UPTEC STS07 010
Examensarbete 20 p
Mars 2007

Emergy evaluation of a Swedish nuclear power plant

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Abstract

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Today it is common to evaluate and compare energy systems in terms of emission of greenhouse gases. However, energy systems should not only reduce their pollution but also give a large energy return. One method used to measure energy efficiency is emergy (embodied energy, energy memory) evaluation, which was developed by the system ecologist Howard T. Odum. Odum defines emergy as the available energy of one kind previously used up directly and indirectly to make a service or product. Both work of nature and work of human economy in generating products and services are calculated in terms of emergy. Work of nature takes the form of natural resources and work of human economy includes labour, services and products used to transform natural resources into something of value to the economy. The quotient between work of nature and work of human economy gives the emergy return on investment of the investigated product. With this in mind the present work is an attempt to make an emergy evaluation of a Swedish nuclear power plant to estimate its emergy return on investment.

The emergy return on investment ratio of a Swedish nuclear power plant is calculated to approximately 11 in this diploma thesis. This means that for all emergy the Swedish economy has invested in the nuclear power plant it gets 11 times more emergy in return in the form of electricity generated by nuclear power. The method used in this work may facilitate future emergy evaluations of other energy systems.

Handledare: Michael Österlund
Ämnesgranskare: Jan Blomgren
Examinator: Elísabet Andrésdóttir
ISSN: 1650-8319, UPTEC STS07 010

Populärvetenskaplig sammanfattning

Den allmänna debatten handlar idag ofta om att energisystem ska ha så låga utsläppshalter av växthusgaser som möjligt. Resurser läggs på att forska om och utveckla nya energisystem som uppfyller dessa önskemål. Dock finns även andra viktiga aspekter. En av dessa är energieffektivitet. I takt med att världen fortsätter att utvecklas ökar energibehovet. Det är därför nödvändigt att energisystemen ger en hög behållning energimässigt.

Det hitintills vanligaste sättet att utvärdera och jämföra energisystem är att göra s.k. energianalyser, ibland i kombination med kostnadskalkyler. En alternativ metod är emergianalysen (emergi = embodied energy, energy memory). Den utvecklades av systemekologen Howard T. Odum, som menade att resultaten som fås av energianalyser och kostnadsanalyser är missvisande. Odum definierade emergi som den ackumulerade mängd resurser som åtgått för att producera en vara, tjänst eller ett bränsle. Alla resurser är omräknade till en enhet som grundar sig på en gemensam energikälla.

Emergianalysen skiljer sig från övriga analyser genom att inta ett systemperspektiv där både arbete uträttat av naturen och människan räknas med i den totala energianvändningen. Arbete uträttat av naturen kan bestå av naturresurser och arbete från den mänskliga ekonomin av den arbetskraft samt de tjänster och produkter som krävs för att kunna omvandla naturresurserna till något som är användbart i samhället. För att mäta hur energieffektivt ett system eller en produkt är divideras emergin som fås från naturen med emergin från den mänskliga ekonomin. Kvoten är då förhållandet mellan emergivinsten från naturen och emergikostnaden eller investeringen från ekonomin. Utmärkande för emergianalysen är också att energier kvalitetsvägs genom att de tilldelas transformiteter. Enligt Odum är det felaktigt att t.ex. en enhet biomassa räknas likvärdig en enhet fossilt bränsle eller en enhet elektricitet, eftersom de har olika potential att uträtta nyttigt arbete.

Syftet med detta examensarbete har varit att göra en emergianalys av ett svenskt kärnkraftverk för att på så sätt undersöka förhållandet mellan emergivinst och gjord investering. För att kunna göra detta har kärnkraftsprocessen undersökts, från utvinning av uran i gruvan till slutförvar av radioaktiva restprodukter. Därefter har kärnkraftsprocessen delats upp i olika steg relaterade till förädling, produktion och slutförvar. För respektive steg har emergin aggregerats i grupperna bränsleanvändning, elektricitetsförbrukning och kostnader. Kostnader är i sin tur uppdelade på drift- och underhållskostnader, kapitalkostnader, transportkostnader och avvecklingskostnader för en del av stegen i kärnkraftsprocessen. Data har samlats in från rapporter, livscykelanalyser, informationssidor på internet samt från personer som arbetar inom kärnkraft.

Resultatet av emergianalysen är ett förhållande mellan emergivinst och investering på ca 11. Det innebär att för varje emergijoule den mänskliga ekonomin behöver investera fås 11 emergijoule tillbaka. Metoden som använts i detta examensarbete skulle eventuellt kunna utgöra en bas för framtida emergianalyser av andra energisystem.

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1 Introduction

Today there is a great focus on climate changes caused by emission of CO_2 and other greenhouse gases. Important steps are taken concerning research, development and implementation of new energy systems with reduced or no emission of these gases. However, it is also important to take other aspects into consideration when energy systems are to be compared and evaluated. As the world continues to develop, there are increasing demands for energy, which makes an extended energy supply necessary. Therefore, energy systems should not only reduce their pollution but also give a large energy return.

In 1974 the International Federation of Institutes for Advanced Study (IFIAS) arranged a workshop in Stockholm where a standardised methodology for energy analysis was established [1]. Since then, evaluations of the efficiency of energy systems are usually made by energy analyses supplemented by cost analyses. However, the system ecologist Howard T. Odum found the results of these analyses misleading. He argued that the energy analysis does neither account for differences in energy quality - an energy unit of biomass counts equal to an energy unit of fossil fuel or electricity - nor does it take all indirect energy in capital and labour into consideration. Standard economics on the other hand, deals with labour and capital but considers the work of nature as free, although the whole economy basically is dependent on natural resources. Odum developed emergy evaluation to overcome these weaknesses [2].

In emergy evaluation, nature and human economy are viewed as parts of an interconnected system where both work of nature and human labour in generating products and services are measured in terms of emergy. Odum defines emergy as “the available energy of one kind [of] previously used up directly and indirectly to make a service or product” [2].

By making an emergy evaluation of a system or a product its emergy return on investment ratio (*I/F*) can be calculated. This is a ratio between emergy input from nature (*I*) and emergy feedback from the economy (*F*). In an emergy evaluation of a nuclear power plant, the emergy in uranium corresponds to the input from nature while the emergy in all production steps, from extraction of uranium to management of the nuclear waste corresponds to feedback from the economy.

1.1 Purpose

The purpose of this diploma work is to make an emergy evaluation of a Swedish nuclear power plant in order to estimate its emergy return on investment.

The emphasis is on developing a possible method for applying emergy evaluation on a Swedish nuclear power plant and not on the actual data. The transformities in this diploma work represent *one* possible way of estimating the value of energy in different kinds of work. The emergy evaluation is made on a generic Swedish nuclear power plant, but because a large fraction of the data stems from the Forsmark nuclear power plant, this is the plant most representative to the study.

1.2 Disposition

- Introduction, chapter 1.The topic is introduced as well as a reason for investigating this topic. This is followed by a short presentation of emergy evaluation. The introduction leads to the purpose of the diploma work and to demarcations that have been made.
- Emergy evaluation, chapter 2. The theory behind the emergy evaluation is presented.
- The Swedish nuclear energy process is introduced in chapter 3. To be able to make an emergy evaluation it is necessary to understand the process behind the evaluated product. By understanding the different steps in the process, estimates can be made on what parts involve significant amounts of emergy and therefore are important to include in the evaluation.
- Application of the emergy evaluation, chapter 4. Emergy evaluations have previously been made on nuclear power plants in the USA. The results of two investigations are presented, which show that the results of an emergy evaluation is highly dependent on what has been included in the evaluation. This is followed by an outline on how the emergy evaluation is carried out in this report.
- Data and calculations, chapter 5. This chapter describes how information has been gained, what assumptions have been made and from where data have been obtained.
- Results and observations, chapter 6. The results of the emergy evaluation are presented.
- Sensitivity analysis, chapter 7. Sensitivity analyses are made to investigate how uncertainties in parameters influence the emergy return on investment.
- Emergy return of biomass, chapter 8. The emergy return on investment ratio of a Swedish nuclear power plant is compared with the ratio of biomass.
- Discussion and conclusions, chapter 9. The results of the emergy evaluation and the results of the sensitivity analyses are discussed.
- Appendices. Appendix A describes transformities used in this report. Appendix B contains a table of all data used to calculate the emergy feedback from the economy. Appendix C contains explanations on the symbols used to describe the emergy flow in Figure 3 and Figure 4.

2 Emergy evaluation

The reference of this chapter is Odum [2]. As mentioned in the introduction, emergy evaluation differs from traditional energy analysis in that it views nature and human economy as interacting systems. The interaction is beneficial to the economy mainly because of the natural resources, which can be used as fuels. Natural resources, however, are not given to us humans for free. We need to use tools, labour, fossil fuels, electricity, etc., to extract natural resources and to transform them into usable fuels. As an illustration of the interaction between human economy and nature the following example is given: To be able to use uranium as fuel for electricity generation, inputs of energy are needed to extract, convert, enrich, transport and process the fuel as well as for managing the waste resulting from the process. These inputs of energy can be measured as the emergy the economy has to “feed back”, i.e., invest, to gain emergy from uranium.

To estimate the emergy of a process, such as the nuclear power process, different kinds of energies need to be summed. To be able to sum the energies they have to be expressed in units of the same kind of energy. Odum used the solar emjoules as unit. This means that all kinds of energy are compared in terms of their solar emergy value. In other words, the energies are valued as if they were produced by solar energy. The value of a product is given as the sum of all solar energies that were used directly or indirectly to make this particular product.

An emergy evaluation includes a quality measure of the direct or indirect energies previously used. This quality measure demonstrates Odum’s thought that different kinds of energy are not equivalent in their abilities to result in useful work. Odum finds a quality measure necessary because the scientific concept of energy used today rates one Joule of for example sunlight and nuclear fission as equal. In that way the different levels of prior effort involved in generating different kinds of energy are ignored. By using a quality measure a solution is given to that problem. Odum calls the quality measure “transformity” and defines it as “The EMERGY of one type required to make a unit of emergy of another type.”

The transformity is expressed as the quotient between the emergy required making the product and its energy. The unit Odum uses for the transformity is solar emjoules per Joule (sej/J). The transformity can also be given as the energy of the product divided by its monetary value. Each time additional emergy is added to a product its transformity increases and it is transformed into a more highly developed product in the economy. If most of the emergy comes from nature the emergy return on investment increases, but if most of the emergy is supplied (or fed back) by the economy the emergy return on investment decreases.

An emergy return on investment larger than one would indicate that the emergy received from the investigated system is larger than the emergy the economy had to put into the system to make it work. The larger values of the emergy return on investment ratio the better for the economy. For an energy system, which must support more than its own system an emergy return on investment ratio larger than one is necessary. If the ratio of an energy system is lower than one the system has to be subsidized from other parts of the economy in order to work. Another way of estimating the energy return is to use the energy yield ratio, $Y/F = (I+F)/F$, where I = emergy input from nature and F = emergy feedback from the economy. Because the I/F ratio of an energy system has to have a value larger than one, the Y/F ratio of an energy system has to have a value larger than two.

2.1 The emergy per unit money index

To calculate transformities for all products involved in a process a wealth of data are needed. These data may, however, be difficult to obtain. To make the emergy evaluation more manageable Odum introduced an “emergy per unit money” index, which is a measure of the buying power of money. The emergy per unit money index is a transformity used to calculate emergy in labour and work related to production; data that are usually provided in a monetary unit instead of joules. The advantage of the index is that it is usually easier to find data about economy than to find data of emergy in, e.g., labour. To calculate the emergy per unit money index the total emergy use in a country during one year is divided by the Gross Domestic Product (GDP) of the same country the same year. The value of the index can differ from one year to another and from one country to another [2].

3 The Swedish nuclear power process

The creation of electricity from nuclear fission is a process involving not only the nuclear power plant but also facilities and people in other parts of the country as well as internationally. The different steps in the nuclear energy process are shown in Figure 1 below and described in the following text.

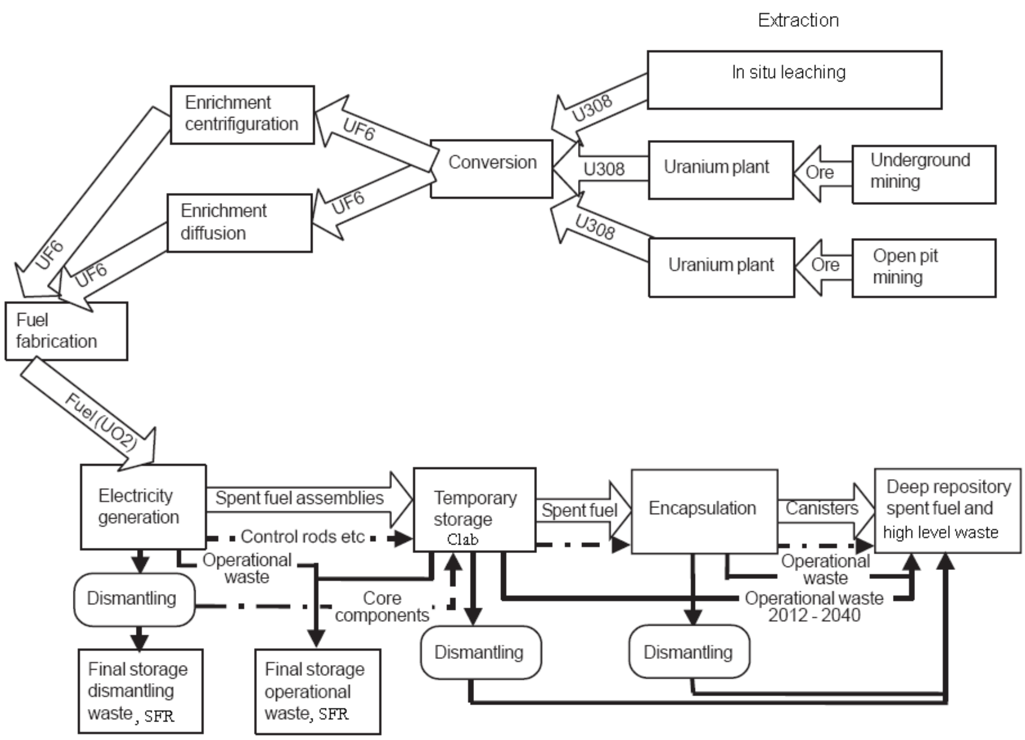

Figure 1. The nuclear energy process from extraction of uranium to deep repository of radioactive waste [4]. Slightly modified by the author.

3.1 Fission

In Swedish nuclear power plants the generation of electricity takes place in light water reactors, which are either boiling water reactors (BWR) or pressurized water reactors (PWR). These two reactor types are by far the most common worldwide. In this diploma work the nuclear power plant contains boiling water reactors.

In a light water reactor (LWR), distilled water is used as coolant and moderator. The purpose of the moderator is to slow down the free neutrons in the reactor to increase their ability to split, or fission, U-235 nuclei [5]. The fission of a U-235 nucleus results in the production of two lighter fission fragments, 2.43 neutrons on the average and releases 200 MeV ($3.22*10^{-13}$ J) energy. As a rule of thumb the fissioning of 1g of U-235 produces approximately 23 400 kWh. This can be compared with combustion of $1m^3$ of oil, which releases approximately 10 000 kWh. The released neutrons split new U-235 nuclei and a chain reaction is created. In nuclear power reactors the fission process is controlled so that exactly one of the released neutrons causes another fission. This results in a steady-state chain reaction with a constant power output.

The energy released in the process heats the cooling water in the reactor system (see Figure 2 below). When passing the steam turbine the heat is transformed into kinetic energy. A generator connected to the steam turbine transforms the kinetic energy into electricity. After the turbine the steam is condensed in a condenser and is pumped back into the reactor. Approximately 35 % of the heat released in the nuclear reactor can be transformed into electricity in this process [6].

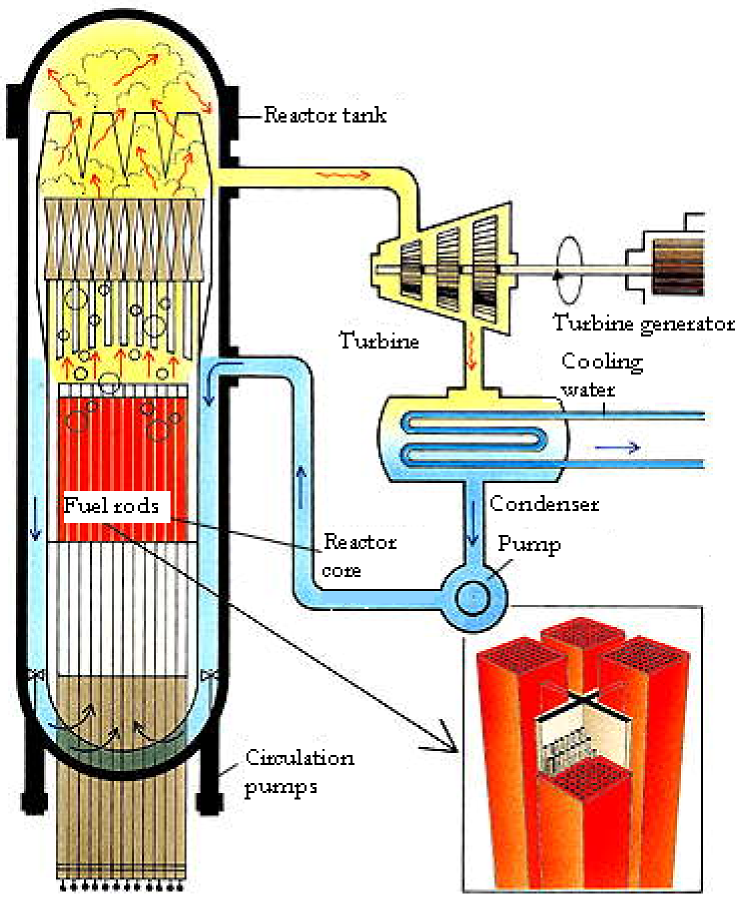

Figure 2. Electricity generation in a boiling water reactor [6]. Slightly modified by the author.

3.2 Extraction of uranium

The fuel used in Swedish light-water reactors is made of uranium, which is a mineral that can be found in the crust or in the sea. Natural uranium consists to 99.3 % of the isotope uranium-238 (U-238) and to 0.7 % of the isotope uranium-235 (U-235). U-235 molecules heavily dominate the release of nuclear energy in a reactor. Uranium is extracted for commercial purposes in more than 15 countries, of which some of the larger exporters are Canada, Australia, Russia, Kazakhstan and Namibia [5].

There are three methods of extracting uranium: open pit mining, underground mining and in situ leaching. Underground mining is the most common method [5]. If mining is used to extract the uranium ore, the ore is thereafter transported to a purification plant where it is crushed, grinded and leached.

When applying in situ leaching a liquid is circulated through porous ore underground. The liquid can be a weak acid or a weak alkaline depending on the density of calcium in the area. Uranium dissolves and is pumped up to the surface where it is extracted from the solvent. Irrespective of the method used for extracting uranium the resulting product is yellow cake (U_3O_8) [7].

3.3 Refinement and conversion

Before yellowcake is converted to a form suitable for enrichment of U-235 it has to be refined from neutron absorbents. This is necessary because remaining neutron absorbers will lower the neutron flux thus impairing the fission process. Yellowcake is refined by adding nitric acid and by vaporising the water through heating. The resulting product is uranium trioxide (UO_3). Thereafter the uranium trioxide is converted to uranium hexafluoride (UF_6) in two steps by adding different fluoride compounds [7].

3.4 Enrichment

After conversion follows enrichment. The purpose of enrichment is to increase the concentration of U-235 from 0.7 % in natural uranium to 3–4 %. The enrichment process is a difficult and energy-intensive activity because the isotopes U-235 and U-238 are similar in weight, U-235 is only 1.26 % lighter than U-238. Enrichment can be done in two ways, centrifugation or diffusion [4].

In the diffusion process uranium hexafluoride gas is forced through a series of porous membranes. Because of its lighter weight molecules containing U-235 diffuse through membranes slightly faster than molecules containing U-238. Thus the part of the gas that diffuses through the membrane is enriched, while the gas that does not pass the membrane is depleted in U-235. The diffusion process has to be repeated approximately 1400 times to reach the concentration of U-235 necessary for LWR nuclear fuel [8].

Most common today is the centrifuge process, because it uses approximately 50 times less electricity than the diffusion process. In the centrifuge process the gas is fed into a series of vacuum tubes, each containing a rotor. The rotors are spun rapidly at 50 000 to 70 000 rpm creating a centrifugal force. As a result of this force the molecules containing U-238 increase in concentration towards the outer edge of the cylinder and the lighter molecules containing U-235 remain in the centre of the cylinder. The UF_6 gas has to continue through a total of 10-20 centrifuge stages to reach the desired enrichment of U-235 [8]. Enrichment facilities are found in several countries. Presently large commercial enrichment plants are in operation in the USA, Russia, Great Britain, France, the Netherlands and Germany.

3.5 Fuel fabrication

The next step in the nuclear energy process is manufacturing of nuclear reactor fuel, which entails the conversion of enriched UF_6 to uranium dioxide (UO_2). There are fuel factories in Sweden and in Germany amongst several other countries. In the fuel factory the solid UF_6 is reheated to gas. Oxygen, hydrogen and ammonia are added, which results in pulverised uranium dioxide. By compressing the UO_2 and by sintering and grinding it fuel pellets are made, which are then encased in metal tubes forming fuel rods. The last step in the nuclear fuel manufacturing is to assemble the fuel rods into a fuel assembly. A typical boiling water reactor contains 400-700 fuel assemblies, each containing 64-100 fuel rods [7]. A boiling water reactor producing 1100 MW of electricity typically contains 120 tons of fuel. Each year 1/4 - 1/5 of the fuel is replaced with new fuel.

3.6 Waste management

When U-235 nuclei fission highly radioactive substances are created, which is the reason nuclear waste needs to be taken care of and kept as safely as possible. The waste can be categorised into three levels: low-level, intermediate-level and high-level waste, based on the amount of radiation it emits. Low-level waste can either be cleaned from radiation in the nuclear power plant or transported to *Slutförvar för radioaktivt driftavfall* (SFR), which is a low- and intermediate-level waste storage situated close to the Forsmark nuclear power plant. The intermediate-level waste is produced during reactor operation and is stored at SFR. In SFR the waste is kept 50 metres under the sea floor in containers that prevent leakage of radiation [7].

High-level waste consists of spent nuclear fuel and other material containing fission products, e.g., strontium-90 and cesium-137, and actinides, e.g., plutonium-239 and americium-241. After extraction from the reactor core spent nuclear fuel bundles are stored in basins adjacent to the reactor for 9-12 months. Thereafter it is enclosed in containers and transported to *Centralt mellanlager för använt bränsle* (Clab) where it is put in deep basins 30 metres underground. Clab is located close to the Oskarshamn nuclear power plant. After 30 years in basins the radioactivity of the waste has decreased by 90 % [7].

Despite the decrease of radioactivity, the part remaining makes it necessary to store the waste in a place where it does no harm to people or nature. Such a place is not yet built, but research is performed and different alternatives are presently being analysed. The idea in favour is a deep repository in primary rock 500 metres underground. There the waste can be kept until its radiation has decreased to the level of natural uranium, which takes about 100 000 years. Possibly the deep repository will be situated either close to the Forsmark or Oskarshamn nuclear power plants. The deep repository is expected to come into use in 2018 [9].

Before the waste is put in the final storage it will be encapsulated in canisters made of copper with an insert of cast iron. The encapsulation plant will most probably be built close to Clab in Oskarshamn. An application for permission to build this encapsulation plant has recently been submitted to the Swedish government, and the construction will start in 2012 at the earliest [10].

4 Application of emergy evaluation

4.1 Previous studies

Previously emergy evaluations have been performed on nuclear power plants in the USA and on biomass in Sweden [11, 12, 13]. In the USA the application of emergy evaluation on nuclear power has been investigated in at least two studies: “The net-energy yield of nuclear power” written 1986 by Tyner, Constanza and Fowler [12] and “Emergy analysis of the nuclear power system in the United States” by Lapp 1991 [13].

There is a significant difference between the results of the two nuclear power investigations. Lapp [13] obtains three different energy yield ratios (*Y/F*) for nuclear power: 4.6, 5.9 and 6.3 depending on what factors are included in the evaluation. Tyner, et al. obtain energy yields that are close to zero [12]. In 1986 nuclear power was comparatively young and costs were therefore higher. According to Odum this was a result of recently built plants with high interest rates and extensive high-quality services of engineers. The differences in results show that there is no self-evident way of applying emergy evaluation on nuclear power plants. In this work the focus is on formulating and investigating an evaluation method applicable to Swedish nuclear power plants.

4.2 This study

In the present work biomass lays the foundation of the transformities. Therefore the unit used is emergy joule based on biomass, abbreviated J_{emb} (J = Joule, em = emergy, b = biomass). Using biomass as the base for emergy calculations means that all products and services included in the emergy evaluation are measured as if they were made of biomass, or to be more precise, cultivated willow, see Appendix A. The transformity of cultivated willow is 1.00 if it is standing on a field untouched. As soon as something is done to it, e.g., fertilisers are added, its transformity increases. Cultivated willow that has been harvested, chipped and transported to an industry or heating plant has the transformity 1.12 [14]. More information about transformities used in this work is given in Appendix A.

In this thesis all emergies involved in the evaluated product or process are divided into the categories input from nature (*I*) and feedback from the economy (*F*). In other examples given by Odum [2] these two categories are also essential, but other categories and quotients are considered too. For example, the input from nature is divided into free renewable emergy such as sun, wind and rain and to free non-renewable resource emergy from the local environment such as minerals. The emergy of minerals, fuels and raw materials that are brought to an area, i.e., they are not local, make up an own category. This last category is the category to which uranium belongs. By dividing inputs from nature into several categories different ratios for evaluating economic uses of resources can be made. One example is the quotient between purchased emergy and free emergy from the environment. Another example is the quotient between non-renewable and renewable resources.

In this work only the emergy return on investment ratio, *I/F*, and the energy yield ratio, *Y/F*, are calculated. This is because uranium is the only input from nature included in the nuclear power process. However, if an emergy evaluation is made on for example biomass the other ratios, i.e., the quotient between purchased emergy and free emergy from the environment and the quotient between non-renewable and renewable resources may be interesting to include as well. The main ratio in this report is *I/F*. This is because it clearly shows how much emergy was gained from nature in proportion to how much emergy the economy had to invest. The reason *Y/F* is also included is to simplify a comparison between the result of this emergy evaluation and other emergy evaluations, which use the *Y/F* ratio.

5 Data and calculations

In this chapter the method of making an emergy evaluation of the nuclear power process for a generic Swedish nuclear power plant is presented. The nuclear power plant is similar to the Forsmark nuclear power plant, which has three boiling water reactors. The nuclear power process is illustrated in Figure 1.

To summarise the method used, the first task was to read literature about emergy evaluation, both theoretical literature and practical examples on how it has been applied. The nuclear power process, from extraction to deep repository, was also studied. The next step consisted of having conversations with people versed in emergy evaluation and other analyses of use to this work, such as lifecycle assessment, and with people knowledgeable in the nuclear power process and in Swedish nuclear power plants. The data collected for this work have been found in annual reports, lifecycle assessments, information sites on Internet, scientific reports and from personal communication. The nuclear power process was divided into ten steps related to refinement of uranium, electricity generation and storage of nuclear waste. In each step the emergy has been aggregated to the following groups: fuel use, electricity use and costs. In all steps except for those related to refinement of uranium, the costs are divided further into operation and maintenance costs, capital costs, transport costs and decommissioning costs. For the refinement steps a total cost replaces the operation and maintenance, capital and decommissioning costs due to lack of more specific data.

5.1 Calculation of the emergy per unit money index

One of the transformities necessary for the emergy calculations is the emergy per unit money index. This chapter shows how the index was arrived at. Information on the other transformities is given in Appendix A.

The emergy per unit money index is calculated for Sweden in the year 2004 and it is referred to as the J_{emb}/SEK index. This index is used as a transformity for all processes where labour is included and where the data are given in a monetary unit, e.g., operation and maintenance (O&M) and capital costs. When calculating the J_{emb}/SEK index the total emergy use of the Swedish economy is divided by the Swedish gross domestic product (GDP). It is assumed in this work that the total emergy is equal to the emergy of the fuels, which were used in the Swedish economy 2004. These fuels are considered as the emergy necessary to maintain the economy. Table 1 presents the data used in the calculations of the J_{emb}/SEK index. The value of the index is given in row I. In the following notes information is given on how the transformities and other data were found.

Table 1. Data used to calculate the J_{emb}/SEK index.

Energy consumption in Sweden 2004	Quantity	Unit	Energy supply (J/year)	Transformity (J_{emb}/J)	Emergy (J_{emb}/year)
A. Food consumed	42.2	PJ	$4.22 \cdot 10^{16}$	3.8	$1.62 \cdot 10^{17}$
B. Crude oil and oil products	568.1	PJ	$5.68 \cdot 10^{17}$	2.2	$1.25 \cdot 10^{18}$
C. Natural gas	15.8	PJ	$1.58 \cdot 10^{16}$	2.2	$3.49 \cdot 10^{16}$
D. Coal and coke	63.0	PJ	$6.30 \cdot 10^{16}$	2.2	$1.42 \cdot 10^{17}$
E. Raw material from forestry	17.9	Mt_{ts}	$3.59 \cdot 10^{17}$	1.3	$4.67 \cdot 10^{17}$
F. Electricity	472.0	PJ	$4.72 \cdot 10^{17}$	2.9	$1.38 \cdot 10^{18}$
G. Peat	3.2	TWh	$5.47 \cdot 10^{16}$	1.1	$6.15 \cdot 10^{16}$
Total			$1.57 \cdot 10^{18}$		$3.50 \cdot 10^{18}$
H. Gross Domestic Product (GDP) at market prices	$2.57 \cdot 10^{12}$	SEK			
I. Emergy/SEK index (total emergy /GNP)	$1.36 \cdot 10^{6}$	J_{emb}/ SEK			

A. The energy supply in feed and food (42.2 PJ) has been estimated from statistics from the Swedish Board of Agriculture. The transformity of food has been estimated by Nilsson and Ebbersten [15].

B. Consumption data of crude oil and oil products have been obtained from "Energy in Sweden facts and figures" [16]. Crude oil and oil products have been calculated by Nilsson [17]. The calculations are based on data from the doctoral thesis of Hagström [18]. The assumption has been made that crude oil and oil products are equal to methanol produced from woods of willow.

C. The consumption data of natural gas and coal have been obtained from "Energy in Sweden facts and figures" [16]. The transformity of oil has been used on natural gas and coal.

D. See C.

E. Data of consumption of raw material from forestry have been obtained from the statistical yearbook of forestry [19]. 50 % of the raw material from forestry is assumed to make up the part used for energy generation. The transformity of raw material from forestry has been estimated by Nilsson based on data from Doherty et al. [11] and Hagström [18], see Appendix A.

F. Data concerning the use of electricity have been obtained from "Energy in Sweden facts and figures" [16]. The transformity for Salix production has been calculated by Nilsson in consultation with Christersson [14], see Appendix A, Table A3. Transformity for electricity production from biomass is calculated according to Hagström [18, pp. 69-71, 427-431]

G. See F.

H. The value of the Swedish GDP in 2004 was obtained from the website of Statistics Sweden [20].

I. The emergy/SEK index is given by the total emergy use in Sweden 2004 divided by the Swedish GDP 2004. The total emergy use is the sum of the emergies of row A to G.

5.2 Calculation of the nuclear power process

The cycle of uranium plays an important part in this emergy evaluation. This cycle beginning with extraction and ending with deep repository is shown in Figure 3. Each rectangular box in the figure makes up a part of the feedback from the economy *(F)* and is described in chapters 5.2.1 to 5.2.5 below. For the first part of the figure, data on the material flow have been available. These data have been used to calculate emergy of the first four steps of the nuclear power process. A detailed description of the symbols used in the figure can be found in Appendix C.

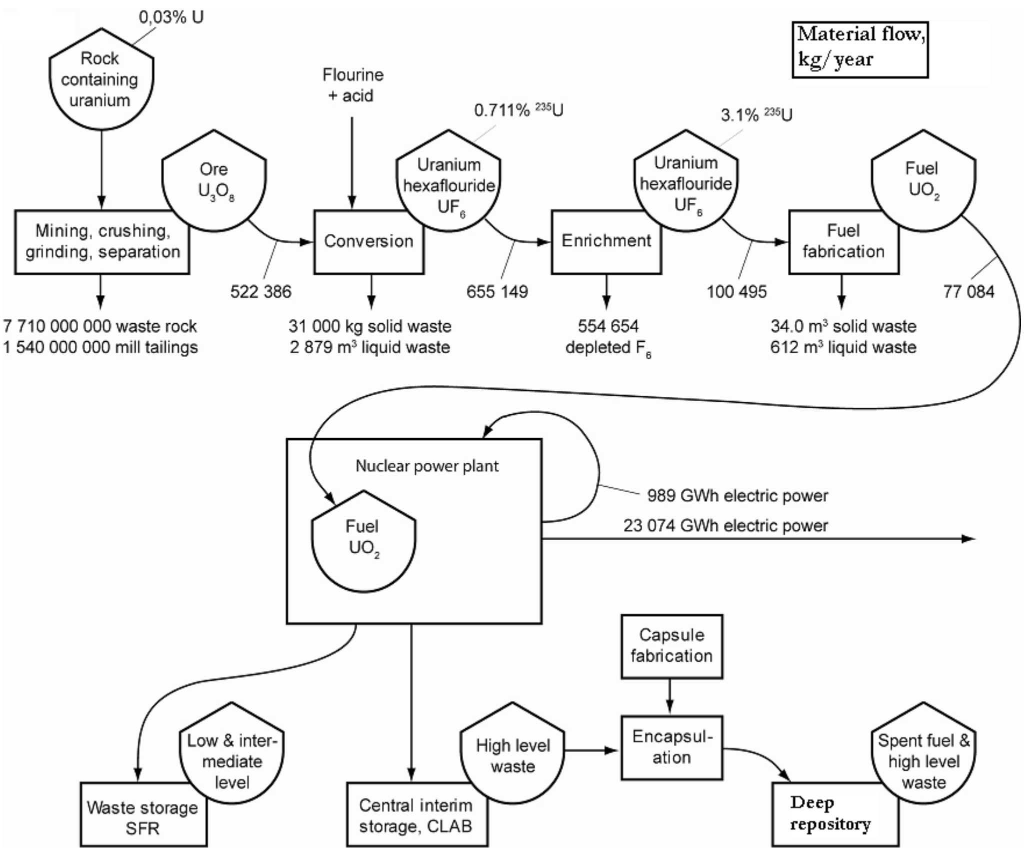

Figure 3. Illustration of the path of uranium from extraction to deep repository. The data in the figure stem from references [4] and [21].

A table containing all data used in the calculations of emergy feedback from the economy can be found in Appendix B. Extracts from this table are given as examples in the chapters 5.2.1 to 5.2.5.

5.2.1 Extraction

A nuclear fuel energy balance calculator from World information service on energy (WISE) was used to calculate the fuel and electricity consumption of the extraction process [21]. The data are presented in Table 2. An underlying assumption of the calculator is that uranium is mined in an open pit or in an underground mine. The calculator only covers the fossil fuel and electricity used for the operation of the plants.

The extraction cost is the total cost of natural uranium after extraction. This cost multiplied with the J_{emb}/SEK index is used to calculate the emergy use in production including human services. It was calculated by the nuclear fuel cost calculator from World information service on energy [22]. The inputs consisted of prices of U_3O_8, converted UF_6 and enriched UF_6 from Ux Consulting Company, LLC [23]. The data are presented in Table 2. 1 USD = 6.96 SEK is the exchange ratio included in the calculations [24]. The transformities used for fuel, electricity and extraction costs are presented in the rows B, F and I of Table 1 as well as in Appendix A.

Table 2. Energy use and costs of the extraction process.

Extraction	**Quantity/year**
Fuel	$1.37 \cdot 10^{15}$ J
Electricity	$1.18 \cdot 10^{14}$ J
Extraction costs	$4.81 \cdot 10^{8}$ SEK

5.2.2 Conversion, enrichment and fuel fabrication

The emergies in conversion, enrichment and fuel fabrication have been calculated using the same method and tools as for the extraction process. A complete table of data is found in Appendix B.

The enrichment process is assumed to take place in a centrifuge plant. This does not completely coincide with reality. Nowadays the major part of the UF_6 is enriched in centrifuge plants, but still there is a small part, which is enriched in diffusion plants.

5.2.3 Transportation

Enough data about transports by truck have been available to make it possible to calculate transformities for transport by truck. Therefore trucks are assumed to be the means of transport in all cases, except for the transports from the nuclear power plant to Clab, which are made by the ship Sigyn. In the case of Sigyn available data have been supplemented with qualified assumptions. In reality, however, ships are usually used for transports between extraction and conversion.

Extraction is assumed to take place in northern Sweden, conversion in southern France, enrichment in England and fuel fabrication in Västerås in Sweden. In reality the distance between extraction and conversion is larger. However, that will to a large degree even itself out, because fuel consumption per kilometre of trucks is larger than that of ships. The remaining parts of the nuclear power process are all situated in Sweden. The nuclear power plant is assumed to be situated in Forsmark and the low and intermediate level waste storage and the future decommissioning waste storage (SFR) is situated close to the nuclear power plant. The central interim storage (Clab) is located near the Oskarshamn nuclear power plant and the capsule factory, the encapsulation facility and the deep repository are all assumed to be built close to Clab.

In the first part of the nuclear power process, from extraction to fuel fabrication, only transports between the facilities have been included in the calculations. Transports calculated for the energy generation process includes internal transports made by trucks, tractors and cars as well as the transports to Clab made by the ship Sigyn. A normal year Sigyn used 966 tons of diesel [25]. According to information from SKB, ca 25 % of the total distance travelled by Sigyn is related to Forsmark [26]. The energy content of one ton of industrial diesel is 45.5 GJ [27].

Table 3 shows data and parameters used for calculation of emergy in transport from the fuel fabrication plant to the nuclear power plant. The same parameters are used for calculation of transports in other parts of the nuclear process. The transformity of crude oil is used as transformity for motor fuel. The J_{emb}/SEK index is used as transformity for services involved in transports, which are presented as transport costs. Data used in these calculations have been estimated by Nilsson [17] and are based on data by Hagström [18].

Table 3. Data used to calculate emergy in transports from fuel fabrication to nuclear power plant.

Operation	**Quantity**	**Transformity**	**Emergy analysis**
	Annual flows		MJ_{emb}/year
J. Motor fuel	$6.82 \cdot 10^{11}$ J	2.20 J_{emb}/J	$5.64 \cdot 10^4$
K. Cargo weight	77.1 t		
L. Maximum load of truck	40 t		
M. Number of turns	5		
N. Distance per turn	150 km		
O. Distance per year	1478 km		
P. Transport costs	14 799 SEK	1.36 MJ_{emb}/SEK	$2.02 \cdot 10^4$
Q. Total emergy in transportation			$7.66 \cdot 10^4$

Notes to Table 3:

J. Motor fuel = (distance/year) · (lower heating value). The lower heating value[1] is $35.3 \cdot 10^6$ J/l.

K. The weight of the reactor fuel, which makes up the cargo, is 77.1 tons. These data are also presented in Figure 3, which shows the material flow.

L. The maximum load of the truck is estimated to 40 tons.

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[1] The lower heating value of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25 °C or another reference state) and returning the temperature of the combustion products to 150 °C. The lower heating value assumes the latent heat of vaporization of water in the reaction products is not recovered. It is useful in comparing fuels where condensation of the combustion products is impractical, or heat at a temperature below 150 °C cannot be put to use.

M. (Cargo weight) / (maximum load of the truck) gives the number of turns the truck has to do if it is loaded to maximum weight. However, in reality the truck may not be loaded to maximum weight due to large volume of the cargo or to safety restrictions. In that case the truck has to drive extra turns. For this reason three extra turns are added.

N. The distance between the fuel fabrication plant and the nuclear power plant is set as the approximate road distance between Västerås and Forsmark.

O. Distance per year = 2 · (number of turns) · (distance per turn). The number two indicates that for each trip to the nuclear power plant the truck has to return to the fuel fabrication plant.

P. Transport cost = (maximum load of the truck) · (distance per year) · (SEK/(ton · km)). Ton · km has the value 0.25.

Q. Total emergy in transportation = emergy in motor fuel + emergy in transport costs.

Data used in the calculations of transports related to the nuclear power plant have been obtained from the Forsmark annual report 2004 [28]. According to these data the nuclear power plant used 32 m^3 petrol and 57 m^3 diesel for transports during 2004. The energy contents of one litre of petrol and diesel are approximately 34.4 MJ/l and 38.0 MJ/l respectively [27].

Included in transports related to the intermediate and low-level storage (SFR) are transports of low and intermediate level waste from Forsmark to SFR, transports of fuel from Forsmark to Sigyn plus use of other vehicles within SFR. Approximately 10 m^3 diesels were used by SFR during 2004 [29].

No transports are calculated between the central interim storage (Clab) and the plant where manufacturing of capsules takes place. Nor are transports included between the capsule plant and the encapsulation facility or between the encapsulation plant and the deep repository.

5.2.4 Electricity generation

Although the investigation of this diploma work refers to a generic Swedish nuclear power plant most data are taken from the Forsmark annual report 2004. The electricity generated in the nuclear power plant during 2004 is estimated to 24 063 GWh. This is the sum of 23 074 GWh, which was delivered by Forsmark 2002 [4] and Forsmark's own use of electricity, which was 989 GWh 2004 [28]. Table 4 shows the parameters used in the calculations of emergy in the electricity generation process. The same parameters are used to calculate emergy in waste management and storage. "Power plant costs", which is the last entry of the table, sums the operation and maintenance costs, capital costs, insurance costs and decommissioning costs.

Table 4. Data used to calculate the emergy in electricity generation at the nuclear power plant.

Operation	**Quantity**	**Emergy evaluation**	
	Annual flows	Transformity	Emergy MJ_{emb}/year
Fuel	$4.98 \cdot 10^{12}$ J	2.20 J_{emb}/J	$1.10 \cdot 10^{7}$
Electricity	$3.56 \cdot 10^{15}$ J	2.92 J_{emb}/J	$1.04 \cdot 10^{10}$
Operation and maintenance costs	$1.13 \cdot 10^{9}$ SEK	1.36 MJ_{emb}/SEK	$1.55 \cdot 10^{9}$
Capital cost	$4.85 \cdot 10^{8}$ SEK	1.36 MJ_{emb}/SEK	$6.62 \cdot 10^{8}$
Insurance costs	$3.31 \cdot 10^{7}$ SEK	1.36 MJ_{emb}/SEK	$4.50 \cdot 10^{7}$
Decommissioning costs	$9.61 \cdot 10^{7}$ SEK	1.36 MJ_{emb}/SEK	$1.31 \cdot 10^{8}$
Power plant costs	$1.71 \cdot 10^{9}$ SEK	1.36 MJ_{emb}/SEK	$2.34 \cdot 10^{9}$
Total emergy			$1.28 \cdot 10^{10}$

Forsmark used 131 m^3 of diesel as reserve fuel during 2004 [28]. Diesel holds approximately 38.0 GJ/ m^3 [27].

Administration costs, O&M costs and costs of inspection made by the Swedish nuclear power inspectorate (SKI) and the Swedish radiation protection authority (SSI) are included in the operation and maintenance costs (O&M). The inspector costs of SKI are estimated to $2.6 \cdot 10^{7}$ SEK. This number is calculated based on data from the SKI annual report 2005 [30]. Approximately 92.5 % of the services carried out by SKI are distributed on the Swedish nuclear power plants and other nuclear related institutions in Sweden. The remaining 7.5 % of the service time is carried out in Eastern Europe. Forsmark accounted for 37 % of the electricity generation by nuclear power in Sweden 2004 [28]. It is therefore assumed that Forsmark accounts for 37 % of the services SKI provides in Sweden, which is 34% of the SKI total labour cost of ca $7.5 \cdot 10^{7}$ SEK. The Forsmark share of the costs for the services of SSI is 2.5 % of ca $7.4 \cdot 10^{7}$ SEK. This cost is based on data from the annual report 2004 of SSI and is calculated in a similar way as the cost of the services of SKI [31].

The capital cost includes a construction cost based on data from the construction of the new third reactor in Olkiluoto in Finland. The capital cost is estimated to $3.2 \cdot 10^{9}$ Euro [32]. 1 Euro = 9.1 SEK [33]. This is divided by the expected lifetime of the new Olkiluoto reactor, which is 60 years [34].

By law Swedish nuclear power plants are required to take out a liability insurance. The annual cost for this insurance is estimated to 9 MSEK per nuclear power plant. Liabilities arising from serious accidents are not covered by insurance. Instead the Swedish government is expected to cover such costs. From risk assessment analysis the cost for these kinds of accidents has been estimated to 0.001 SEK/kWh [35].

All Swedish nuclear power plants that generate electricity have to contribute to the nuclear waste foundation. The money in the nuclear waste foundation is set to cover the costs of the waste management of nuclear waste including decommissioning. The amount a nuclear power plant had to pay 2004 was relative to its electricity generation. The total amount of the nuclear waste fond 2004 was 36.3 billion SEK [36]. The Forsmark share was 10.5 billion SEK, which makes up 29 % of the total amount. It is therefore assumed that the investigated nuclear power plant share of the costs and energy use related to decommissioning, waste management and storage is 29 %. The total decommissioning cost of all Swedish nuclear power plants is $1.3 \cdot 10^{10}$ SEK [37]. The lifetime of a Swedish reactor is estimated to 40 years.

5.2.5 Management and storage of nuclear waste

Table 5 shows the energy use and the costs in nuclear waste management and storage that apply to a nuclear power plant similar to Forsmark. In accordance with the line of argument in chapter 5.2.4, the nuclear power plant share of the total costs is 29 %. To calculate the cost of one year, 2004, the costs are divided by the estimated lifetime of the nuclear reactor, which is 40 years.

Information about the use of electricity and fossil fuels in waste management and storage facilities is presented in Table 5. The table is not complete, because data on fuel and electricity use have not been available for the deep repository and the storage of decommissioning waste. In other cells where information on either electricity or fuel is missing it is assumed that the energy use is aggregated into one number including both the use of electricity and fossil fuels. Transports are not included in the table, because they are already presented in chapter 5.2.3.

Table 5. Energy use and costs in nuclear waste management and storage.

<table>
<tr><th>Nuclear waste facilities</th><th>Fuel (J)</th><th>Electricity (J)</th><th>O&M costs (SEK)</th><th>Capital costs (SEK)</th><th>Decommissioning costs (SEK)</th></tr>
<tr><td>R. SFR</td><td></td><td>$5.86 \cdot 10^{12}$</td><td>$8.83 \cdot 10^{6}$</td><td>$9.49 \cdot 10^{6}$</td><td>$1.61 \cdot 10^{6}$</td></tr>
<tr><td>S. Clab</td><td></td><td>$5.76 \cdot 10^{13}$</td><td>$2.92 \cdot 10^{7}$</td><td>$1.24 \cdot 10^{7}$</td><td>$3.36 \cdot 10^{6}$</td></tr>
<tr><td>T. Capsule manufacturing</td><td rowspan="2">$3.92 \cdot 10^{13}$</td><td></td><td>$2.59 \cdot 10^{7}$</td><td>$1.64 \cdot 10^{6}$</td><td rowspan="2">$1.39 \cdot 10^{6}$</td></tr>
<tr><td>U. Encapsulation</td><td></td><td>$1.43 \cdot 10^{7}$</td><td>$1.66 \cdot 10^{7}$</td></tr>
<tr><td>V. Deep repository</td><td></td><td></td><td>$3.45 \cdot 10^{7}$</td><td>$7.56 \cdot 10^{7}$</td><td>$2.46 \cdot 10^{7}$</td></tr>
</table>

R. Electricity use relates to the existing part of SFR, that is the low and intermediate level waste storage. It used 5603 MWh during 2004 [29]. The other costs of SFR include both the existing facility and the storage of decommissioning waste, which is not yet built. These costs have been received from SKB [37, 38].

S. Data on electricity use in the central interim storage of high-level waste (Clab) are obtained from reference [39]. The O&M and capital costs were found on the SKB website [40] and the decommissioning cost in “Plan 2006”[37], which is a report about the costs of radioactive residues from nuclear power.

T. 1194 GJ per capsule is the total amount of energy needed for the capsule, from extraction of raw material used to manufacture the capsule to the stage when the waste has been encapsulated and is ready to be placed in the deep repository [41]. This energy used is divided between the manufacturing of capsules and the encapsulation process. The calculations are based on use of the materials and the Electron Beam Welding (EBW) method that have the largest impact on the environment compared to other available methods and materials. A method more likely to be used is friction stir welding. A total of approximately 4500 capsules will be used to encapsulate the nuclear waste [38].

The O&M cost and the capital cost were obtained from the SKB website [38]. The decommissioning cost is the estimated total cost of manufacturing of capsules and of encapsulation [37]. This cost has been divided evenly between the manufacturing of capsules and the encapsulation process.

U. O&M cost and capital cost were found on the SKB website [42].

V. Included in the costs of the deep repository are costs for final storage of high-level waste and low and intermediate long-term waste. No data were found about future fuel and electricity consumption of the deep repository and the storage of decommissioning waste. However, in this diploma work they are assumed to be small compared to the energy use in the majority of the other steps included in the nuclear process. Data on O&M cost, capital cost and decommissioning cost were found in "Plan 2006" [37].

5.3 Limitations of the methodology

The data used to calculate the total emergy of the nuclear power process differs in level of detail. Some data are more specific while other data are generic or based on assumptions. This depends on the availability of data. Data regarding the processes carried out in Sweden have been easier to obtain than data from facilities abroad. That is mainly because it has been easier to get in contact with key persons knowledgeable in the field in Sweden. Limitations in time available for collecting data have also restricted the data to what is presented in this diploma thesis.

If more specific data on material use had been used instead of the cost of different processes multiplied with the J_{emb}/SEK index the results would probably have been somewhat different and presumably more exact. However, this would imply a significant larger amount of transformities that would have to be produced, a task too big for the time frames of this work. Furthermore, there is no guarantee that the transformities of different materials leads to more exact results than the J_{emb}/SEK index. Therefore the J_{emb}/SEK index has been used for several inputs.

The use of electricity and fossil fuels in the nuclear power process refers to energy used in operation and maintenance. Thus, it does not include energy used in the construction or decommissioning of the plants, or in the production of any raw materials required. The assumption that all enrichment takes place in centrifuge plants also affects the result. All in all, this implies that the use of fossil fuels and electricity calculated in this work is smaller than in reality. However, in the near future enrichment in centrifuge plants will replace enrichment in diffusion plants. There are also some double counting of the use of electricity and fossil fuels in this report. First, the emergy of fossil fuels and electricity used in the processes are calculated separately. Then the total emergy in O&M, construction and decommissioning is calculated based on costs. Included in these emergies is also the cost of energy use. Hence it follows that the energy is doubly counted. This may fill the gap between the energy use presented in this report and the real total energy use to some extent.

There is one factor that may have a large impact on the emergy related to nuclear power in the future. That is energy use and costs related to the mines. When the mines are no longer in use they need to be filled and the area around them need to be cleaned. This cost has not been available and is therefore not included in this report. Other facilities in the nuclear power process may also have an impact on the environment in the future.

The lifetime of the nuclear power plant is estimated to 40 years in accordance with the assumption made in "Plan 2006” [37]. However, the nuclear power plant may be in use longer than that. How this would affect the emergy return on investment depends on how much longer the nuclear power plant could operate in proportion to possible reparation costs related to the age of the reactor.

The reference year of this evaluation is 2004. This means that all data used should be valid for the year 2004. However, in some cases data have not been available for this specific year. Data related to the uranium cycle shown in Figure 3 are taken from a lifecycle assessment of the Forsmark nuclear power plant, which has the reference year 2002. Although this means that some of the data differ from data related to the reference year, 2004, the differences are relatively small. Therefore the results are still representative for electricity generation at a Swedish nuclear power plant in the year 2004.

Data from reliable sources in combination with assumptions are used in the calculations. Although the results of the calculations are approximate rather than exact they are still considered as useful for the purpose of this work.

6 Results and observations

Figure 4 outlines the emergy flow and distribution of the nuclear power process. The nuclear power process is defined in the large rectangular box. The steps of the process are comprised into four boxes: (1) Concentration of uranium, which includes extraction, conversion, enrichment and fuel fabrication. (2) Electricity generation in the nuclear power plant. (3) The waste management and temporary storage, which includes Clab, manufacturing of capsules and encapsulation. (4) The final storage of nuclear waste, which includes SFR and the deep repository. The nuclear power system is dependent on emergy inputs from outside; hence the arrows from the symbols outside the big square to the nuclear power process inside the square.

All emergy involved in the nuclear power process is divided into the categories input from nature, *I*, and feedback from the economy, *F*. The total emergy yield *Y* is the sum of *I* and *F*. To estimate *Y*, the gross electricity, i.e., $8.66 \cdot 10^{16}$ J, generated in the nuclear power plant during 2004, is multiplied by the transformity of electricity, 2.92 J_{emb}/J, as calculated in Appendix A, Table A3. The feedback from the economy, i.e., *F*, which is to the right in the figure, includes the three parameters: (1) fuel, (2) electricity and (3) labour, goods, services and capital. The parameter fuel includes fuel used in production and in transports. Labour, goods, services and capital include operation and maintenance costs, capital costs, transport costs and decommissioning costs. The input from nature, *I*, is presented to the left as rock containing uranium and has the value $2.32 \cdot 10^{17}$ J_{emb}/year. It is calculated as the difference between emergy yield *Y* and emergy feedback *F*. The transformity of *I* is $2.32 \cdot 10^{17} / 8.66 \cdot 10^{16} = 2.68$ J_{emb}/J.

Figure 4 clarifies how the emergy from the economy is distributed. The exact meanings of the symbols in the figure are explained in Appendix C. The emergies in the different steps of the nuclear process are also presented in Table 6.

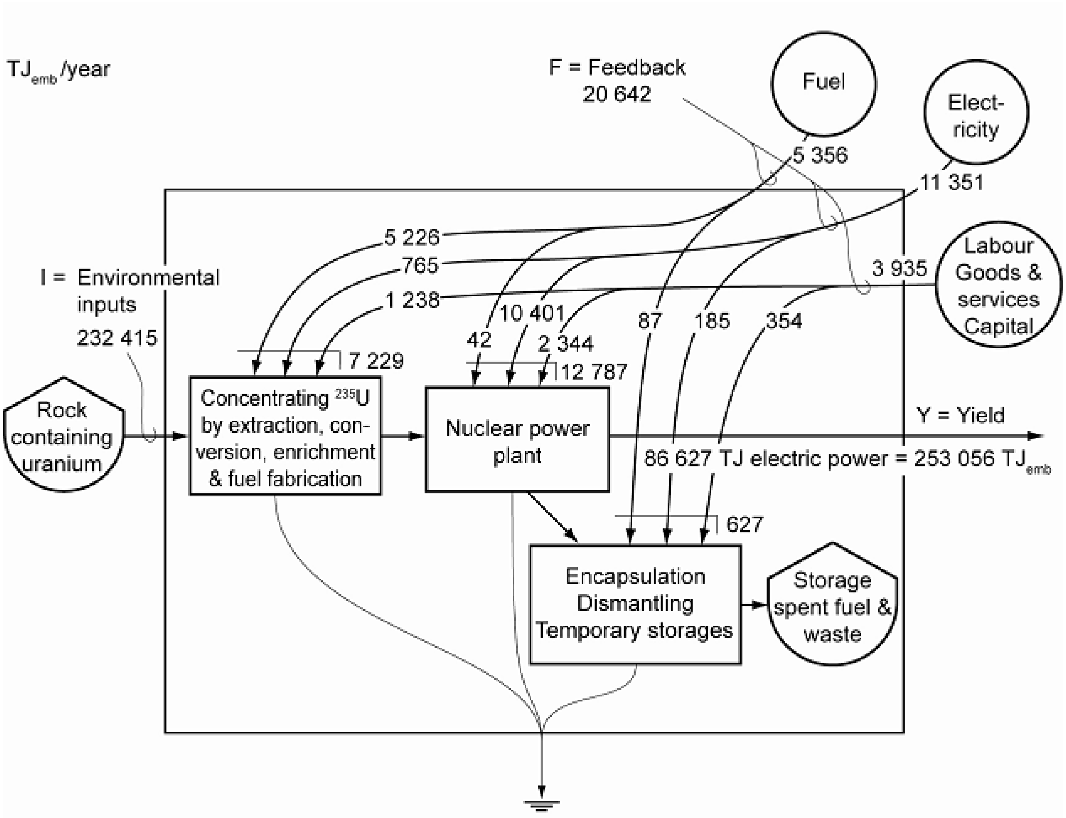

Figure 4. Emergy flow of the nuclear power process. The nuclear power process inside the square is dependent on the emergy input from nature, to the left and the emergy feedback from the economy, to the right in the figure.

Table 6 presents the emergy the economy has to feed back in order to receive electricity. The emergy feedback is divided on the same factors as in Figure 4. The most emergy demanding step in the nuclear power process is the generation of electricity at the nuclear power plant. This is mainly because an extensive amount of electricity is needed and because of the high costs included in labour, goods, services and capital of which the cost of operation and maintenance is the highest. A more detailed table of the factors included in the emergy evaluation can be found in Appendix B. The results are also illustrated in Figure 5 and in Figure 6 below.

Table 6. Data of emergy feedback from the economy and costs related to electricity generation in a Swedish nuclear power plant.

Emergy evaluation of a Swedish nuclear power plant					
Operation	Cost analysis	Fuel	Electricity	Labour, goods, services, capital	Total Emergy
	SEK/kWh	TJ_{emb}/year	TJ_{emb}/year	TJ_{emb}/year	TJ_{emb}/year
Extraction	0.020	3032	345	658	4036
Conversion	0.002	1394	68	53	1516
Enrichment	0.011	393	136	330	860
Fuel fabrication	0.006	406	215	196	818
Electricity generation	0.073	42	10401	2389	12832
Storage of low and intermediate level waste and decommissioning waste, (SFR)	0.001	1	17	27	45
Central interim storage of high level waste (Clab)	0.002		49	61	110
Capsule manufacturing	0.001	43		39	82
Encapsulation of high level waste	0.001	43		43	86
Deep repository of high level waste	0.006			184	184
Sum	0.122	5356	11232	3980	20568

The cost analysis in Table 6 gives an indication of the reliability of labour, goods, services and capital costs. The sum of the costs of extraction, conversion, enrichment and fuel fabrication is 0.04 SEK/kWh. This is a little higher than 0.03 SEK/kWh, which was the cost calculated by the Analysis Group of the Nuclear Training and Safety Center (KSU) [5]. According to the same group the future waste management will cost approximately 0.01 SEK/kWh, which agrees with the costs of waste management in Table 6. The Analysis Group of KSU has roughly estimated the total cost of generating nuclear power electricity to 0.20 SEK/kWh. The power utility Vattenfall has estimated this cost to 0.15-0.20 SEK/kWh [43]. In this work the cost per kWh is calculated to approximately 0.12 SEK. However, there is a tax of 0.03 SEK/kWh, which Swedish nuclear power plants have to pay. If this tax is added the total cost increases to 0.15 SEK/kWh.

Figure 5 illustrates parts of the data in Table 6. It shows the distribution of emergy in the different steps of the nuclear power process. Visible in the figure is the large amount of emergy in electricity generation, but also the small amount of emergy in waste management and storage. One reason for the low emergy in deep repository could be that electricity and fuel data were not included, because data were not available. However, even if electricity or fuel use were included in the deep repository the emergy related to management and storage of nuclear waste would still be small compared to the other steps in the process. In the first part of the nuclear process, in which uranium is refined, the largest amount of emergy occurs in the extraction process. That is because this process requires a lot of fuel but also a relatively large amount of electricity. The labour, goods, services and capital costs of extraction are also the second largest cost of this kind in the nuclear power process.

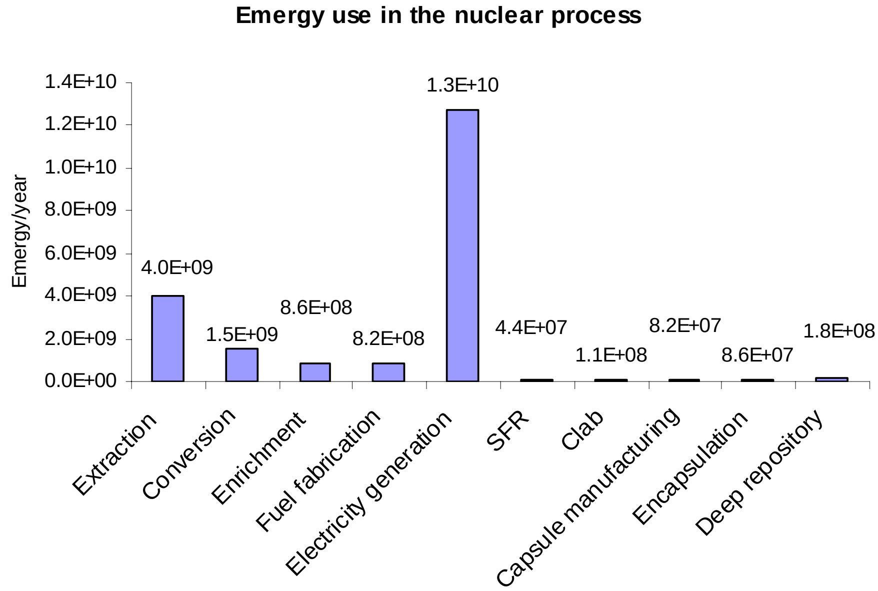

Figure 5. Emergy feedback from the economy divided on the different steps of the nuclear power process.

Figure 6 shows that most of the emergy feedback from the economy is related to electricity, but that the use of fuel is large too. From the figure it is clear that nuclear power is not a labour intensive energy system. All emergy related to transports are represented as a separate category. The emergy in transports is small in this context. Thus, uncertainties in transport data are not significant for the final result.

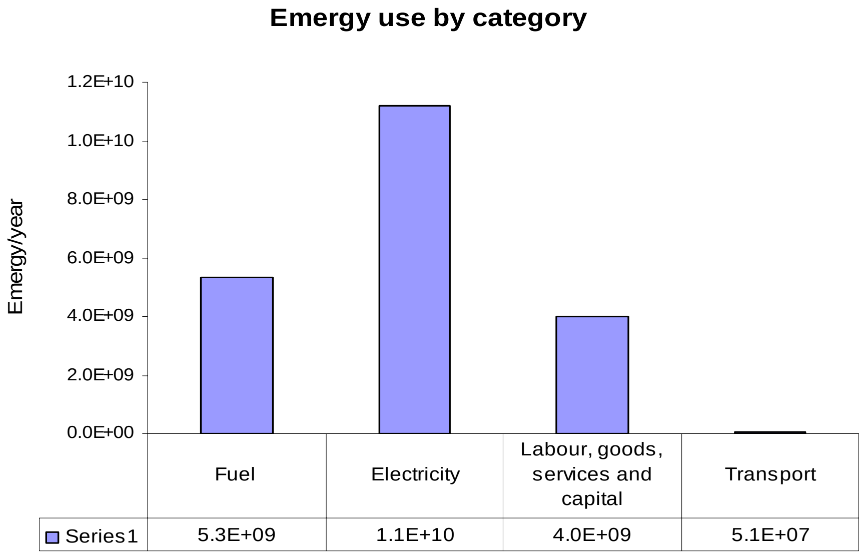

Figure 6. Emergy feedback from the economy divided on the categories fuel, electricity, labour, goods, services and capital costs and transport.

An emergy return on investment ratio is calculated based on the results of the emergy evaluation made. This ratio has the value 11.3 and is presented in the last row of Table 7. The value 11.3 means that for every bio emergy joule the economy has to put into the nuclear power process to receive nuclear power electricity it gets 11.3 bio emergy joules in return. The yield ratio, *Y/F*, which denotes the proportion between the total yield of the nuclear power plant and the emergy feedback from the economy is also calculated. The total yield, Y, is the sum of the input from nature *(I)* and the feedback from the economy *(F)*. The result, 12.3, means that if the economy contributes with one bio emergy joule it receives a gross yield of 12.3 bio emergy joules. Odum used this quotient in his book “Environmental Accounting” [2]. There is not a large difference between the calculations and the results of the emergy return on investment and the yield ratio. If one of the indexes is calculated the other one can easily be calculated based on the first one. In this emergy evaluation emergy return on investment has been chosen to show the return of a Swedish nuclear power plant.

Table 7. Emergy return on investment and other ratios.

Yield ratios	**Calculations**	**Results**
Yield = *Y*	*Y* = *I*+*F* = the total yield of the nuclear power plant = the transformity of electricity	2.92 J_{emb}/J
Feedback from the economy = *F*	*F* = total emergy input from the economy / the gross electricity generated in the nuclear power plant = $2.06 \cdot 10^{16}$ / $8.66 \cdot 10^{16}$	0.24 J_{emb}/J
Input from the environment = *I*	*I* = *Y* - *F* = 2.92 - 0.24	2.68 J_{emb}/J
Net yield ratio = *Y/F*	*Y/F* = *I/F* + 1 = 2.92 / 0.24	12.3
Emergy return on investment = *I/F*	2.68 / 0.24	11.3

7 Sensitivity analysis

Sensitivity analysis is a tool used for estimating how chosen data and methods affect the results of a study. This can be done by changing the value of one parameter at a time and analysing the result compared to the original result [44].

In this chapter four sensitivity analyses have been made to investigate how uncertainties in parameters influence the emergy return on investment. The following parameters are investigated: transformities, J_{emb}/SEK index, use of fuel in operation processes and transports and finally electricity use in operation processes. The transformities and the J_{emb}/SEK index are analysed because their values are not absolute and because labour, services and other monetary costs are main factors that distinguish an emergy evaluation from an energy analysis. Fuel use is analysed, because it involves the second largest amount of emergy. The use of electricity has the highest emergy in the nuclear power process and is therefore interesting to analyse in a sensitivity analysis.

7.1 Sensitivity analysis of transformities

First two different sets of transformities have been tested in order to compare their emergy return on investment with the result of the transformities used in this diploma work. Depending on what transformities are used and on how these transformities have been calculated the results of the emergy evaluation will differ. Therefore it is of interest to compare different sets of transformities. The first set of comparison consists of transformities used by Odum [2], but converted from solar emjoules to bio emjoules. The other set represents the scenario when all forms of fuel are considered equal in their ability to do work. These transformities together with the transformities used in this report are presented in Table 8.

Table 8. Transformities

Transformities	Odum's trans-formities (J_{emb}/J)	All transformities = 1 (J_{emb}/J)	Transformities used in this report (J_{emb}/J)
Food consumed	100.0	1.0	3.8
Crude oil and oil products	8.2	1.0	2.2
Natural gas	7.3	1.0	2.2
Coal and coke	6.1	1.0	2.2
Raw material from forestry	1.0	1.0	1.3
Electricity	24.2	1.0	2.9
Peat	2.9	1.0	1.1
Emergy/SEK index (total emergy /GNP)	8.31 MJ_{emb}/SEK	0.61 MJemb/SEK	1.36 MJ_{emb}/SEK

The transformities of oil and electricity and the J_{emb}/SEK index are the transformities that are most frequently used in this work. An average value of these transformities using Odum's values shows that the transformities of Odum are on average 500 % larger than the transformities used in this work. Calculating an average value of the transformities that are equal to one shows that they are 58 % smaller than the transformities used in this report.

Despite large differences in transformities the emergy return on investment ratios do not differ as much. In Table 9 below the emergy return on investment ratios resulting from the sets of transformities presented in Table 8 are shown. An additional set has been included, which is the scenario when all forms of fuel are considered equal in their ability to do work but with the exclusion of the J_{emb}/SEK index. This means that a large part of the emergy feedback from the economy is excluded in the calculations, i.e., a part that consists of operation and maintenance costs, capital costs, insurance cost, costs in transports and decommissioning costs. By this exclusion and using the same value, i.e., one, for all transformities the result is that of a traditional energy analysis.

Table 9. Emergy return on investment related to different sets of transformities

Transformity	**Emergy return on investment (*I/F*)**
Transformities used in this diploma thesis	11.3
All transformities =1	9.7
All transformities =1 and no J_{emb}/SEK index included	12.7
Odum's transformities converted into J_{emb}/J	14.2

An emergy return of 9.7 is a 14 % decrease compared to the emergy return on investment ratio calculated in this report. Odum’s transformities give 14.2 emergy joules in return for an investment of one joule. This is a 26 % increase compared to the original ratio. The scenario when all transformities are given the value one and the J_{emb}/SEK index is excluded, which means that no costs are included, can be called a traditional energy analysis. The energy analysis gives an emergy return on investment that is 12 % higher than the emergy return on investment calculated in this thesis.

7.2 Sensitivity analysis of the J_{emb}/SEK index

In the sensitivity analysis of the J_{emb}/SEK index the test values of the index ranges from a 100 % decrease to a 100 % increase. As shown in Figure 7 a 100 % increase of the index gives the value 9.3 to the emergy return on investment, which is an 18 % decrease of the original emergy return on investment, 11.3. A 100 % decrease of the index gives a 25 % higher emergy return on investment compared to the original value of this report.

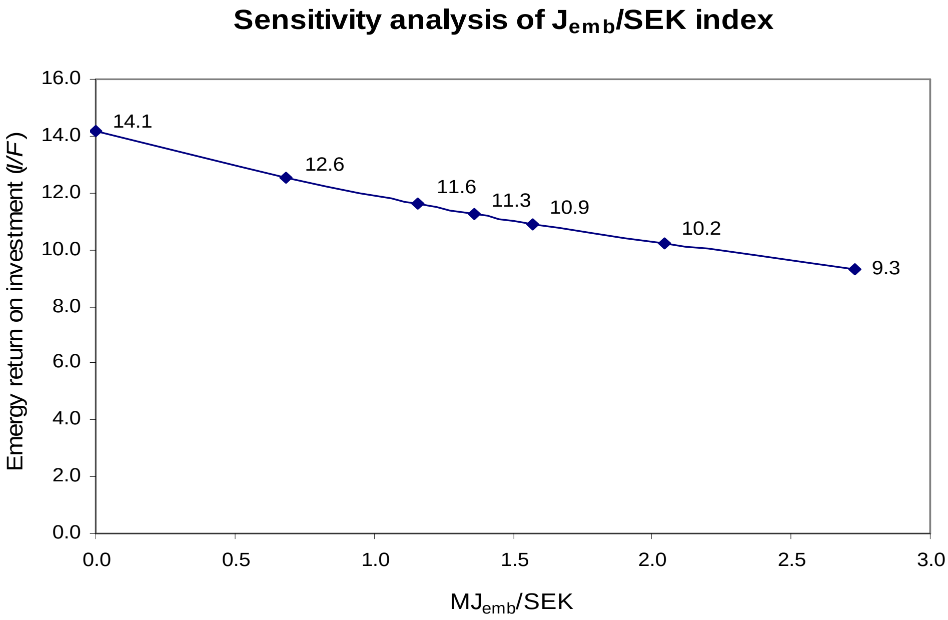

Figure 7. An illustration on how changes of the J_{emb}/SEK index affects the emergy return on investment.

7.3 Sensitivity analysis of fuel use

In Figure 8 sensitivity analysis is made of the total fuel use, which includes fuel used in operation processes and in transports. The figure shows that if the use of fuel would increase 100 % the emergy return on investment ratio (*I/F*) would decrease with 22 %. If the fuel use is eliminated the emergy return on investment increases with 37 %.

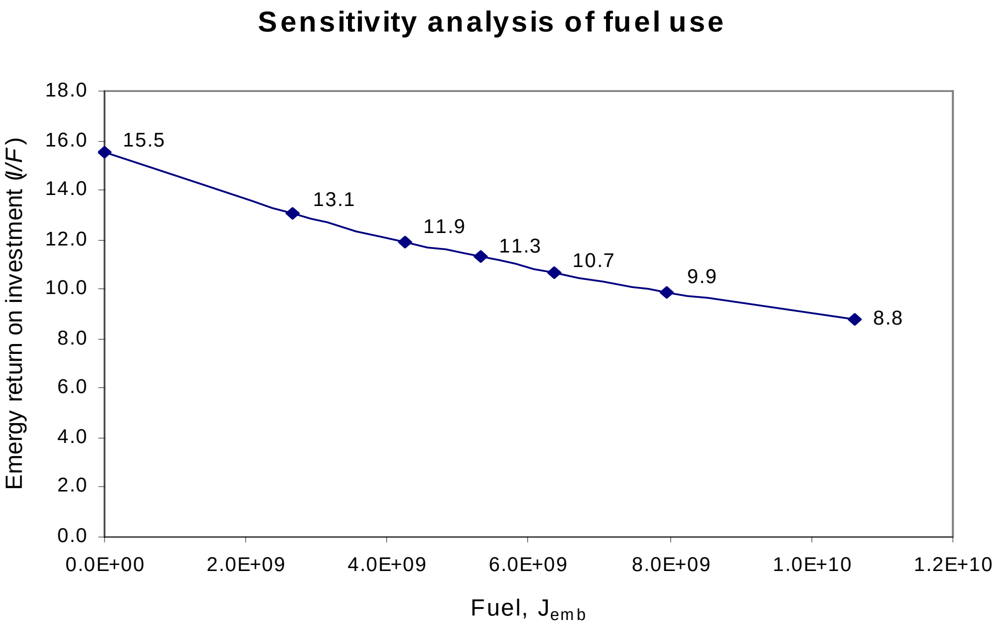

Figure 8. An illustration on how changes in fuel use affect the emergy return on investment.

7.4 Sensitivity analysis of the use of electricity

That electricity use accounts for a large amount of the total emergy was showed already in Figure 6. The impact of electricity use on the emergy return on investment is therefore significant. Figure 9 illustrates that if the use of electricity would increase 100 % the emergy return on investment would decrease with 39 %. A 100 % decrease of electricity use would lead to a 133 % increase of the emergy return on investment ratio. Also smaller changes in electricity use result in larger changes of the emergy return on investment compared to similar changes in the other parameters analysed.

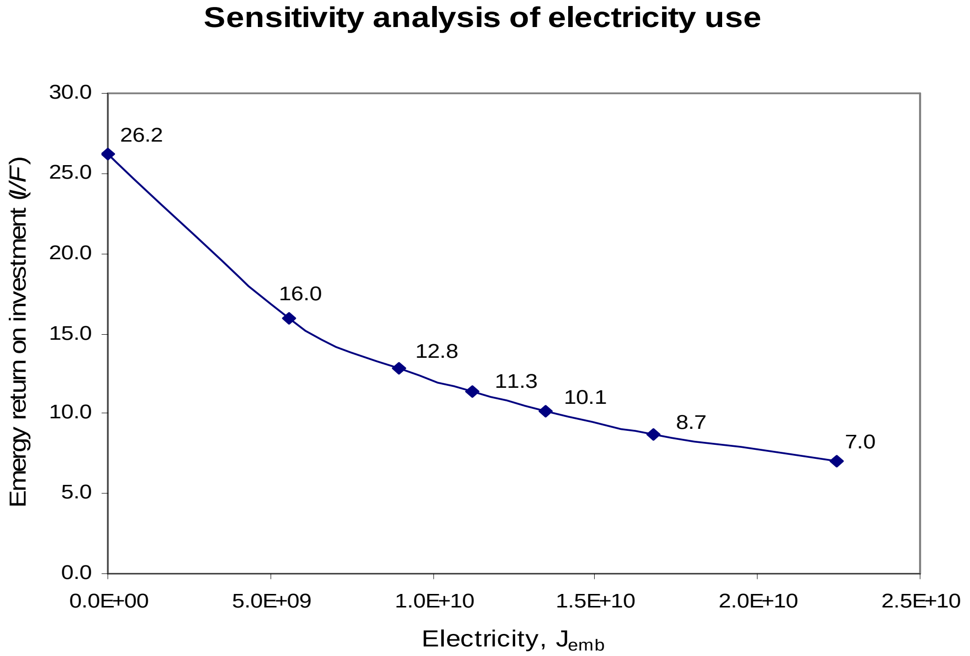

Figure 9. An illustration on how changes in electricity use affects the emergy return on investment.

7.5 Calculation of uncertainties

Uncertainties have been estimated for the J_{emb}/SEK index, fuel use and electricity use in order to calculate an uncertainty of the emergy return on investment. The uncertainty of the J_{emb}/SEK index has been estimated to 15 % and the uncertainties of fuel use and electricity use are estimated to 20 % respectively. This results in an uncertainty of the emergy return on investment of ± 1.6.

8 Emergy return of biomass

Is the value *I/F* = 11.3 a good emergy return on investment ratio for an energy system? Considering that the economy gets 11.3 times more emergy back in relation to what has been invested it can be seen as a good result. However, as already mentioned in the introduction it can be of interest to make a comparison with other energy systems in terms of emergy return. Biomass in the form of harvested willow crop about to be used as fuel, heat from wood chips combustion and heat from wood powder have all been estimated to have a yield ratio (*Y/F*) of approximately 1.3 [11]. This is a solar emergy yield ratio calculated with the use of Odum’s transformities, which were presented in Table 8. The calculations of harvested willow and of wood are associated with production of one hectare of short rotation willow and one hectare of spruce/pine annual forest production respectively. Although there are differences between Odum's transformities and the transformities used in this work it still gives an indication on the differences between the emergy return on investment (*I/F*) of a Swedish nuclear power plant, which is 11.3 and the emergy return on investment of Swedish biomass, which is 0.3 ($I/F = Y/F - 1$).

9 Discussion and conclusions

The emergy return on investment ratio calculated in this work is 11.3. Compared to the emergy return of biomass this is a good result, which means that a Swedish nuclear power plant is profitable for the economy in terms of emergy. But how do we know if this is an exact, true or at least reasonable value? Because there are no previous emergy evaluations made on a Swedish nuclear power plant there are no results to compare with. Thus, it is not possible to give a straight answer to the question. However, the method and data leading to the result can be analysed and tested in a sensitivity analysis, which was done in chapter 7. Based on the outcome of the analysis the method and data can be judged, which in turn leads to a judgment of the result.

Calculations of transformities may be a matter of controversy. The transformities can be considered as subjective or failing to include important aspects. The sensitivity analysis showed that a major change of the transformities did not have a significant impact on the emergy return on investment ratio. When the transformities were increased 500 % on average it resulted in a 26 % increase of *I/F*. A 58 % decrease of the transformities, i.e., the scenario when all transformities, except the J_{emb}/SEK index, are given the value one, resulted in a 14% decrease of the emergy return on investment.

A 100 % increase and a 100 % decrease of the J_{emb}/SEK index caused an 18 % decrease and a 25 % increase of *I/F* respectively. This shows that a major change of these parameters do not cause a major change of the result. Even if the J_{emb}/SEK index or the total cost would be based on incomplete or faulty data or if some parameters should be missing the “real” emergy return on investment ratio would still be relatively large.

The use of electricity on the other hand has a larger impact on the result. Firstly it is the parameter using most emergy in the nuclear power process. Secondly it is more sensitive to changes in data than the other parameters. A 100 % increase of electricity use results in a 39 % decrease of *I/F* and a 100 % decrease of the use of electricity results in a 133 % increase of *I/F*. Such large changes in electricity use may not be probable in reality, but that does not change the fact that electricity use is a sensitive parameter. Figure 9 shows that also smaller decreases and increases of electricity use, e.g. 50 % or 20 %, affects the result more than a corresponding change of the other parameters that have been tested. Considering a 50 % increase of electricity use *I/F* would decrease 24 % to 8.6. Depending on the results of other energy systems 8.6 may still be high enough for the nuclear power plant to be considered as profitable to the economy.

No matter if the electricity use as it has been calculated in this report is used or if it is doubled, the corresponding emergy return on investment is several times larger than the yield ratios calculated in previous studies [12, 13]. This may be because the costs have proved to be lower than what was expected at the time of the other investigations. This decrease in costs might be a result of increased efficiency and a longer expected lifetime of the nuclear reactors.

In addition to calculating the emergy return on investment ratio an emergy evaluation shows how emergy is distributed on the different steps of the nuclear power process. Knowing this distribution makes it possible to actively try to decrease emergy in the steps that consume large amounts.

There are different methods for measuring different aspects of an energy system. Emergy evaluation measures energy efficiency while life cycle assessment measures the environmental impact of an energy system. Therefore, to get an insight into the advantages and the disadvantages of an energy system it may be of value to make more than one analysis or evaluation. However, emergy evaluation alone gives an indication of the rate of emissions related to the energy system. If the energy system has an emergy return on investment lower than one it means that it has to be backed up by another energy system in order to provide sufficient emergy. This need of two or more energy systems in combination may lead to a higher amount of pollution and a lower emergy return on investment than what would be the case if one energy system would be sufficient.

There is not a big difference in results between the emergy evaluation and the energy analysis made in this work, see Table 9. Emergy return on investment of the energy analysis is 12 % higher than that of the emergy evaluation. With such a small difference in result it may seem unnecessary to make emergy evaluations. However, this is the case when a nuclear power plant is investigated. For other energy systems, e.g., more labour intensive systems the difference may be larger.

9.1 Outlook

The main focus of this diploma work has been to present a possible method for applying an emergy evaluation on a Swedish nuclear power plant. The next step could be to concentrate on the collecting of data to make the result of the emergy evaluation as exact as possible. Further fields of study within this area could be to investigate if there is a way to simplify the calculations and use of transformities and how to make the J_{emb}/SEK index more exact by including more clearly specified factors.

The method used in this report may facilitate further investigation and use of emergy evaluation. The results of emergy evaluations of other energy system, both new and old ones, would be an interesting input in the debate on what energy systems should be used in Sweden as well as in other countries. Complementing other analyses with emergy evaluations may lead to a broadened perspective and a change in how energy systems are judged. The opinions on what is an environmentally friendly and efficient energy system may alter along with the introduction of new or somewhat modified methods of evaluating energy systems. Emergy evaluations, if carried out carefully, may help society to prevent emergy losses caused by energy systems that deliver small emergy returns on investment.

Although it is important to find new energy systems with little impact on the environment the existing systems should also be taken into account. Different kinds of analyses for comparison of new and old energy systems may show that both have advantages and disadvantages depending on what is measured.

For several years it has been discussed whether nuclear power should remain an electricity provider in the Swedish society or not. The risk of accidents causing discharge of radioactive radiation, which may harm humans and nature, is a main argument for a closedown of Swedish nuclear power plants. However, before the nuclear plants can be closed down substitutes must be found. Therefore efforts have been made to find new energy systems and a few alternatives have entered the market. One problem remains though; none of the substitutes has the capacity to produce as much electricity as nuclear power at the same low cost. What can be a possible reason for this? Perhaps the answer lies in the emergy return on investment?

Acknowledgements

I would like to thank my supervisor Michael Österlund for his excellent support, for his patience and interest in my work. Next I would like to thank Per Olov Nilsson who has spent a lot of time calculating transformities as well as discussing and explaining emergy evaluation.

I have been fortunate to have very nice colleagues at the Department of Neutron Research, Uppsala University. Thank you all for showing interest in my work and for contributing to a pleasant working environment. Finally I would like to thank my family and friends. You are the best, what more can I say.

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Appendix A. Transformities

Professor emeritus Per Olov Nilsson has provided the following text.

Biomass as a base for transformities

When energy flows of different kinds are compared they have to be related to each other by transformities (Odum, 1996, p. 33). A transformity is defined as the quotient of a product's emergy divided by its energy (Odum, 1996, p. 10). In his later works Odum uses solar energy as the base for calculations as the sun is the main energy source driving all processes on earth. Besides solar energy there are two other independent primary energy sources: *tides* caused by gravitational forces from the moon and the sun, and *earth heat* from radioactive disintegration and residual heat from earth formation. Odum converts these sources to solar emergy equivalents, *i.e.*, as if they where made by the sun, by calculations shown in Odum (1996, Chapter 3).

The concept is logical but not easily understood by everybody involved in the present discussion about replacing fossil fuels and nuclear power with biomass, wind power, solar energy and other renewable sources. People not used to relate the earth's biological and geological cycles to oil and nuclear power might find it less confusing to use biomass as a common denominator. Anyway, by using biomass, which is a manifestation of the aforementioned energies, one can avoid getting stuck in a discussion on the relevance of land uplift in considerations about biomass as an energy resource for the Swedish economy.

Hence, the base chosen for comparison of different energies in this paper is biomass standing in the field. This means that, by definition, 1 joule of biomass standing in the field has the transformity 1 emjoule denominated 1 J_{emb} .

The solar transformity (sej) for cultivated biomass standing in the field is somewhere between 4 800 and 7 500 sej/J (see Odum, 1996, p. 80; Doherty *et al.* 2002, pp. 63, 65). Conversion of solar transformities to biomass transformities can be done by dividing the actual solar transformity by the solar transformity for biomass. Such a transposition is made in Table A1 using a biomass transformity of 6 600 sej/J.

Willow farming

Willow farming is assumed to be carried out according to Hagström (2006, p.56-59) with following modifications made in consultation with Lars Christersson, professor emeritus in energy forestry:

- The rotation period is extended from 22 to 23 years.
- Yield is increased with 1 tonne dry matter per year.
- Fertilization is reduced from 14 to 7 occasions during the rotation period.
- The fertilization rate of nitrogen is increased from 80 to 100 kg per ha and occasion.
- No need for fertilization with phosphorus or potassium.
- No need for stone picking, rolling or trimming.
- Ash recycling is carried out two times during the rotation period, 1 000 kg ash each time.

The silviculture regime is shown in Table A2. Data for the operations are from Hagström (2006, pp. 342-391). Calculations of the transformity and emergy return on investment are shown in Table A3.

Fodder and food

Statistics on mean supply of energy, protein, fat and carbohydrates per capita and day by different foodstuffs in 2004 have been published by the Swedish Board of Agriculture in Yearbook of Agricultural Statistics 2006. These figures are multiplied by fodder equivalents (winter wheat) estimated in consultation with Sten Ebbersten, professor emeritus in agriculture. For example, raising a pig takes about three joules of wheat per joule of pork. Production of one joule of sugar takes 1/0,18 = 5.56 joules of biomass containing 18% sugar, etc., see Table A3. The emergy in wheat equivalents per person and year is multiplied by the average population in 2004 and this figure is converted to willow biomass equivalents by multiplying by the willow biomass transformity for winter wheat, see Table A4. The calculations of winter wheat transformity are based on a report by Sonesson (1993, pp. 34-47). Some of the data are modified in consultation with Sten Ebbersten.

Fuel wood

Hagström (2006, pp. 322-324, 329-333)

Truck transport

Hagström (2006, pp. 398-400).

Comminution

Hagström (2006, pp. 403-405).

Electric power generation from biomass

Hagström (2006, pp. 69-71, 427-431).

Methanol production from biomass

Hagström (2006, pp. 71-73, 436-439).

Emergy per unit money

As the transformities of the various energy sources are interdependent the calculation of emergy per unit money index has to be done in an iterative process. First the transformities of the various energy sources are calculated with an anticipated index, which may result in a new value. This will then be used in a new calculation, which may give a new value and so on. The iterations are carried on until the result is equal to the inserted value.

Total emergy use 2004, see Table A6:	$3.49 \cdot 10^{12}$	MJ_{emb}
Gross Domestic Production 2004, see Table A7:	2 565 056	MSEK
Emergy per unit money	1.3627	MJ_{emb}/SEK

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Table A1. Transformities for energy sources in solar emjoules per joule (sej/J) according to Odum (1996) converted to biomass emjoules per joule (J_{emb}/J).

	sej/J	J_{emb}/J
Provisions	660 000 [a)]	100.00
Crude oil	54 000 [b)]	8.18
Natural gas	48 000 [c)]	7.27
Coal and coke	40 000 [d)]	6.06
Forest biomass	6 600 [e)]	1.00
Electric power	160 000 [f)]	24.24
Peat	19 000 [g)]	2.88

[a)] Arbitrary chosen value as an interpolation of solar transformities for food in Odum (1996, Table C.5, p. 312).
[b)–g)] Odum (1996, Table C.2, p. 308).

Table A2. Silviculture regime for willow farming.

			1st cutting cycle			2nd–6th cutting cycle			7th cutting cycle			Totalt per ha and rotation	Occa-tions
Year number Operation	1	2	3	4	5	—	19	20	21	22	23		
Harrowing 1	1												1
Planting	1												1
Harrowing 2	2	1											3
Fertilizing			370			370			370			2 593 kg	7
Ash recirculation												2 000 kg	2
Cutting				24			30			30		204 t_{dm}	7
Field transport													7
Spraying herbicides										4		4 liter	1
Stump milling											1		1

Table A3. Willow farming

Operation	Flow per ha per rotation	Flow per ha per year	Cost analysis SEK/t$_{dm}$	Cost analysis SEK/ha	Emergy analysis Transformity MJ$_{emb}$/unit	Emergy MJ$_{emb}$/t$_{dm}$	Emergy MJ$_{emb}$/ha
PREPARATIONS FOR A NEW STAND							
Chemical stump treatment or weed control					176.57		246.7
Herbicides	4.0	0.17			101.20 MJ$_{emb}$/kg		17.6
Fuel	1.4	0.1 kg			101.20 MJ$_{emb}$/kg		6.0
Machine wear	0.04	0.00 kg/ha			303.60 MJ$_{emb}$/kg		0.1
Labour	27	1.16 SEK/ha		1.16	1.36 MJ$_{emb}$/SEK		1.6
Fuel	10	0.43 SEK/ha		0.43	1.36 MJ$_{emb}$/SEK		0.6
Capital cost	24	1.06 SEK/ha		1.06	1.36 MJ$_{emb}$/SEK		1.4
Herbicides	4 000	173.91 SEK/ha		173.91	1.36 MJ$_{emb}$/SEK		237.0
Accumulated value				176.57			246.7
Stump milling				33.46			174.2
Fuel	26.3	1.1 kg/ha			101.20 MJ$_{emb}$/kg		115.5
Machine wear	1.00	0.04 kg/ha			303.60 MJ$_{emb}$/kg		13.2
Labour	234	10.19 SEK/ha		10.19	1.36 MJ$_{emb}$/SEK		13.9
Fuel cost	190	8.25 SEK/ha		8.25	1.36 MJ$_{emb}$/SEK		11.2
Capital cost	345	15.02 SEK/ha		15.02	1.36 MJ$_{emb}$/SEK		20.5
Accumulated value				210.02			420.9
CULTIVATION							
Harrowing				8.03			39.9
Fuel	6.0	0.3 kg/ha			101.20 MJ$_{emb}$/kg		26.4
Machine wear	0.19	0.01 kg/ha			303.60 MJ$_{emb}$/kg		2.5
Labour	54	2.33 SEK/ha		2.33	1.36 MJ$_{emb}$/SEK		3.2
Fuel cost	43	1.89 SEK/ha		1.89	1.36 MJ$_{emb}$/SEK		2.6
Capital cost	88	3.81 SEK/ha		3.81	1.36 MJ$_{emb}$/SEK		5.2
Accumulated value				218.05			460.8
Planting				48.84			560.4
Fuel	7.9	0.3 kg/ha			101.20 MJ$_{emb}$/kg		34.8
Machine wear	0.63	0.03 kg/ha			303.60 MJ$_{emb}$/kg		8.4
Cuttings	486	21.12 kgts/ha			21.48 MJ$_{emb}$/kg		453.6
Labour	225	9.78 SEK/ha		9.78	1.36 MJ$_{emb}$/SEK		13.3
Fuel cost	57	2.48 SEK/ha		2.48	1.36 MJ$_{emb}$/SEK		3.4
Capital cost	793	34.48 SEK/ha		34.48	1.36 MJ$_{emb}$/SEK		47.0
Cuttings	48	2.09 SEK/ha		2.09	1.36 MJ$_{emb}$/SEK		2.8
Accumulated value				266.89			1 021.2
Mechanical weed control				122.81			425.4
Fuel	50.7	2.2 kg/ha			101.20 MJ$_{emb}$/kg		222.9
Machine wear	4.31	0.19 kg/ha			303.60 MJ$_{emb}$/kg		56.9
Labour	1 200	52.17 SEK/ha		52.17	1.36 MJ$_{emb}$/SEK		71.1
Fuel cost	366	15.92 SEK/ha		15.92	1.36 MJ$_{emb}$/SEK		21.7
Capital cost	1 258	54.71 SEK/ha		54.71	1.36 MJ$_{emb}$/SEK		74.5
Accumulated value				389.70			1 446.6
Fertilizing				117.42			1 782.3
Fertilizer	700	30.4 kgN/ha			48.77		1 484.4
Fuel	28.0	1.2 kg/ha			101.20 MJ$_{emb}$/kg		123.2
Machine wear	1.12	0.05 kg/ha			303.60 MJ$_{emb}$/kg		14.7
Labour	365	15.88 SEK/ha		15.88	1.36 MJ$_{emb}$/SEK		21.6
Fuel	202	8.80 SEK/ha		8.80	1.36 MJ$_{emb}$/SEK		12.0
Capital cost	383	16.65 SEK/ha		16.65	1.36 MJ$_{emb}$/SEK		22.7
Fertilizer	1 750	76 SEK/ha		76.09	1.36 MJ$_{emb}$/SEK		103.7
Accumulated value				507.12			3 228.9

Table A3 continued

Ash recycling				16.11			148.1
Ash	2 000	87.0 kg/ha			1.00 MJ_{emb}/kg		87.0
Fuel	9.4	0.4 kg/ha			101.20 MJ_{emb}/kg		41.5
Machine wear	0.38	0.02 kg/ha			303.60 MJ_{emb}/kg		5.0
Labour	123	5.35 SEK/ha		5.35	1.36 MJ_{emb}/SEK		7.3
Fuel cost	68	2.97 SEK/ha		2.97	1.36 MJ_{emb}/SEK		4.0
Capital cost	129	5.61 SEK/ha		5.61	1.36 MJ_{emb}/SEK		7.6
Ash. cost	50	2.17 SEK/ha		2.17	1.36 MJ_{emb}/SEK		3.0
Accumulated value				523.23		380.7	3 377.0
HARVESTING AND FIELD TRANSPORT							
Harvesting				354.15			2 898.4
Fuel	223.6	23.00 kg/ha			101.20 MJ_{emb}/kg		2 327.6
Machine wear	8.62	0.29 kg/ha			303.60 MJ_{emb}/kg		88.3
Labour	2 188	95 SEK/ha		95.11	1.36 MJ_{emb}/SEK		129.6
Fuel cost	1 616	166 SEK/ha		166.27	1.36 MJ_{emb}/SEK		226.5
Capital cost	8 936	93 SEK/ha		92.78	1.36 MJ_{emb}/SEK		126.4
Accumulated value				877.38		707.5	6 275.5
Field transport							7 016.5
Fuel		44.9 kg/ha			101.20 MJ_{emb}/kg		4 542.9
Machine wear		1.72 kg/ha			303.60 MJ_{emb}/kg		521.1
Labour		561 SEK/ha			1.36 MJ_{emb}/SEK		764.5
Fuel cost		325 SEK/ha			1.36 MJ_{emb}/SEK		442.1
Capital cost		547 SEK/ha			1.36 MJ_{emb}/SEK		745.8
Accumulated value			98.92	877.38		1 498.6	13 292.0
ADMINISTRATION AND COMMON COSTS							
Administration		14 %		119.64	1.36 MJ_{emb}/SEK		163.0
Common costs			3 000.00		1.36 MJ_{emb}/SEK		4 087.5
Accumulated value			112.41	997.02		1 977.8	17 542.5
TRANSPORT AND COMMINUTION							
Truck transport			26.96			173.6	
Fuel		1.3 kg/tts			101.20 MJ_{emb}/kg	132.4	
Machine wear		0.01 kg/tts			303.60 MJ_{emb}/kg	4.4	
Labour		7 SEK/tts			1.36 MJ_{emb}/SEK	9.9	
Fuel cost		9 SEK/tts			1.36 MJ_{emb}/SEK	12.9	
Capital cost		10 SEK/tts			1.36 MJ_{emb}/SEK	13.9	
Accumulated value			125.88			2 151.4	
Comminution			31.25			259.0	
Fuel		2.1 kg/tts			101.20 MJ_{emb}/kg	213.3	
Machine wear		0.01 kg/tts			303.60 MJ_{emb}/kg	3.2	
Labour		8 SEK/tts			1.36 MJ_{emb}/SEK	10.3	
Fuel cost		15 SEK/tts			1.36 MJ_{emb}/SEK	20.8	
Capital cost		8 SEK/tts			1.36 MJ_{emb}/SEK	11.5	
Accumulated value			157.13			2 410.4	

Yield 8.9 t_{dm}/ha
172 957 MJ/ha

Position	Transformity	Emergy return on investment
standing in the field	1.02 J_{emb}/J	51.22
in stack at road side	1.10 J_{emb}/J	9.86
after transport and comminution	1.12 J_{emb}/J	8.09
after electric power generation	2.92 J_{emb}/J	0.52
after methanol production	2.20 J_{emb}/J	0.83

Table A4. Energy and emergy (wheat equivalents, J_{emw}) in provisions per capita in Sweden 2004.

	Body [a] metbolism kJ/day	Transformity in [b] fodder units J_{emw}/J	Emergy in fodder equivalents kJ_{emw}/capita and day
Bread and cereals	3 793	1.00	3 793
Meat and meat products	1 599	3.40	5 437
Fish, crustaceans and mollusc	273	3.00	819
Milk	840	5.00	4 200
Cream and milk powder	285	5.00	1 425
Cheese	626	5.00	3 130
Eggs	150	5.00	750
Cooking fat	968	1.00	968
Vegetables	316	1.00	316
Fruits and berries	814	1.00	814
Potatoes and potato products	613	1.00	613
Sugar and syrup	383	5.56	2 128
Other provisions	1 347	5.00	6 735
Malt liquors and soft drinks	459	3.00	1 377
Alcoholic beverages	404	3.00	1 212
	12 870		33 716

Population in average 2004 [c]	8.994 million people
Energy in food for the whole population 2004 [d]	42.25 PJ/year
Transformity based on fodder units (winter wheat equivalents) [e]	2.62 J_{emw}/J
Transformity based on willow biomass equivalents [f]	3.83 J_{emb}/J

a) Yearbook of Agricultural Statistics 2006, Table 17.3, p. 283.

b) Estimates in consultation with Sten Ebbersten, professor emeritus in agricultural cropping systems.

c) Yearbook of Agricultural Statistics 2006, Table 17.1, p. 280.

d) $12\ 870 \times 8.994 \times 10^6 = 42.25$ PJ/year

e) 33 716/12 870 = 2.62 J_{emw}/J

f) Wheat transformity for food x Willow transformity for wheat = 2.62 x 1.46 = 3.83 J_{emb}/J

Table A5. Winter wheat production.

Operation	Flow per ha and year		Cost analysis SEK/ha	Emergy analysis Transformity MJ_{emb}/unit	Emergy MJ_{emb}/ha
CULTIVATION					
Stubble treatment			785		4 728
Fuel	30.2	kg/ha		101.22 MJ_{emb}/kg	3 061
Machine wear	1.97	kg/ha		303.66 MJ_{emb}/kg	597
Labour	180	SEK/ha	180	1.36 MJ_{emb}/SEK	245
Fuel cost	219	SEK/ha	219	1.36 MJ_{emb}/SEK	298
Capital cost	387	SEK/ha	387	1.36 MJ_{emb}/SEK	527
Accumulated value			785		4 728
Ploughing			1 100		6 376
Fuel	42.8	kg/ha		101.22 MJ_{emb}/kg	4 336
Machine wear	1.78	kg/ha		303.66 MJ_{emb}/kg	541
Labour	255	SEK/ha	255	1.36 MJ_{emb}/SEK	347
Fuel cost	310	SEK/ha	310	1.36 MJ_{emb}/SEK	422
Capital cost	536	SEK/ha	536	1.36 MJ_{emb}/SEK	730
Accumulated value			1 886		11 104
Harrowing			596		3 312
Fuel	20.7	kg/ha		101.22 MJ_{emb}/kg	2 092
Machine wear	1.34	kg/ha		303.66 MJ_{emb}/kg	408
Labour	123	SEK/ha	123	1.36 MJ_{emb}/SEK	168
Fuel cost	149	SEK/ha	149	1.36 MJ_{emb}/SEK	204
Capital cost	324	SEK/ha	324	1.36 MJ_{emb}/SEK	441
Accumulated value			2 482		14 416
Sowing			342		1 984
Fuel	10.2	kg/ha		101.22 MJ_{emb}/kg	1 029
Machine wear	0.69	kg/ha		303.66 MJ_{emb}/kg	211
Utsäde	10.0	kg/ha		27.79 MJ_{emb}/kg	278
Labour	123	SEK/ha	123	1.36 MJ_{emb}/SEK	168
Fuel cost	74	SEK/ha	74	1.36 MJ_{emb}/SEK	100
Capital cost	145	SEK/ha	145	1.36 MJ_{emb}/SEK	198
Utsädeskostnad	0	SEK/ha		1.36	0
Accumulated value			2 823		16 400
Rolling			140		686
Fuel	3.3	kg/ha		101.22 MJ_{emb}/kg	339
Machine wear	0.52	kg/ha		303.66 MJ_{emb}/kg	157
Labour	41	SEK/ha	41	1.36 MJ_{emb}/SEK	55
Fuel cost	24	SEK/ha	24	1.36 MJ_{emb}/SEK	33
Capital cost	75	SEK/ha	75	1.36 MJ_{emb}/SEK	103
Accumulated value			2 963		17 086
Fertilization			2 292		3 697
Fuel	5.1	kg/ha		101.22 MJ_{emb}/kg	512
Machine wear	0.20	kg/ha		303.66 MJ_{emb}/kg	61
Labour	66	SEK/ha	66	1.36 MJ_{emb}/SEK	90
Fuel cost	37	SEK/ha	37	1.36 MJ_{emb}/SEK	50
Capital cost	64	SEK/ha	64	1.36 MJ_{emb}/SEK	88
Fertilizer	2 125	SEK/ha	2 125	1.36 MJ_{emb}/SEK	2 896
Accumulated value			5 255		20 783
Lastning och transport av gödsel			117		511
Fuel	3.0	kg/ha		101.22 MJ_{emb}/kg	308
Machine wear	0.15	kg/ha		303.66 MJ_{emb}/kg	45
Labour	48	SEK/ha	48	1.36 MJ_{emb}/SEK	65
Fuel cost	22	SEK/ha	22	1.36 MJ_{emb}/SEK	30
Capital cost	47	SEK/ha	47	1.36 MJ_{emb}/SEK	64
Accumulated value			5 372		21 294

Table A5 continued

Chemical weed control			1 247		2 284
Fuel	5.1	kg/ha		101.22 MJ_{emb}/kg	512
Machine wear	0.24	kg/ha		303.66 MJ_{emb}/kg	72
Labour	66	SEK/ha	66	1.36 MJ_{emb}/SEK	90
Fuel cost	37	SEK/ha	37	1.36 MJ_{emb}/SEK	50
Capital cost	124	SEK/ha	124	1.36 MJ_{emb}/SEK	170
Herbicides	1 020	SEK/ha	1 020	1.36 MJ_{emb}/SEK	1 390
Accumulated value			6 619		23 578
HARVESTING AND TRANSPORT					
Harvesting			4 505		10 641
Fuel	28.8	kg/ha		101.22 MJ_{emb}/kg	2 910
Machine wear	5.24	kg/ha		303.66 MJ_{emb}/kg	1 592
Labour	188	SEK/ha	188	1.36 MJ_{emb}/SEK	256
Fuel cost	208	SEK/ha	208	1.36 MJ_{emb}/SEK	283
Capital cost	4 109	SEK/ha	4 109	1.36 MJ_{emb}/SEK	5 600
Accumulated value			11 124		34 219
Transport of grain			113		602
Fuel	3.7	kg/ha		101.22 MJ_{emb}/kg	377
Machine wear	0.24	kg/ha		303.66 MJ_{emb}/kg	72
Labour	45	SEK/ha	45	1.36 MJ_{emb}/SEK	61
Fuel cost	27	SEK/ha	27	1.36 MJ_{emb}/SEK	37
Capital cost	41	SEK/ha	41	1.36 MJ_{emb}/SEK	56
Accumulated value			11 237		34 821
Drying			488		6 599
Olja	30.6	kg/ha		101.22 MJ_{emb}/kg	3 101
Electric power	95.2	MJ/ha		4 MJ_{emb}/MJ	381
Machine wear	8.0	kg/ha		303.66 MJ_{emb}/kg	2 415
Labour	1	SEK/ha	1	1.36 MJ_{emb}/SEK	1
Oil cost	221	SEK/ha	221	1.36 MJ_{emb}/SEK	302
Electric power	26.44	SEK/ha		1.36 MJ_{emb}/SEK	36
Capital cost	266	SEK/ha	266	1.36 MJ_{emb}/SEK	362
Accumulated value			11 725		41 420
Yield	89 544	MJ/ha			
Harvest	5 600	kg/ha		2.09 SEK/$kg_{18\%}$	
Moisture content	18	%			
Harvest, dry matter	4 592	kg_{dm}/ha		2.55 SEK/kg_{dm}	
Transformity	1.46J_{emb}/J				

Table A6. Energy and emergy use in Sweden 2004.

Item	Annual flow		Conversion factor		Energy use J/year	Trans-formity J_{emb}/J	Emergy J_{emb}/year	
Provisions for domestic consumption [a)]	42.2	PJ	$1.00 \cdot 10^{15}$	J/PJ	$4.22 \cdot 10^{16}$	3.83	$1.62 \cdot 10^{17}$	4.6%
Crude oil and oil products [b)]	568.1	PJ	$1.00 \cdot 10^{15}$	J/PJ	$5.68 \cdot 10^{17}$	2.21	$1.25 \cdot 10^{18}$	35.8%
Natural gas [c)]	15.8	PJ	$1.00 \cdot 10^{15}$	J/PJ	$1.58 \cdot 10^{16}$	2.21	$3.49 \cdot 10^{16}$	1.0%
Coal and coke [d)]	63.0	PJ	$1.00 \cdot 10^{15}$	J/PJ	$6.30 \cdot 10^{16}$	2.21	$1.39 \cdot 10^{17}$	4.0%
Forest biomass, energy part of [e)]	17.9	Mt_{dm}	$2.01 \cdot 10^{16}$	J/Mt_{dm}	$3.59 \cdot 10^{17}$	1.30	$4.67 \cdot 10^{17}$	13.3%
Electric power [f)]	472.0	PJ	$1.00 \cdot 10^{15}$	J/PJ	$4.72 \cdot 10^{17}$	2.92	$1.38 \cdot 10^{18}$	39.4%
Peat [g)]	3.2	TWh	$3.60 \cdot 10^{15}$	J/TWh	$5.47 \cdot 10^{16}$	1.12	$6.15 \cdot 10^{16}$	1.8%
Total energy and emergy use 2004					$1.57 \cdot 10^{18}$		$3.49 \cdot 10^{18}$	

Table A7. Sweden's Gross Domestic Production in 2004. Million SEK. Source: Statistics Sweden <http://www.scb.se>, table BNPkvartal20063, flik FV_LP.

GDP at market prices				2 565 056
Market producers and producers for own final use			2 051 816	
Taxes on products			333 393	
Subsidies on products			-15 641	
Value added at basic prices, market producers			1 734 064	
Producers of goods		659 853		
Agriculture, forestry, fishing	39 519			
Mining and quarrying	7 615			
Manufacturing	443 093			
Electricity, gas, water	67 859			
Construction	101 767			
Producers of services		1 074 211		
Wholesale and retail trade	240 286			
Hotels and restaurants	33 153			
Transport and communication	162 274			
Financial intermediation	101 111			
Real estate, business activities	430 219			
Education, health and social work	58 611			
Community, social and personal service	48 557			
Value added, NPISH			34 218	
Value added, government			479 022	
Central government and social security funds		127 143		
Local authorities		351 879		

Appendix B. Emergy feedback from the economy

Table B. Emergy in all steps of the nuclear power process

Electricity from nuclear power 24,063 GWh_e

Operation	Quantity Annual flows	Cost analysis SEK/year	 SEK/kWh	Emergy analysis Transformity	Emergy MJ_{emb}/year	 MJ_{emb}/kWh
Extraction			0.01999		4.03E+09	0.16730
Fuel	1.37E+15 J			2.20 J_{emb}/J	3.03E+09	0.12572
Electricity	1.18E+14 J			2.92 J_{emb}/J	3.45E+08	0.01434
Labour costs				1.36 MJ_{emb}/SEK		
Operation & maintenance costs				1.36 MJ_{emb}/SEK		
Capital costs	SEK			1.36 MJ_{emb}/SEK		
Extraction costs	4.81E+08 SEK	4.81E+08	0.01999	1.36 MJ_{emb}/SEK	6.56E+08	0.02725
Accumulated sum			0.01999		4.03E+09	0.16730
Transportation			0.00008		9.98E+06	0.00041
Motor fuel	3.33E+12 J			2.20 J_{emb}/J	7.35E+06	0.00031
Quantity	522.3 t					
Load size	40 t					
Number of turns	16					
Distance per turn	6,000 km					
Distance per year	192,690 km					
Transport costs	1,929,161 SEK	1.93E+06	0.00008	1.36 MJ_{emb}/SEK	2.63E+06	0.00011
Accumulated sum			0.02007		4.04E+09	0.16772
Conversion			0.00160		1.51E+09	0.06286
Fuel	6.31E+14 J			2.20 J_{emb}/J	1.39E+09	0.05784
Electricity	2.34E+13 J			2.92 J_{emb}/J	6.83E+07	0.00284
Labour costs						
Operation and maintanence costs						
Captial costs	SEK			1.36 MJ_{emb}/SEK		
Conversion costs	3.85E+07 SEK	3.85E+07	0.00160	1.36 MJ_{emb}/SEK	5.25E+07	0.00218
Accumulated sum			0.02167		5.55E+09	0.23058
Transportation			0.00002		3.01E+06	0.00013
Motor fuel	1.01E+12 J			2.20 J_{emb}/J	2.22E+06	0.00009
Quantity	655.1 t					
Load size	40 t					
Number of turns	19					
Distance per turn	3,000 km					
Distance per year	58,136 km					
Transport costs	582,044 SEK	5.82E+05	0.00002	1.36 MJ_{emb}/SEK	7.94E+05	0.00003
Accumulated sum			0.02169		5.55E+09	0.23071
Enrichment			0.01074		8.59E+08	0.03569
Fuel	1.78E+14 J			2.20 J_{emb}/J	3.93E+08	0.01632
Electricity	4.67E+13 J			2.92 J_{emb}/J	1.36E+08	0.00567
Labour costs	8.53E+06 SEK					
Operation and maintanence costs						
Capital costs	2.24E+07 SEK		0.00026			
Enrichment costs	2.42E+08 SEK	2.42E+08	0.01048	1.36 MJ_{emb}/SEK	3.30E+08	0.01370
Accumulated sum			0.03243		6.41E+09	0.26640
Transportation			0.00001		8.56E+05	0.00004
Motor fuel	2.86E+11 J			2.20 J_{emb}/J	6.31E+05	0.00003
Quantity	100.5 t					
Load size	40 t					
Number of turns	6					
Distance per turn	3,000 km					
Distance per year	16,537 km					
Transport costs	165,565 SEK	1.66E+05	0.00001	1.36 MJ_{emb}/SEK	2.26E+05	0.00001
Accumulated sum			0.03244		6.41E+09	0.26643
Fuel fabrication			0.00624		8.18E+08	0.03398
Fuel	1.84E+14 J			2.20 J_{emb}/J	4.06E+08	0.01688
Electricity	7.37E+13 J			2.92 J_{emb}/J	2.15E+08	0.00894
Labour costs	SEK					
Operation and maintanence costs						
Capital costs						
Fuel fabrication costs	1.44E+08 SEK	1.44E+08	0.00624	1.36 MJ_{emb}/SEK	1.96E+08	0.00815
Accumulated sum			0.03867		7.23E+09	0.30041
Transportation			0.00000		7.66E+04	0.00000
Motor fuel	2.56E+10 J			2.20 J_{emb}/J	5.64E+04	0.00000
Quantity	77.1 t					
Load size	40 t					

Table B. Emergy in all steps of the nuclear power process continued

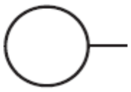
Electricity production				0.07263		1.28E+10	0.53173
Fuel	4.98E+12	J			2.20 J_{emb}/J	1.10E+07	0.00046
Electricity	3.56E+15	J			2.92 J_{emb}/J	1.04E+10	0.43223
Labour costs					1.36 MJ_{emb}/SEK		
Operation and maintanence costs	1.13E+09	SEK	1.13E+09	0.04710	1.36 MJ_{emb}/SEK	1.55E+09	0.06422
Capital costs	4.85E+08	SEK	4.85E+08	0.02017	1.36 MJ_{emb}/SEK	6.62E+08	0.02750
Insurance	3.31E+07	SEK	3.31E+07	0.00137	1.36 MJ_{emb}/SEK	4.51E+07	
Decommissioning costs	9.61E+07	SEK	9.61E+07	0.00399	1.36 MJ_{emb}/SEK	1.31E+08	0.00544
Power plant costs	1.75E+09	SEK	1.75E+09	0.07263	1.36 MJ_{emb}/SEK	2.38E+09	0.09904
Accumulated sum				0.11130		2.00E+10	0.83214
Transportation				0.00017		3.70E+07	0.00154
Motor fuel	1.43E+13	J			2.20 J_{emb}/J	3.14E+07	0.00131
Quantity	655.1	t					
Load size	40	t					
Number of turns	19						
Distance per turn	20	km					
Distance per year	388	km					
Transport costs	4.E+06	SEK	4.07E+06	0.00017	1.36 MJ_{emb}/SEK	5.55E+06	0.00023
Accumulated sum				0.11147		2.01E+10	0.83367
Low and intermediate level waste storage (SFR present)+Decommissioning waste storage (SFR future)				0.00083		4.44E+07	0.00184
Fuel					2.20 J_{emb}/J		
Electricity	5.89E+12	J			2.92 J_{emb}/J	1.72E+07	0.00072
Labour costs		SEK			1.36 MJ_{emb}/SEK		
Operation and maintanence costs	8.83E+06	SEK	8.83E+06	0.00037	1.36 MJ_{emb}/SEK	1.20E+07	0.00050
Capital costs	9.49E+06	SEK	9.49E+06	0.00039	1.36 MJ_{emb}/SEK	1.29E+07	0.00054
Decommissioning costs	1.61E+06	SEK	1.61E+06	0.00007	1.36 MJ_{emb}/SEK	2.19E+06	0.00009
Storage costs	1.99E+07	SEK	1.99E+07	0.00083	1.36 MJ_{emb}/SEK	2.72E+07	0.00113
Accumulated sum				0.11230		2.01E+10	0.83552
Transportation						8.38E+05	
Motor fuel	3.80E+11	J			2.20 J_{emb}/J	8.38E+05	
Labor costs							
Operation & maintenance costs							
Capital costs							
Transport costs		SEK			1.36 MJ_{emb}/SEK		
Accumulated sum				0.11230		2.01E+10	0.83552
Central interim storage (CLAB). Storage of high level waste				0.00187		1.10E+08	0.00459
Fuel					2.20 J_{emb}/J		
Electricity	1.682E+13	J			2.92 J_{emb}/J	4.91E+07	0.00204
Labour costs		SEK			1.36 MJ_{emb}/SEK		
Operation and maintanence costs	2.92E+07	SEK	2.92E+07	0.00121	1.36 MJ_{emb}/SEK	3.98E+07	0.00165
Capital costs	1.24E+07	SEK	1.24E+07	0.00052	1.36 MJ_{emb}/SEK	1.69E+07	0.00070
Decommissioning costs	3.36E+06	SEK	3.36E+06	0.00014	1.36 MJ_{emb}/SEK	4.58E+06	0.00019
Storage costs	4.50E+07	SEK	4.50E+07	0.00187	1.36 MJ_{emb}/SEK	6.13E+07	0.00255
Accumulated sum				0.11417		2.02E+10	0.84011
Capsule manufacturing				0.00117		8.18E+07	0.00340
Fuel	1.96E+13				2.20 J_{emb}/J	4.32E+07	0.00180
Operation and maintanence costs + the cost for the	2.59E+07	SEK	2.59E+07	0.00108	1.36 MJ_{emb}/SEK	3.53E+07	0.00147
Capital costs	1.64E+06	SEK	1.64E+06	0.00007	1.36 MJ_{emb}/SEK	2.24E+06	0.00009
Decommissioning costs	6.94E+05	SEK	6.94E+05	0.00003	1.36 MJ_{emb}/SEK	9.46E+05	0.00004
Capsule manufacturing costs	2.83E+07	SEK	2.83E+07	0.00117	1.36 MJ_{emb}/SEK	3.85E+07	0.00160
Accumulated sum				0.11534		2.03E+10	0.84351

Table B. Emergy in all steps of the nuclear power process continued

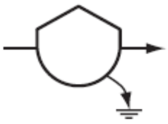
Encapsulation of high level waste				0.00132		8.64E+07	0.00359
Fuel	1.96E+13				2.20 J_{emb}/J	4.32E+07	0.001797
Electricity							
Labour costs		SEK			1.36 MJ_{emb}/SEK		
Operation and maintanence costs	1.43E+07	SEK	1.43E+07	0.00059	1.36 MJ_{emb}/SEK	1.95E+07	0.00081
Capital costs	1.66E+07	SEK	1.66E+07	0.00069	1.36 MJ_{emb}/SEK	2.27E+07	0.00094
Decommissioning cost	6.94E+05	SEK	6.94E+05	0.00003	1.36 MJ_{emb}/SEK	9.46E+05	0.00004
Encapsulation costs	3.16E+07	SEK	3.16E+07	0.00132	1.36 MJ_{emb}/SEK	4.32E+07	0.00179
Accumulated sum				0.11666		2.04E+10	0.84710
Deep repository of high level waste				0.00559		1.84E+08	0.00763
Fuel							
Electricity							
Labour costs		SEK			1.36 MJ_{emb}/SEK		
Operation and maintanence costs	3.45E+07	SEK	3.45E+07	0.00143	1.36 MJ_{emb}/SEK	4.70E+07	0.00195
Capital costs	7.56E+07	SEK	7.56E+07	0.00314	1.36 MJ_{emb}/SEK	1.03E+08	0.00428
Decommissioning cost	2.46E+07	SEK	2.46E+07	0.00102	1.36 MJ_{emb}/SEK	3.35E+07	0.00139
Storage costs	1.35E+08	SEK	1.35E+08	0.00559	1.36 MJ_{emb}/SEK	1.84E+08	0.00763
Accumulated sum				0.12225		2.06E+10	0.85472

Appendix C. Energy systems symbols

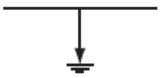
Energy circuit. A pathway whose flow is proportional to the quantity in the storage or source upstream.



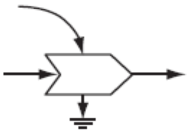
Source. Outside source of energy delivering forces according to a program controlled from outside; a forcing function.



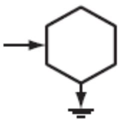
Tank. A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.



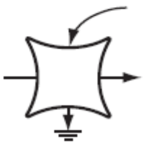
Heat sink. Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.



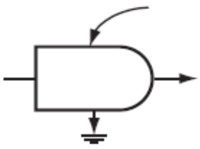
Interaction. Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate.



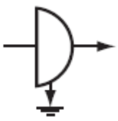
Consumer. Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.



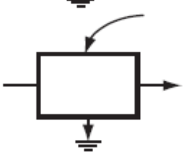
Switching action. A symbol that indicates one or more switching actions.



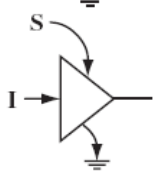
Producer. Unit that collects and transforms low-quality energy under control interactions of high-quality flows.



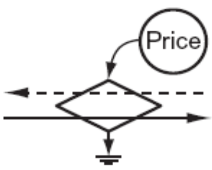
Self-limiting energy receiver. A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reacting on a circular pathway within.



Box. Miscellaneous symbol to use for whatever unit or function is labeled.



Constant-gain amplifier. A unit that delivers an output in proportion to the input I but changed by a constant factor as long as the energy sourcc S is sufficient.



Transaction. A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

Figure C. Symbols and definitions of the emergy language diagramming used to represent systems [2].