an exergy analysis is made on an cultivation instead of an energy analysis.

The EMERGY analysis differs more from the energy analysis than the exergy analysis when it comes to valuing of the resources used in the cultivation. As seen in Figure 5.4, the EMERGY analysis gives highest priority to the nitrogen fertilizer used, closely followed by the use of machines. Since the EMERGY analysis is a record of all the energy required to produce a flow or storage, it gives a higher value to the use of phosphorus fertilizer, which is found in third place in the EMERGY analysis, whereas in both the energy-, and the exergy analyses it is placed as the next but last contributor. The EMERGY analysis also gives a high value to used labour.

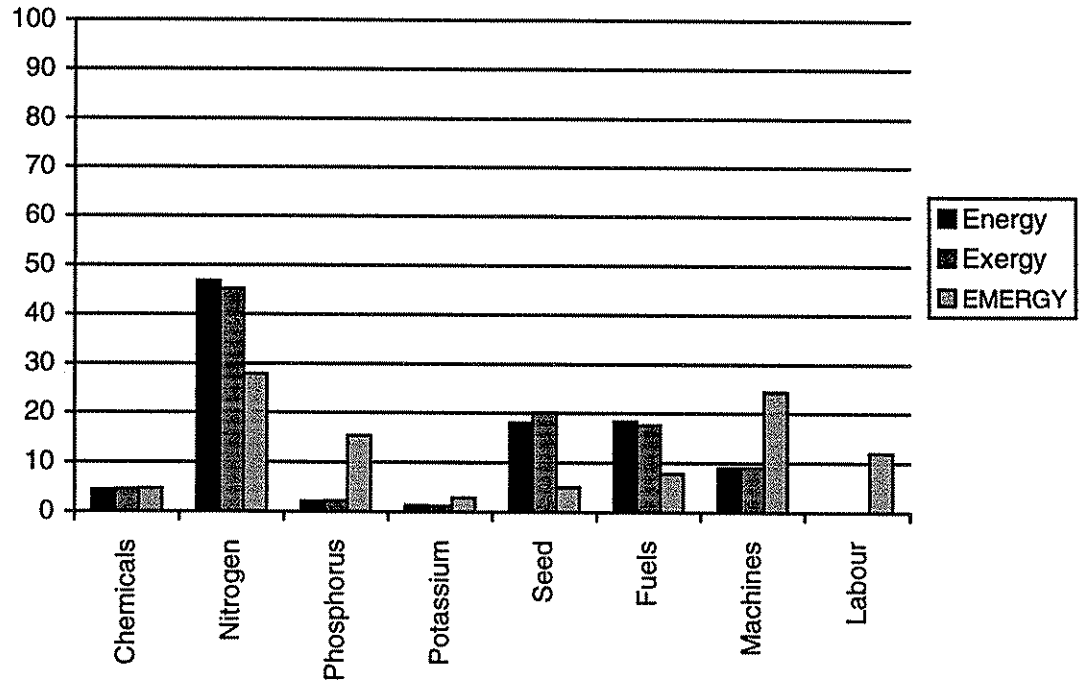



**Figure 5.4.** Percentage contribution of resources used from energy-, exergy-, and EMERGY perspectives for a Swedish winter wheat cultivation.

For the winter rape cultivation almost the same phenomenon is seen as for the winter wheat cultivation when the cultivation has been analyzed with the three different methods (see Figure 5.5).

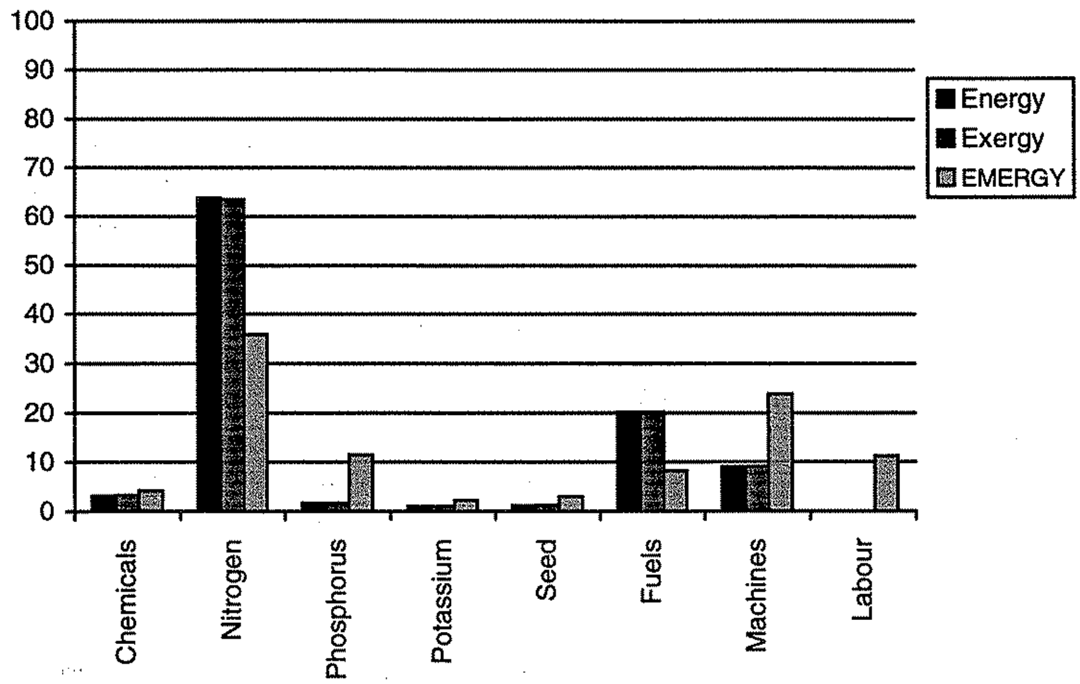



**Figure 5.5.** Percentage contribution of used resources from energy-, exergy-, and EMERGY perspectives for a Swedish winter rape cultivation.

### 5.3 Sensitivity analysis

As seen in Figure 4.1, the change in the exchange is almost the same in both the energy and the exergy analysis when the use of machinery in the winter wheat cultivation has been halved. This result gives us an idea about how the energy and the exergy analyses react in almost the same way when this change in machines is made.

When the use of machines has been halved it results in the transformity decreasing by over 12 percent (see Figure 4.1). Thus, the use of EMERGY for this winter wheat production has decreased by 12 percent. At the same time, the ratio between EMERGY invested from society and EMERGY invested from the environment has decreased by 14 percent. The ratio between the EMERGY yield and the EMERGY invested from society has increased by approximately one percent.

When instead the use of fuels for this winter wheat cultivation has been assumed to be only half as large (see Figure 4.2), both the energy-, and the exergy exchanges increase by approximately 11 percent. The transformity and the EMERGY investment ratio decrease by more than 12 and 14 percent respectively. The net EMERGY yield ratio increases, if only by 0.30 percent.

## 5.4 Need of further research

Exergy is an more interesting and true concept than energy analysis because the exergy analysis shows the amount of useful energy. This is why it is important to use this concept more widely than have been done in the past.

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. Additionally it would be interesting and valuable to study and optimize a hole farm from an exergy perspective.

## 6 CONCLUSIONS

Energy, exergy and EMERGY analyses are valuable methods when studying cultivation of energy crops. Energy and exergy are based on the thermodynamics and EMERGY is based on systems ecology why is that these different methods give different results and that the exchange varies depending on the method chosen for the analysis.

Exergy is an more proper way of studying our resourses, than energy, because it describes the quality that is produced or consumed. Energy and matter only serve as carriers of quality, and it is the quality that is consumed during the conversion of energy and matter, why it is wrong to talk about production or consumption of energy.

The energy analysis gives an energy exchange of 28 times for this Swedish salix cultivation. For the winter wheat cultivation, the same value is 8.1, and the energy exchange from a winter rape cultivation is 5.7. Thus, all the studied cultivations have a higher energy output than the corresponding input.

When, instead, the same cultivations are studied from an exergy point of view, we get an exchange of 39 for the salix cultivation, 9.3 for the winter wheat cultivation, and 6.6 for the winter rape cultivation. Thus, according to the exergy analysis, we get a higher profit when the crops are cultivated than from an energy point of view. The biggest difference between the energy- and the exergy analyses is in the way the products are valuated, i. e. salix chips, wheat, and rape seed.

The EMERGY analysis differs considerably from the energy and the exergy perspectives. The total EMERGY use for this salix cultivation is 2.85E+16 sej/ha and 25 years, 4.43E+15 sej/ha for winter wheat cultivation, and 4.52E+15 sej/ha for cultivation of winter rape. The transformity for salix is 1.04E+11 sej/kg DM, for winter wheat 3.85E+11 sej/kg DM, and for winter rape 1.03E+12 sej/kg DM. This EMERGY analysis gives an EIR of 2.23 and an NEYR of 1.10 for this salix cultivation, with corresponding values of11.5 and 0.66 for winter wheat and 11.8 and 0.66 for winter rape respectively.

# 7 REFERENCES

## 7.1 Literature

Andersson, R. 1981. *Energianalys av ett modernt jordbruk.* Institute of Physical Resource Theory, Chalmers University of Technology. Gothenburg, 1981.

Berry, S. 1972. *Bulletin of the Atomic Scientists*, vol. 9, p. 8, 1972.

Chapman, P. F. & Roberts, F. 1983. *Metal Resources and Energy.* Butterworths, 1983.

Ericsson, O. Ahlborg, U. Andersson, A. Ascard, J. Barklund, P. Bernson, V. Bång, U. Bärring, U. Dalin Cronborg, M. Eidman, H. H. Ekström, U. Erne, K. Gummesson, G. Hagenvall, H. Hellekant, A. Jönsson, B. Nedstam, B. Olvång, H. Sjölander, A. Stark, J. Svensson, S E. Tornéus, C. Torstensson, L. Magnusson, L. 1995. *Bekämpningsmedel 1996.* LTs förlag. Borås, 1995.

Green, M B. 1987. *Energy in Pesticide Manufacture, Distribution and Use.* Energy in World Agriculture 2. Energy in Plant Nutrition and Pest Control. Helsel ed. Elsevier, 1987.

Hood, C. F. & Kidder, G. 1992. *Fertilizers and Energy.* University of Florida, Institute of Food and Agricultural Sciences. Florida Cooperative Extension Service, Fact Sheet EES-58. Florida, 1992.

IFIAS, 1974. IFIAS: International Federation of Institutes of Advanced Study. Workshop reports *Energy Analysis*, report no. 6, 1974 and *Energy Analysis and Economics*, report no. 9, 1975.

Johansson, Thomas B. Lönnroth, Måns. 1975. *Energianalyser - en introduktion.* Framtidsstudien Energi och samhälle. Stockholm, 1976.

Kemikalieinspektionen. 1995. *Kemikalieinspektionens förteckning över Bekämpningsmedel m.m.* Stockholm, 1995.

Kristoferson, L & Nilsson, S. 1976. *Ambio*, vol. 5, p. 27, 1976.

Ledin, S. 1996. *Willow Wood Properties, Production and Economy.* Biomass and Bioenergy, 11, pp. 75-83. 1996.

Malmö Hus Läns Hushållningssällskap. 1995. *Bidragskalkyler -95.* Malmö Hus Läns Hushållningssällskap, Bjärred, 1995.

Månsson, B Å. McGlade, J M. 1993. *Ecology, thermodynamics and H. T. Odum's conjectures.* Oecologia no. 93, pp. 592-596.

Norén, Olle. 1994. *Eldning med rapsolja.* JTI-report no. 195. Swedish Institute of Agricultural Engineering. Uppsala, 1994.
Odum, H T. 1996. *Environmental Accounting.* John Wiley & Sons. 360p

Odum, H. T. 1988. *Self-Organization, Transformity, and Information.* Science, volume 242, pp. 1132-1139.

Odum, H T. 1984. *Energy analysis of the Environmental Role in Agriculture.* Energy and agriculture (ed. G. Stanhill), pp. 25-51. Springer-Verlag. Berlin, Germany (1984).

Odum, H T. 1983. *Systems Ecology - An Introduction.* John Wiley & Sons, 1983.

Prax, Olev. 1993:a. *Eldning med rörflenspelletter och spannmål i mindre förbränningsanläggningar. (Combustion of Reed Canary Grass and Grain in small Furnaces; Summary in English.)* Special Report nr 197. Swedish University of Agricultural Sciences, Department of Farm Buildings. Lund, 1993.

Prax, Olev. 1993:b. *Eldningsförsök med Rapsexpeller.* (Summary in English) Swedish University of Agricultural Sciences, Department of Farm Buildings. Lund, 1993.

Sonesson, Ulf. 1993. *Energianalyser av biobränslen från höstvete, raps och salix (Energy Analysis of Biofuels from Winter wheat, Rape seed and Salix; Summary in English).* Report, 174. Swedish University of Agricultural Sciences, Department of Agricultural Engineering. Uppsala, 1993.

Szargut, Jan. Morris, David R. Steward, Frank R. 1988. *Exergy analysis of thermal, chemical, and metallurgical processes.* Springer-Verlag. Berlin, 1988.

Szargut, Jan. 1980. *International Progress in Second Law Analysis.* Energy, 5 (8/9), pp. 709-718. 1980.

Tillman, A-M. Lundström, H. Svingby, M. 1996. *Livscykelanalys av alternativa avloppssystem i Bergsjön och Hamburgsund. Delrapport från ECOGUIDE-projektet.* Rapport 1996: 1b, Databilaga. Department of Technical Environmental Planning, Chalmers University of Technology. Gothenburg, 1996.

Wall, Göran. 1990. *Exergy Conversion in the Japanese Society.* Energy vol 15, No. 5, pp. 435-444. Great Britain, 1990.

Wall, Göran. 1986. *Exergy - a Useful Concept.* Thesis, Chalmers University of Technology. Gothenburg, 1986.

Wall, Göran. 1977. *Exergy - a Useful Concept within Resource Accounting.* Report no. 77-42 Inst of Theoretical Physics. Chalmers University of Technology and University of Gothenburg. Gothenburg, 1977.

## 7.2 Personal communications

Ledin, Stig. 1996.
Lundén, Fredrik. 1996.

# APPENDIX

# 8 APPENDIX

## 8.1 Appendix 1. Energy, exergy, and EMERGY use for manufacturing

### *8.1.1 Chemicals*

#### *8.1.1.1 Arelon*

The active ingredient in Arelon is Isoproturon, 500 g/liter (Kemikalieinspektionen, 1995). The energy use for manufacturing has been calculated as an average of all herbicides according to Green (1987). This gives the total energy amount used for Isoproturon manufacturing to 269 GJ/ton active ingredient. The manufacturing mainly uses electricity with a quality factor of 1.00 (Wall, 1977) and a transformity of 2.0E5 sej/J (Odum, 1984).

This information gives following values for manufacturing of Arelon:

- Energy use is approximately 135 MJ/l.
- Exergy use is thus approximately 135 MJ/l.
- The transformity is approximately 2.69E+13 sej/l.

#### *8.1.1.2 Cougar*

The active ingredient in Cougar are Isoproturon, 500 g/liter, and Diflufenican, 100 g/liter (Ericsson et al., 1995). The energy use for manufacturing of the active ingredients has been calculated as an average of all herbicides according to Green (1987). This gives the total energy amount used for both Isoproturon and Diflufenican manufacturing to 269 GJ/ton active ingredient. The manufacturing mainly uses electricity with a quality factor of 1.00 (Wall, 1977) and a transformity of 2.0E5 sej/J (Odum, 1984).

These assumption gives:

- The energy use for manufacturing of Cougar to 161 MJ/l.
- The exergy use for manufacturing of Cougar to 161 MJ/l.
- The transformity for Cougar is 3.22E+13 sej/l.

#### *8.1.1.3 Decis*

The active ingredient in Decis is Deltametrin, 25 g/liter (Ericsson et al., 1995). The energy use for manufacturing has been calculated as an average of all insecticides according to Green (1987). This gives the total energy amount used for Deltametrin manufacturing to 249 GJ/ton. The manufacturing mainly uses electricity with a quality factor of 1.00 (Wall, 1977) and a transformity of 2.0E5 sej/J (Odum, 1984).

This information gives following values for manufacturing of Decis:

- Energy use is approximately 6.2 MJ/l.
- Exergy use is thus approximately 6.2 MJ/l.
- The transformity is approximately 1.24E+12 sej/l.

*8.1.1.4 Gardoprim*

The active ingredient in Gardoprim is Terbuthylazine (Kemikalieinspektionen, 1995). The manufacturing mainly uses electricity with a quality factor of 1.00 (Wall, 1987) and a transformity of 2.00E+5 sej/J (Odum, 1984). The energy use for manufacturing has been calculated as an average of all herbicides according to Green (1987). This gives the total energy amount used for Terbuthylazine manufacturing to 269 GJ/ton active ingredient.

Gardoprim has a density of 1.10 kg/l and contens mainly a mixture of water and Terbuthylazine (Lundén, 1996). The content of Terbuthylazine is 490 g/l (Kemikalie-inspektionen, 1995) and the amount of water is consequently 0.61 kg/l (1.10-0.490).

Thus the:

- energy use for manufacturing is approximately 132 MJ/l.
- exergy use for manufacturing is approximately 132 MJ/l.
- The transformity is approximately 2.64E+13 sej/l.

*8.1.1.5 Mantrac*

- The energy use for manufacturing is approximately 101.5 MJ/l (Andersson, 1981).
- Thus the exergy use for manufacturing is approximately 101.5 MJ/l.
- The transformity is 2.03E+13 sej/l.

*8.1.1.6 Roundup*

The active ingredient in Roundup is Glyphosate (Ericsson et al., 1995). According to Green (1987), the total energy use for Glyphosate manufacturing is 461 GJ/ton. Roundup Bio has a density of 1.17 kg/l and consists largely of a mixture of water and Glyphosate (Lundén, 1996). The content of Glyphosate is 360 g/l (Ericsson et al., 1995) and the amount of water is therefore 0.81 kg/l (1.17-0.360).

The manufacturing is mainly done using electricity (Green, 1987). Electricity has a quality factor of 1.00 (Wall, 1977) and a transformity of 2.00E5 sej/J (Odum, 1984).

This information gives the:

- energy use for manufacturing to approximately 166 MJ/liter
- exergy use for manufacturing to approximately 166 MJ/liter
- The transformity is approximately 3.32E13 sej/liter

*8.1.1.7 Starane*

The active ingredient in Starane is Fluroxypyr, 180 g/liter (Kemikalieinspektionen, 1995). The energy use for manufacturing of the active ingredient has been calculated as an average of all herbicides according to Green (1987), the total energy amount used for manufacturing of Fluroxypur being 269 GJ/ton active ingredient. The manufacturing is largely done using electricity with a quality factor of 1.00 (Wall, 1977) and a transformity of 2.0E5 sej/J (Odum, 1984).

These assumptions give:

- The energy use for manufacturing is 48 MJ/l.
- The exergy use for manufacturing is 48 MJ/l.
- The transformity is 9.60E+12 sej/l.

*8.1.1.8 Sumi-alpha 5 FW*

The active ingredient in Sumi-alpha 5 FW is Esfenvalerate, 50 g/l (Kemikalie-inspektionen, 1995). The energy use for manufacturing of the active ingredient has been calculated as an average of all insecticides according to Green (1987), the total energy amount used for manufacturing of Esfenvalerate being 249 GJ/ton active ingredient. The manufacturing foremost uses electricity, with a quality factor of 1.00 (Wall, 1977) and a transformity of 2.0E5 sej/J (Odum, 1984).

These assumptions give:

- The energy use for manufacturing is 12 MJ/l.
- The exergy use for manufacturing is 12 MJ/l.
- The transformity is 2.40E+12 sej/l.

*8.1.1.9 Tilt Top*

The active ingredient in Tilt Top are Fenpropimorph, 375 g/l and Propiconazol, 125 g/liter, (Ericsson et al., 1996). The energy use for manufacturing of the active ingredients has been calculated as an average of all fungicides according to Green (1987). This gives the total energy amount used for both Fenopropimorph and Propiconazol manufacturing to 170 GJ/ton active ingredient. The manufacturing foremost uses electricity with a quality factor of 1.00 (Wall, 1977) and a transformity of 2,0E5 sej/J (Odum, 1984).

These assumptions give:

- The energy use for manufacturing is 85 MJ/l.
- The exergy use for manufacturing is 85 MJ/l.
- The transformity is 1.70E+13 sej/l.

***8.1.2 Fertilizers***

Nitrogen fertilizer manufacturing is a very energy-demanding process. Depending on technology and type of nitrogen the energy use for manufacturing may vary widely. In this scenario, the assumption is made that the used nitrogen is ammonium nitrate. Natural gas is mostly used for manufacturing and the amount is about 50.3 MJ/kg nitrogen (Tillman et al., 1996). Natural gas has a quality factor of 0.95 which gives the exergy use for production to 47.8 MJ/ha. According to Odum (1996), the transformity for ammonia fertilizer is 3.8E+09 sej/g and since there is 82% nitrogen in the ammonia fertilizer, the transformity for nitrogen is 4.63E+12 sej/kg.

In this scenario, superphosphate is used. Superphosphate is manufactured from raw phosphate which, together with sulphuric acid, makes phosphoric acid which then reacts to form super phosphate. The total energy use for superphosphate manufacturing is 16.6 MJ/kg P (Hood and Kidder, 1992) and it is foremost oil with a quality factor of

0.95. Thus, the exergy use for superphosphate production is 15.8 MJ/kg. The transformity for phosphate fertilizers is 1.78E+13 sej/kg (Odum, 1996).

Potassium fertilizers are made from potassium chloride or different clay minerals. The energy use for manufacturing is 5.0 MJ/kg K and it is foremost oil that is used in the process, which is why the exergy use is 4.8 MJ/kg. According to Odum (1996), the transformity for potassium is 1.74E+12 sej/kg.

The energy and exergy demands mentioned earlier versus transformities for fertilizer manufacturing, give the following data for some fertilizers, see table 1.

**Table 8.1.** Energy use, exergy use (MJ/kg) and transformities (sej/kg) for some ordinary fertilizers

| Fertilizer | Energy use for manufacturing | Exergy use for manufacturing | Transformity |
|---|---|---|---|
| PK 11-21 | 2.88 | 2.75 | 2.32E+12 |
| NPK 20-5-9 | 11.3 | 10.8 | 2.16E+12 |
| N 28 | 14.1 | 13.4 | 1.30E+12 |
| Calcium nitrate 15.5% | 7.80 | 7.41 | 7.18E+11 |

### *8.1.3 Other*

#### *8.1.3.1 Diesel*

Diesel has an high heating value of 37.8 MJ/l and its quality factor is 0.95 (Wall, 1977) which gives an exergy content of 35.9 MJ/l. The transformity for diesel oil is 6.60E+4 sej/J (Odum, 1996). The energy use for production and manufacturing of diesel oil has not been taken into consideration in the calculations.

#### *8.1.3.2 Cuttings*

The energy use for production of cuttings is 16.2 MJ/kg (Sonesson, 1993).

#### *8.1.3.3 Seed*

The energy use for manufacturing of winter rape seed is, according to Sonesson (1993), 26 MJ/kg and the energy use for winter wheat seed production is 16.0 MJ/kg.

#### *8.1.3.4 Lime*

According to Tillman et al. (1996), the energy use for manufacturing of lime is 0.17 MJ/kg. Lime is made from fossil energy which is why the quality factor for production is 0.95. Thus, the exergy use for manufacturing is 0.16 MJ/kg.

## 8.2 Appendix 2. Footnotes for EMERGY analysis

**Table 8.2.** Footnotes to EMERGY analysis of a Swedish salix cultivation

| Footnote | | Comments | Input per hectare | Transformity (sej/Unit) |
|---|---|---|---|---|
| | **Environment** | | | |
| 1 | Sun | production area * average radiation from sun * (1-medium albedo) =1 (ha) * 10000 ($m^2$) * 85.4 (cal/$cm^2$/year) * 4186 (J/kcal) * 1E+4 ($cm^2/m^2$) * (1-0.28) = 2.57E+13 * 25 | 6.425E+14 J | 1.00 |
| 2 | Wind, kinetic energy | (the vertical gradient of wind)$^2$ * height of atmospheric boundary * production area * density of air * Eddy diffusion coefficient * sec./year = (2.7 [m/s] / 1000[m])$^2$ * 1000 [m] * 1 [ha]* 1E+4[$m^2$/ha] * 1.23 [kg/$m^3$] * 25 [$m^2$/s] * 31.54E+6 [s/year] = 7.07E10 * 25 | 1.768E+12 J | 1.50E+03 |
| 3 | Rain, evapotranspiration | production area * amount of rain * "evapotranspiration" * Gibb's free energy = 1[ha] * 1E+4[m2/ha] * 0,8[m] * 0,49 * 4940[J/kg] * 1000[kg/m3] = 1.94E+10 * 25 | 4.85E+11 J | 1.82E+04 |
| 4 | Total | Only the biggest is taken into consideration, then they all are calculatedfrom each other. The biggest will include all the other environmental contributions. | J | 1.82E+04 |
| | **Chemicals** | | | |
| 5 | Roundup | Active ingredient: Glyphosate (Kemikalieinspektionen, 1995). Total energy use for Glyphosate manufacturing is 461 GJ/ton and made foremost using electricity (Green, 1987). Transformity for electricity is 2.0E5 sej/J (Odum, 1996). The content of Glyphosate in Roundup is 360 g/l (Kemikalieinspek-tionen, 1995) | 24 l | 3.32E+13 |

| | | | | |
|---|---|---|---|---|
| 6 | Gardoprim | Active ingredient: Terbuthylazine, 490 g/l (Kemikalieinspektionen, 1995). Energy use in manufacturing is calculated as an average of all herbicides according to Green (1987), which gives a total energy of 269 GJ/ton active ingredient and it is foremost electricity. Transformity for electricity is 2.0E5 sej/J (Odum, 1996). | 5 l | 2.64E+13 |
| | **Fertilizer** | | | |
| 7 | Nitrogen | Ammonia fertilizer a the transformity of 3.8E+09 sej/g (Odum, 1996). The nitrogen content in ammonia is 82%. | 1 665 000 g | 4.63E+09 |
| 8 | Phosphate | Phosphate formation and mining in Florida: Forming and mining 200 kg 10% Phosphorus rock after its concentration from 2000 kg original limestone marl by percolation of organic-rich swamp waters.(Odum, 1996). | 19 800 g | 1.78E+10 |
| 9 | Potash | Potassium chloride from Dead Sea works in Israel. Emergy based on solar energy of evaporating water, energy in dry air, fresh water in processing, fuel, electricity, services and hydrostatic head of water in processing (Odum, 1996). | 37 800 g | 1.74E+09 |
| | **Other** | | | |
| 10 | Cuttings | Assumed price for cuttings is 0.33 SEK/pce. Transformity for price is 2.40E+11 sej/SEK. | 18 000 pce. | 7.92E+10 |
| 11 | Fuel | Liquid motor fuel has the transformity 6.60E4 sej/J (Odum, 1996) | 632 l | 2.49E+12 |
| 12 | Machinery | 1.98E+09 sej/g(Odum. 1984) | 44.48 kg | 1.98E+12 |
| 13 | Labour | Assumed salary is 110 SEK/h. Transformity for price is 2,40E11 sej/SEK. | 22.89 h | 2.64E+13 |
| 14 | Service | Cuttings: 5940 SEK. Fertilizer: PK-2.11 SEK/kg, N28-2.08 SEK/kg, thus 12747 SEK. Roundup: 3456 SEK. Gardoprim: 720 SEK. Fuel: 2654 SEK. Maintenance: 800 SEK. Salary: 2530 SEK. Machinery: 3500 SEK | 28847 SEK | 2.40E+11 |

**Table 8.3.** Footnotes to EMERGY analysis of a Swedish winter wheat cultivation

| Footnote | | Comments | Input per hectare | Transformity (sej/Unit) |
|---|---|---|---|---|
| | **Environment** | | | |
| 1 | Sun | production area * average radiation from sun * (1-medium albedo) = 1 (ha) * 10000 ($m^2$) * 85.4 (cal/$cm^2$/year) * 4186 (J/kcal) * 1E+4 ($cm^2/m^2$) * (1-0.28)= 2.57E+13 * 25 | 2.57E+13 J | 1.00 |
| 2 | Wind, kinetic energy | (the vertical gradient of wind)$^2$ * height of atmospheric boundary * production area * density of air * Eddy diffusion coefficient * sec./year = (2.7[m/s] / 1000[m])$^2$ * 1000 [m] * 1 [ha]* 1E+4[$m^2$/ha]* 1.23 [kg/$m^3$]* 25 [$m^2$/s] * 31.54E+6 [s/year] = 7.07E+10 * 25 | 7.07E+10 J | 1.50E+03 |
| 3 | Rain, evapotranspiration | production area * amount of rain * "evapotranspiration" * Gibb's free energy = 1[ha] * 1E+4[$m^2$/ha] * 0.8[m] * 0.49 * 4940[J/kg] * 1000[kg/$m^3$] = 1.94E+10 * 25 | 1.94E+10 J | 1.82E+04 |
| 4 | Total | Only the biggest is taken into consideration then they are calculated out from each other. The biggest will include all the other environment contribution. | | |
| | **Fertilizers** | | | |
| 5 | Nitrogen | Ammonia fertilizer has a transformity of 3.8E+09 sej/g (Odum, 1996). The nitrogen content in ammonia is 82%. | 140 kg | 4.63E+12 |
| 6 | Phosphorus | Phosphate formation and mining in Florida: Forming and mining 200 kg 10% Phosphorus rock after its concentration from 2000 kg original limestone marl by percolation of organic-rich swamp waters (Odum, 1996). | 20 kg | 1.78E+13 |
| 7 | Potassium | Potassium chloride from Dead Sea works in Israel. Emergy based on solar energy of evaporating water, energy in dry air, fresh water in processing, fuel, electricity, services and hydrostatic head of water in processing (Odum, 1996). | 38 kg | 1.74E+12 |

| | | | | |
|---|---|---|---|---|
| | **Chemicals** | | | |
| 8 | Herbicide | The herbicide is made out of 1 liter Arelon, 0.5 liter Cougar and 0.4 liter Starane. The transformity for Arelon is 2.69E+13 sej/l, the transformity for Cougar is 3.22E+13 sej/l, and the transformity for Starane is 9.60E+12 sej/l, see appendix 2. | 1.9 l | 2.60E+13 |
| 9 | Insecticide | The insecticide used is Sumi-alpha, with a transformity of 2.40E+12 sej/l, see appendix 2. | 0.3 l | 2.60E+13 |
| 10 | Fungicide | The fungicide is made out of 0.8 liter Tilt Top and 0.5 liter Mantrac. The transformity for Tilt Top is 1.70E+13 sej/l, and the transformity for Mantrac is 2.03E+13 sej/l, see appendix 2. | 1.3 l | 2.60E+13 |
| 11 | Roundup | The transformity for Roundup is 3.32E13 sej/liter. | 0.6 l | 3.32E+13 |
| 12 | Lime | Limestone with 18% CaO has a transformity of 1.0E+9 (Odum, 1996). | 143 kg | 5.56E+09 |
| | **Other** | | | |
| 13 | Seed | Calculated from the price which is 2.90 SEK/kg. The transformity for price is 2.40E+11 sej/SEK (Odum, 1996). | 170 kg | 6.96E+11 |
| 14 | Fuel | Liquid motor fuel has a transformity of 6.60E+4 sej/J (Odum, 1996). Diesel = 37.8 MJ/l, thus 2.49E12 sej/l | 73 liter | 2.49E+12 |
| 15 | Machinery | According to Malmö Hus Läns Hushållningssällskap margin costs (1995), the costs for machinery are maintenance = 805 SEK and fixed costs = 1566 SEK = total 2371 SEK. The transformity of SEK is 2.40E+11 sej (Odum, 1996). | 2371 SEK | 2.40E+11 |
| 16 | Labour | Assumed salary is 110 SEK/h. Transformity for price is 2.40E11 sej/SEK (Odum, 1996), thus 2.64E13 sej/h | 11 h | 2.64E+13 |
| 17 | Service | | 7249 SEK | 2.40E+11 |

**Table 8.4.** Footnotes to EMERGY analysis of a Swedish winter rape cultivation

| Footnote | | Comments | Input per hectare | Transformity (sej/Unit) |
|---|---|---|---|---|
| | **Environment** | | | |
| 1 | Sun | production area * avarange radiation from sun * (1-medium albedo) = 1 (ha) * 10000 ($m^2$) * 85.4 ($cal/cm^2/year$) * 4186 (J/kcal) * 1E+4 ($cm^2/m^2$) * (1-0.28)= 2.57E+13 * 25 | 2.57E+13 J | 1.00 |
| 2 | Wind, kinetic energy | (the vertical gradient of wind)$^2$ * height of atmospheric boundary * production area * density of air * Eddy diffusion coefficient * sec./year = (2.7[m/s] / 1000[m])$^2$ * 1000 [m] * 1 [ha]* 1E+4[$m^2$/ha]* 1.23 [kg/$m^3$]* 25 [$m^2$/s] * 31.54E+6 [s/year] = 7.07E10 * 25 | 7.07E+10 J | 1.50E+03 |
| 3 | Rain, evapotranspiration | production area * amount of rain * "evapotranspiration" * Gibb's free energy = 1[ha] * 1E+4[m2/ha] * 0.8[m] * 0.49 * 4940[J/kg] * 1000[kg/m3] = 1.94E10 * 25 | 1.94E+10 J | 1.82E+04 |
| 4 | Total | Only the biggest is taken into consideration, then they are calculated out from each other. The biggest will include all the other environmental contributions. | | |
| | **Fertilizers** | | | |
| 5 | Nitrogen | Ammonia fertilizer has the transformity 3.8E+09 sej/g (Odum, 1996). The nitrogen content in ammonia is 82%. | 185 kg | 4.63E+12 |
| 6 | Phosphorus | Phosphate formation and mining in Florida: Forming and mining 200 kg 10% P rock after its concentration from 2000 kg original limestone marl by percolation of organic-rich swamp waters (Odum, 1996). | 15 kg | 1.78E+13 |
| 7 | Potassium | Potassium chloride from Dead Sea works in Israel. Emergy based on solar energy of evaporating water, energy in dry air, fresh water in processing, fuel, electricity, services and hydrostatic head of water in processing (Odum, 1996). | 29 kg | 1.74E+12 |

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|---|---|---|---|---|
| | **Chemicals** | | | |
| 8 | Herbicide | The used herbicide is Butisan with a transformity of 2.60E+13 sej/l. | 2.0 l | 2.60E+13 |
| 9 | Insecticide | The insecticide used is made out of 0.2 l Decis Autumn + 0.2 l Decis Spring + 0.5 l Mantrac | 0.90 l | 2.60E+13 |
| 10 | Roundup | Every 5th year: 3 l Roundup Bio + 0.3 l Lissapol Bio. Transformity for Roundup is 3.32E+13 sej/liter, and the transformity for Lissapol Bio is 2.60E+13 sej/l. See appendix 2. | 0.66 l | 3.32E+13 |
| 11 | Lime | Limestone with 18% CaO has a transformity of 1.0E+9 (Odum, 1996). | 143 kg | 5.56E+09 |
| | **Other** | | | |
| 13 | Seed | Calculated from a price of 45.00 SEK/kg (Malmö Hus Läns Hushållningssällskap, 1995). The transformity for price is 2.40E+11 (Odum, 1996). | 6.5 kg | 1.08E+13 |
| 14 | Fuel | Liquid motor fuel has a transformity of 6.60E+4 sej/J (Odum, 1996). Diesel = 37.8 MJ/l, thus 2.49E+12 sej/l | 78 liter | 2.49E+12 |
| 15 | Machinery | According to Malmö Hus Läns Hushållningssällskap marginal costs (1995). the costs for machinery are maintenance which is 805 SEK and fixed costs which is 1566 SEK = total 2371 SEK. The transformity for SEK is 2.40E+11 sej (Odum, 1996). | 2 371 SEK | 2.40E+11 |
| 16 | Labour | Assumed salary is 110 SEK/h and the transformity for price is 2.40E11 sej/SEK (Odum, 1996), thus 2.64E13 sej/h. | 10 h | 2.64E+13 |
| 17 | Service | | 7434 SEK | 2.40E+11 |