BIOENERG

Emergy Evaluation of Forest Production and Industries in Sweden

Steven J. Doherty
Per Olov Nilsson
Howard T. Odum

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Abstract

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Sweden is heavily dependent on imported fossil fuels and takes measures to replace them with biofuels from its forestry and agriculture. This study evaluates the feasibility to use more of the forest resource in Southern Sweden as a fuel with respect to the need for raw material supply to the forest industry.

As standard economic theory does not take nature in account explicitly a new evaluation method based on emergy values was used. Emergy is defined as the available energy of one kind previously required directly and indirectly to generate an ecosystem component, a market commodity or service. Its measure is the solar emjoule abbreviated sej.

Sweden's total emergy use in 1988 (the year of study) was $2\,580 \times 10^{20}$ sej of which 28% came from natural resources in Sweden. The gross national product was 178 billion dollars, which gives an emergy to dollar ratio of 1.45×10^{12} sej/\$.

The emergy input to one hectare forest land is carried by rain, 352×10^{12} sej/year at a rain fall of 800 mm/year. A forest biomass production of 9 cubic meters solid per year means 39×10^{12} sej/m^3 4485 sej/J of forest biomass. Inputs for silviculture and harvesting were estimated at 204×10^{12} sej/ha giving 9500 sej/J harvested wood (6.4 m^3 solid at forest roadside). After transport and processing to sawn wood, pulp and paper products and heat the total amount of emergy input carried by the 57 million m^3 harvest of solid wood was roughly 387×10^{20} sej.

Total market revenues derived from export sales of forest industry products was about 8 billion U.S. dollars, representing about five percent of the GNP in 1988. This study indicates about 250×10^{20} sej of the solar emergy supporting Sweden's forest industry was sold as forest products in export markets. This translates into roughly 17 billion dollars in macro-economic value, representing about 10% of Sweden's emergy use in 1988 or twice the contribution accounted for by market revenues.

Net yields and investment ratios were compared between product transformations of naturally grown coniferous forest and intensively cultured willow. Net yield ratios approach 1.0 for district heat produced from both forest wood and short rotation willow, indicating that these alternate sources cannot at this time replace existing fossil fuels which yield between 3 and 6 times more emergy. Harvested willow, because of intensive management, requires investments five times that of spruce/pine. This results in an investment ratio of purchased to environmental resources of almost 20 to 1 for heat derived from willow cuttings compared with a 4 to 1 ratio for silvicultured and processed spruce/pine.

The harvest of the forest in Southern Sweden could be increased within limits of sustainability. If agriculture land also was converted to forestry the emergy contribution to the national economy could be increased from present level up to about 485×10^{20} sej/year.

Keywords: emergy, forest energy, short rotation forestry, willow cultivation, wood powder, forest industry, economics.

Author's addresses:

Steven J. Doherty, Natural Resource Management, Sustainable Systems Science, PREE, 101 ECB, Slippery Rock University, Slippery Rock, PA 16057-1326, U.S.A.

Per Olov Nilsson, Department of Bioenergy, Swedish University of Agricultural Sciences, SE-750 07 Uppsala, Sweden

Howard T. Odum, Center for Environmental Policy and Department of Environmental Engineering Sciences, University of Florida, Gainesville, Florida 32611, U.S.A.

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Preface

The background of this study goes back to the oil crises caused by the October war in 1973 when the Arab states attacked Israel and simultaneously proclaimed an oil embargo which – as the war itself – came as a surprise and a shock to the superpowers U.S.A. and the Soviet Union, as well as Western Europe and Japan. Western Europe had at that time during the last 20 year period changed its energy signature from self-sufficiency to 60 percent dependence on imports, mainly in the form of oil.

Sweden was especially vulnerable with no indigenous fossil fuels, a high energy consumption due to a well developed heavy industry based on steel manufacturing and forest products, a cold climate and long transport distances. As much as 70 percent of the total energy supply came as imported oil, mainly from the Arab states.

The crisis was over within a couple of month, but it was quite obvious that Sweden had to change its energy supply situation, at that time emphasizing reduction of the dependence on imported oil. In this context scientists at the Royal College of Forestry (later on merged into the Swedish University of Agricultural Sciences) proposed a research and development program to use forest residues and intensively grown energy forests (salix plantations on wet lands or abandoned farmlands) to replace fossil fuels. The program was almost immediately approved by the Swedish government and Parliament. A couple of years later the program was expanded to also include bioenergy from agriculture crops (straw, energy grass, sugar beat, artichoke and others).

Quite another controversial issue arouse during the 1970s: nuclear power. Three months after the atom bombs were felled over Hiroshima and Nagasaki in August 1945, the Swedish government started planning for a research and development program for nuclear power with emphasis on civil applications but also including nuclear weapons. The Swedish peace movement was very strong and politically influential with leaders as Alva Myrdal and Inga Thorsson. After heavy debates in the 1950s whether to continue the development of nuclear weapons, this part of the program was abandoned in the beginning of the 1960s.

The development of civil nuclear power continued and the first Swedish nuclear power reactor, Oskarshamn 1, was put into commercial operation in 1972, the twelfth and last in 1985. Much of the generated electricity could replace fossil fuels which were reduced from about 350 TWh/year to about 250 TWh/year during that period. Nuclear power continued to be a controversial issue in the Swedish parliament. The resistance came, and still comes, from environmentalists in all political parties, who claim that nuclear power production is unsafe with risks for radioactive outlets, and that the plutonium in the residues can be used for production of nuclear weapons or might get into the hands of terrorists.

Sweden has large deposits of low grade uranium. In the 1970s there were plans to use the assets but the public opinion and a veto from the concerned local community put an end to ore-mining plans in 1977, and the issue has so far not been brought up again.

The incident in a nuclear reactor at Three Mile Island, Harrisburg, U.S.A. in 1979 raised the heat in the Swedish nuclear power debate. A referendum was held in 1980 resulting in a political decision to allow operation in the six reactors already built and the next six reactors that were planned for, but all nuclear power should then be phased out by the year 2010. The decision has been modified since then, and the date for final shut down is now kept open. The first nuclear reactor, Barsebäck 1, was taken out of operation in November 1999.

The focus of the energy issue had rapidly change from replacement of imported fossil fuels to replacement of nuclear power. The need for alternative energy sources was the same and our bioenergy program still had strong political and financial support.

In the 1990s the focus changed again: green house gases and climatic change became the main issue. The Swedish research and development efforts to establish bioenergy as an alternative to fossil fuels are still extensive. Since the oil crises in 1973 the bioenergy supply in Sweden has grown from about 40 TWh to almost 100 TWh in 2001. The increase is mainly due to that biomass of different kinds now is the main fuel in the rapidly expanding district heating sector.

The Swedish forest industry, especially the board industry but also the pulp and paper industry, has all the time disliked the idea to use wood for energy outside its own control. The competition from such a big and strong conglomerate of actors as the energy sector might cause difficulties to get the raw material in wanted quantities at reasonable prices. The forest industry also needs large quantities of low cost electricity for its highly power and energy demanding processes and would not support a rapid phase-out of nuclear power. On the other hand the private forest owners, who control fifty percent of the forest land, are strong bioenergy promoters as a wood fuel assortment, in addition to saw logs and pulpwood, would raise or maintain the economic value of their forests.

Vattenfall, the largest of the Swedish electric power companies, run a special bioenergy project from 1987 to the mid 1990s in cooperation with the forest owners association in Southern Sweden (Södra). They were interested in the forest energy potential and carried out an extensive investigation of the physical resource (Danielsson *et al.* 1990). This study needed to be followed up by a study on the economic feasibility to harvest and utilize the resource with respect to on-going traditional forestry and the existing energy supply system and energy sources.

Some of the scientists at our university were involved in this task. It became obvious to us that standard economic evaluation methods might be misleading when trying to find scientifically based and rigid answers to the questions. In fact it is increasingly understood by scientists and others that the prevailing theories for use and management of natural resources are insufficient and partly irrelevant. This has caused a reappraisal of science which derives from the insights about finite resources, the limits of the environment to dispose of waste, and the interdependence

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of all living and non-living systems on our planet. Standard economic models are criticized as they deal only with the human economy and do not explicitly account for nature's contributions to economic wealth or human well-being.

In a draft (1992) to his book Environmental accounting (1996) Howard T. Odum points out that

> "Many if not most people of the world assume that the economy is not subject to scientific prediction but is a result of human free choice by businesses and individuals motivated by their individual needs. A different point of view is that the human economy, like many other self-organizing systems of nature, operates according to principles involving energy, materials, information, hierarchical organization, and consumer uses that reinforce production."

Hall *et al.* (1986, p. 35) have addressed the same issue and state that standard economics seems to have missed the important point that

> "...goods and services are derived ultimately from natural resources, which are the real source of material wealth for humans, not the money that represents them in market transactions. Unfortunately many economists appear to have lost sight of this truth and have resorted to manipulating money flows as a proxy for the physical flows of goods and services. This approach is not always effective because natural resources obey a different set of laws from monetary flows."

Traditional economics has been described as a merry-go-round without physical constraints, whereas in reality all productive processes are unidirectional flows of energy and matter which are limited in supply. Methods attempting to bridge the gap between human economies and nature are now beginning to be developed by scientists from many fields. Trials are made to develop traditional economic models to also include the environment. This is not easy because traditional models treat nature and environmental processes as "externalities" and therefore almost by definition do not fit the objectives of an integrated study.

One approach that seems to be of profound importance is **emergy evaluation** pioneered by Dr. Howard T. Odum and his colleagues at the Center for Environmental Policy at the University of Florida, U.S.A. It allows studies of the combined macro-economy of humans and nature within the same model. Energy, both direct and embodied (hence emergy), is the measure quantifying the interactions in the system, since all resource storages and processes can be expressed in energy terms. The concept is based on systems theory and founded in general principles of self-organization and thermodynamics.

Professor Ulf Sundberg contacted Dr. H.T. Odum at University of Florida who became interested in the issues we wanted to study. After mutual visits to Sweden and Florida a cooperation was established and one of Dr. Odum's assistants, Steven Doherty, came to Sweden and joined the bioenergy group at the Swedish University of Agricultural Sciences in Garpenberg for half a year financed by Vattenfall. The study was carried out by Steven Doherty assisted by the bioenergy group who specified the questions of interest and provided the data needed for the calculations. Dr. Odum in Florida supervised the study and made the inferences of the studied cases. He also wrote the chapters on forest contributions to the Swedish national economy, trade benefits from foreign sales of forest products as well as the final summary and recommendations.

Some readers might find it strange that one third of the report is about the Swedish economy in general and that the report to a large extent is dealing with forestry and forest industry when the intended focus is on wood for energy. The explanation is that it is not possible to make a relevant analysis of any sector of the economy without considering the next larger scale level of the hierachical web. Thus forestry has to be seen as a part of Sweden and forest energy as a part of forestry. Another reason for studying the whole economy is that the emergy evaluation method requires that a general value of how many basic energy units a monetary unit can buy, a solar emergy to dollar index, is established.

Uppsala in July 2002

Per Olov Nilsson

P.S.

On 22 August 2002 I received the following e-mail message from Mark T. Brown, for two decades H.T. Odum's esteemed partner in energy systems projects, coteaching and graduate instruction:

> Dear friends, colleagues...
>
> This is not easy to write and there is no gentle ways to say this. HT's brain cancer is progressing, rapidly. As a result, his condition is deteriorating daily. I have discussed this email with Betty and HT and both have said that I should write. His condition is such that his doctors optimistically give him 2–4 weeks. So...if you were considering coming to see HT this fall, you should do so now. After his passing, we will have a memorial service for HT in the back yard of the Center for Wetlands...in the shade of the three cypress trees planted there in the early 1970's. We will notify everyone when that will be.
>
> Warmest regards,
> Mark

Howard T. Odum died on 11 September 2002.

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Introduction

In order to consider alternative plans for production and use of forest products in Sweden in times of increasing concern over energy, a systems evaluation was made of forest reserves, annual production, utilization, exports and alternatives for the future. All resource inputs were synthesized using a common measure in order to make a comprehensive analysis of Sweden's forest sector and its role in the national ecological-economic system.

Forests, the dominant ecological land cover in Sweden, are harvested as timber for the saw milling industry, pulpwood for the pulp and paper industry and board wood for the board industry. A minor part of the harvest is directly used as fuel wood but about forty percent of the raw material in the forest industry form by-products as sawdust, bark, and lignin in the lyes of the chemical pulp industry, all used for energy purposes either internally or in district heating plants. Currently, logging residues including branches, tops and some of the needles are used as alternative fuels for district heating, being processed into wood chips, pellets or wood powder. Increasingly forest resources are being developed as an energy source to compete with and possibly replace imported fuels.

Historically, forests have been a primary energy source for Sweden. During the Swedish Baltic Empire of the 17th and 18th centuries, charcoal burners supplied the steel and copper works with energy (Sundberg 1991). Together, along with its metal and mineral ore reserves and its hydro power facilities, forests continue to supply Sweden with an indigenous resource base to develop and prosper from. Overview maps in Figure 1 and Figures A–I in Appendix A are showing Sweden´s major urban areas, district heating facilities, forest areas, forest industries, agricultural lands, mining districts, and hydroelectric rivers and nuclear power plants.

An alternative biophysical measure to economic valuation, **emergy**, (spelled with an m) was used to evaluate current and alternative uses of Sweden's forests. Emergy is the work previously required to generate a product or service and constitutes a scientific measure of contribution and potential influence a given input has on a production process. The concept developed from comprehensive analyses of systems and from an understanding of general system properties such as self-organization.

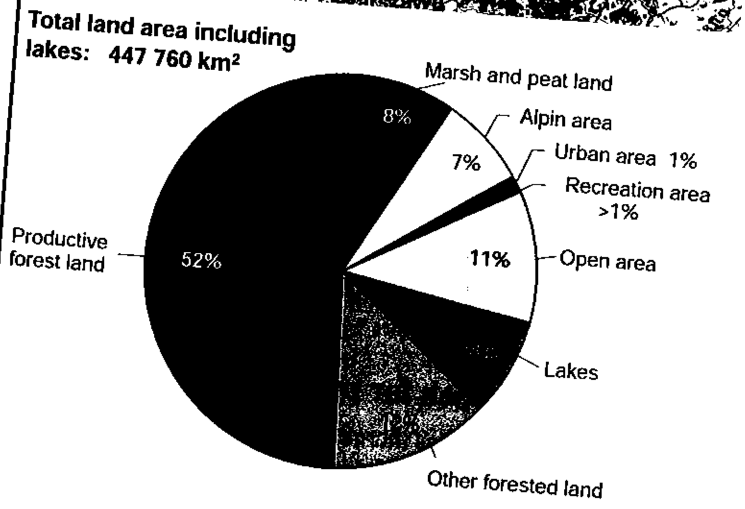
Emergy is defined as the available energy of one kind previously required directly and indirectly to generate an ecosystem component, a market commodity or service. It is an accounting measure of system storages and flows, each expressed in common units, **emjoules**, so that all inputs can be related based on their ability to influence the system in question. (The theoretical basis, calculation procedures, and applications of emergy analysis is further explained by Odum, 1996.)

A systems approach for public policy

Traditional economics has increasingly been criticized for using models and valuation methods that are outdated and inadequate for addressing public policy issues such

Figure 1a. Overview map of Sweden and its negihbouring countries.

Figure 1b. Sweden's land class distribution. (Source: National Atlas of Sweden, The Forests.)



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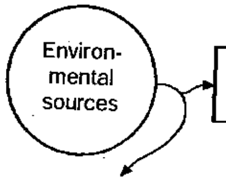

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as resource use. One problem is that money only pays for human work and not for the contributions from nature. Also, valuation models based on willingness to pay are subject to market temperament, resulting in prices that do not always reflect the physical, environmental or energetic base supporting an economy. Further, price is generally inverse to a resource's real contribution; scarce resources are often high priced yet their ability to drive the larger ecological-economic system in which they are embedded is often minimal.

Although economics and energetics are often closely correlated, it is the resource base available to an economy that drives it (Figure 2). Using a systems approach, however, the vital interconnections of humanity and nature can begin to be seen and understood in the context of the next larger system. Policy decisions regarding development, distribution and use of public resources can then be more appropriately addressed for the common good of both interdependent systems. In Figure 2, this interdependency of human society and nature is shown. Money is shown as a counter current to resource flows, circulating between local economic sectors and the main economy. Environmental source inputs are diagrammed at the left, driving ecosystem production.

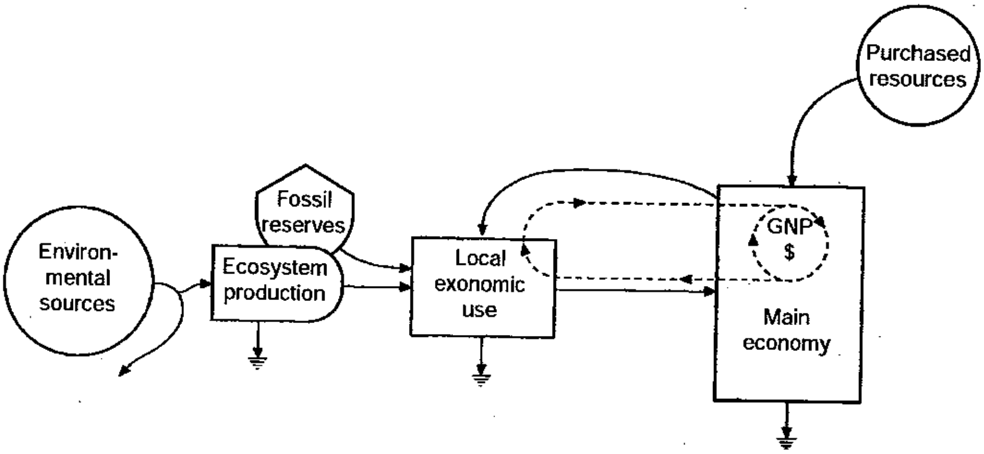

Figure 2. Conceptual diagram of interdependency of economic and ecologic processes. Explanation of symbols is given in figure 7 on page 28.

Under current management paradigms there are often no feedback mechanisms to reinforce nature's contribution to economic prosperity. Nor is a value placed on those resource contributions using traditional economic valuation methods. Rather, ecosystem services are considered "free", and by-product impacts from economic activities are termed "externalities" and often not considered. From a systems perspective, these inadequacies can begin to be identified and addressed. The appropriate scale to set goals and address problems is the next larger scale. Systems analyses can facilitate policy decisions by identifying those public policies which will be sustainable and benefit the combined of environment and society.

Energy language diagramming

Diagramming of systems was used as a first step in each analysis in order to organize system components, flows and interactions and to better understand the linkages between forest agro-ecosystems, forest industry sectors and the larger, national ecological-economic system. An energy language diagram representing Sweden is presented in Figure 3 for national overview and to illustrate conventions used in diagramming; details are outlined in the methods section of this report (pages 26–29, for explanation of symbols see Figure 7 on page 28).

Energy flows move from left to right. Dispersed, environmental and meteorological source inputs are shown driving Sweden's major forest and agricultural production systems. Geologic uplift builds mountains and draws mineral and metal ore deposits near the surface. These deposits along with the renewable production systems form Sweden's resource base. Imports of concentrated fuels, goods and services enter the diagram at the right. Forest biomass, crops and extracted metal ores are matched by these purchased imports to fuel power plants, industry and cities, diagrammed to the right. Rain and snow concentrate in mountain stream flow, and this energy is harnessed through hydro-electric dams. Money is drawn as a dotted line moving in opposite direction of energy and material, circulating between urban centers and industry and exchanged for purchases and sales.

Diagramming helps to understand seemingly complex systems by organizing the flows and storages, inputs and interactions, production and consumption components, and outflows according to hierarchical rules of thermodynamics. It can also help locate target areas of interest and weak points in management systems. By identifying the next larger system and independent, external forcing functions, real contributions can be assessed and system performance can be forecast.

General systems principles

Systems theory arose from the observation that models describing and predicting diverse "systems" often have certain common or similar principles which influence the design and outcome of the models. In Figure 4, principles of self-organization, hierarchical ordering and energy transformation are illustrated as thermodynamic principles common to all systems. Relating these concepts to ecosystems, an Eltonian trophic web is identified in which many small components with short life spans (rapid turnover) and small territories are required to support few large individuals with greater life longevity and larger territories.

Common to all levels or systems shown here is an energy source shown at the left and converging through transformations at the right of each diagram. As the solar energy is transformed from one type of energy to another, losses occur according to the second law of thermodynamics. Thus there is very little available energy remaining after several transformations of the original energy. Because each of these steps are required, the total influx of independent energies (in this example there is only one, *i.e.* sunlight) is required to support each transformation step. It takes increasingly more solar energy to support a given unit of energy going from left to right along the energy hierarchy.

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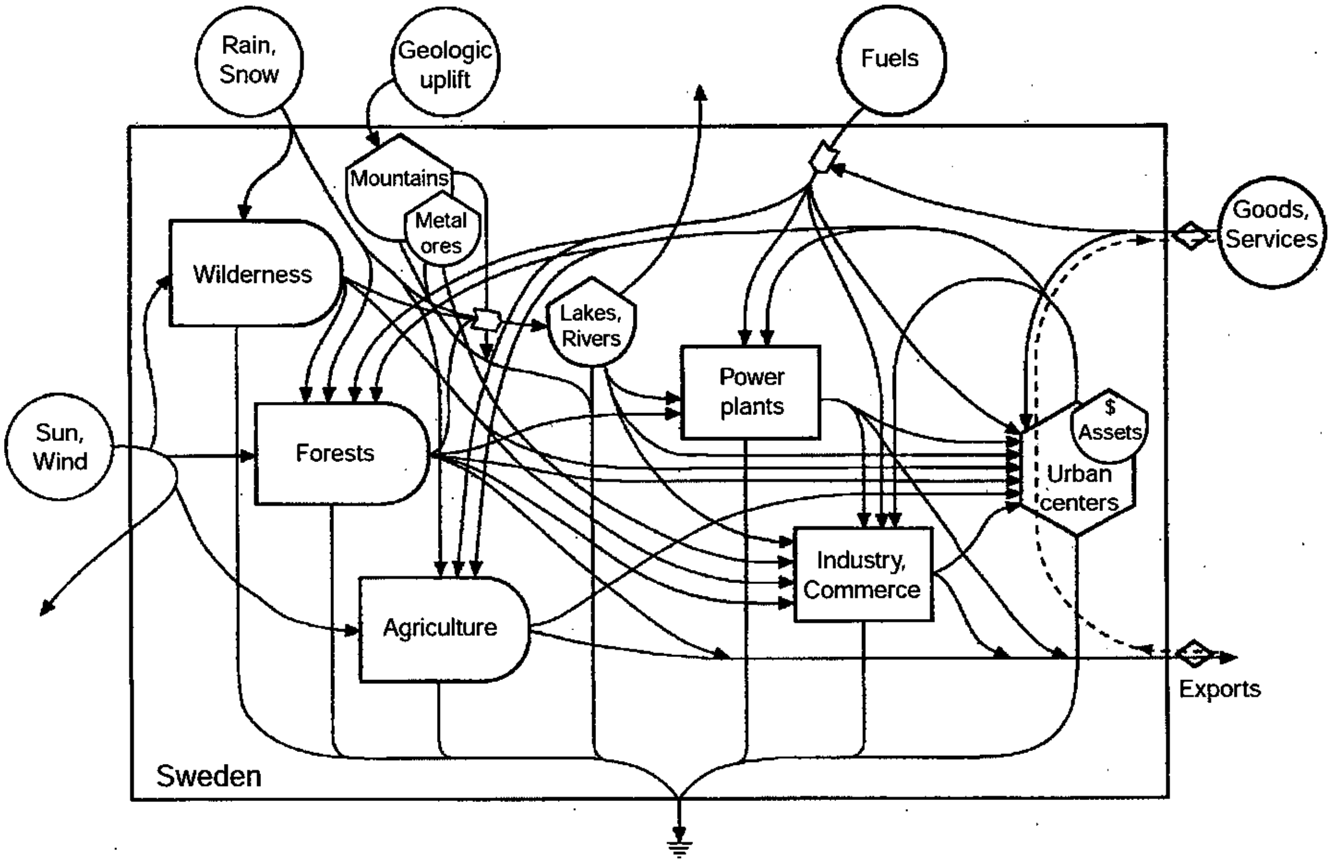

Figure 3. Overview energy language diagram of Sweden, its resource basis, major ecosystems, economic sectors, and interactive flows. Symbols and diagram conventions are explained in the methods section on pages 26–29.

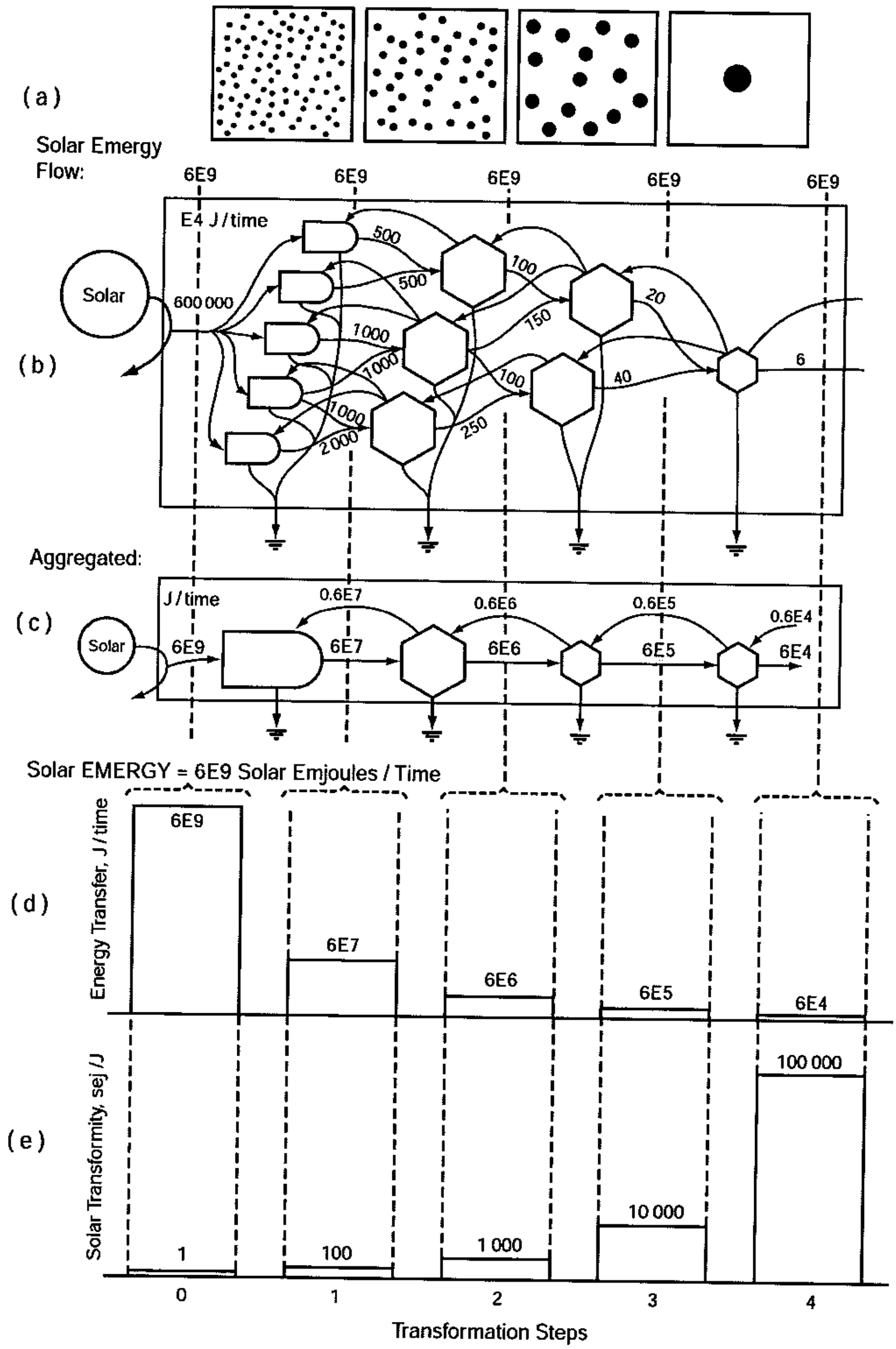

Figure 4. Energy transformations and hierarchical ordering of ecosystem components: (a) spatial pattern; (b) system network; (c) network aggregation by hierarchical levels; (d) energy flows; and (e) solar transformities (from Odum 1996, p 23).

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A biophysical measure of system support and economic vitality

Real wealth to human economies are the resources available to it – fuels, food, lumber, information. There is energy in everything, including information. Energies drive systems. Without an energy source, a system cannot be created and should that source be cut off, the system cannot be maintained. The requirements of a system process or product then, can be analyzed according to the energy that goes into system production and maintenance. Because different processes and products have different requirements, energy sources must be corrected for differences in hierarchical position. This is accomplished using two fundamental measures, derived from observations of system self-organization and resource requirements supporting productive pathways.

The **solar transformity** estimates the amount of source energy of one type (*i.e.* solar) required through transformations to produce the available energy of another type. It is a measure of position and influence within a system. The work that potential energy can do is then dependent upon its position in the hierarchical web of energy transformations.

Solar emergy is the product of the solar transformity and the available energy, measured in solar emjoules (abbreviated sej). It is an energy-based measure of the work previously required to develop a product or drive a process, defined as the solar energy required directly and indirectly to produce a flow or storage of another type of energy. These definitions are illustrated with an example of annual coniferous forest production in Southern Sweden (Figure 5).

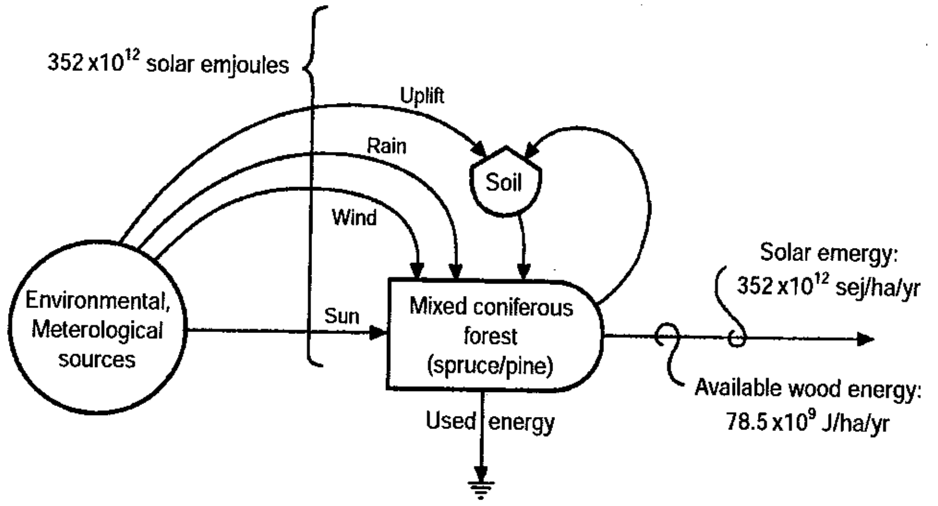
Emergy may be a measure of real contributions commensurate to its requirements. Environmental flows, use of internal storages, and purchased inputs from the main economy can then be summed to estimate the total support basis for a given yield and the inputs can be compared based on their relative contributions. A central theorem in this study is that activities which use large amounts of solar emergy have the ability to influence other activities and thus have greatest potential impacts on the combined ecological-economic system with which they are a part.

Self-organization for maximum emergy-use

Another general hypothesis emerges from this understanding of thermodynamic laws, energy transformations and hierarchical ordering: Systems organize over time to develop designs and cooperative pathways that stimulate productive processes which capture and use effectively at least as much energy as they require. Components and processes at the top of the hierarchy, requiring a lot of source energy, contribute to lower level processes through feed back mechanisms which amplify these lower level actions, insure and possibly increase influx of energy from sources.

This is now termed the **Maximum empower principle** (Lotka 1925; Odum 1988). It states that the system design (*i.e.* production system or development alternative) that will prevail in competition with others is the one that develops designs such as reinforcement actions, that yield the most useful work with inflowing emergy sources. Designs that draw more resources overcome more limitations, and displace alternatives. Energy dissipation without "useful" contributions does not reinforce, and thus cannot compete with systems that use inflowing emergy in self-reinforcing ways.

In general, economically developed resources prevail over the undeveloped ones because the environmental emergy contributions are augmented by additional



1 hectare forest production, steady state

$$\text{Solar transformity} = \frac{\text{Solar emergy}}{\text{Actual energy}} = \frac{352 \times 10^{12}\ \text{sej}}{78.5 \times 10^9\ \text{J}} = 4\,490\ \text{sej/J}$$

Figure 5. Systems diagram of annual mixed coniferous forest (Norway spruce and Scotch pine) production in southern Sweden, its *solar emergy* basis, and calculation of a *solar transformity* for forest biomass (9 m^3f/ha/year).

Footnotes to Figure 5:

Solar emergy flows:
(For solar transformities of environmental and meteorological flows, see Table 1 on page 22.)

1. Solar insolation = (1 ha)(85 kcal/cm^2/yr)(10^8 cm^2/ha)(100−37% albedo)(4 186 J/kcal)(1 sej/J) = = 22.4×10^{12} sej/ha/yr
2. Kinetic wind energy = (1 ha)[(2.7 m/s)/1 000 m]^2 (1 000 m)(10 000 m^2/ha)(1.23 kg/m^3) * *(25 m^2/s)(31.54×10^6 s/yr)(1 500 sej/J) = 105.9×10^{12} sej/ha/yr
3. Chemical potential energy in rainfall = (10^4 m^2/ha)(0.8 m/yr rain)(49% evapotranspired) * *(1000 kg/m^3 water)(4 940 J/kg water)(18 200 sej/J) = 352.4×10^{12} sej/ha/yr
4. Net uplift = (47.0×10^{20} sej/yr Sweden)/44.8×10^6 ha = 104.9×10^{12} sej/ha/yr; see footnote 5, table 2, page 38.

Total solar emergy from environmental, meterological flows is estimated by summing inputs and subtracting byproduct flows to avoid double counting of source inputs (see Table 1, page 23, and related text): [(sunlight, 22 + wind, 106 + rainfall, 352 + net uplift, 105)−(22+106+105)] x 10^{12} sej/ha/yr = 352×10^{12} sej/ha/yr

Net annual forest production: (9 m^3f/ha/yr)(425×10^3 g/m^3f)(20.52×10^3 J/g) = 78.5×10^9 J/ha/yr resource inputs paid for from investments and sales. This doesn't necessarily mean that technologically advanced systems are always benefits to human economies since the required purchased inputs often far out weigh the environmental contributions, leaving little 'net' return on society's investment. It also doesn't mean that high emergy configurations will prevail over less intensive, environmental systems – only that they will be selected while the required high quality primary fuels are available. Once energy sources driving the system become limiting, more efficient, less consumptive designs will prevail.

Further, maximum emergy production only benefits systems that have had time to self-organize and develop strategies for effective use of emergy available to them. Over-consumption may only produce wastes and inefficiencies. In other words, a commodity with a high solar transformity indicates it should be used for high quality operations, but a lower quality product may be just as appropriate (though less costly) if the high emergy commodity is so because of faulty design. In this case, the system producing the product has not had time enough to develop the proper configuration to maximize empower, relative to other competing systems designs. Selection of project plans for maximum emergy can, however, generate wealth according to an area's potential. Design criteria of systems are dependent on the emergy available to them.

Estimation of solar transformities for major source inputs

Solar transformities, used to convert inputs to production systems into solar emergy, form the basis for emergy evaluation methodology. Transformities for commodities are drawn from independent studies (Odum *et al.* 1983, Odum *et al.* 1986, Odum *et al.* 1987, McClanahan and Brown 1991, Odum and Arding 1991, Odum 1996). Environmental sources and primary fuels transformities are estimated as given below. New transformities for forest products in Sweden are then calculated based on subsystems analyses undertaken in this study. The solar emergy supporting direct labor and indirect but related human services was estimated by multiplying the associated monetary cost by the emergy/SEK index for Sweden, drawn from the national analysis. These derivations are explained below.

Solar emergy basis for global resources

Sweden and its forests are shown in Figure 6 as a regional subsystem of the geobiosphere. Environmental, atmospheric and meterological flows are shown as co-products of the world systems network which is driven by independent sources of direct solar insolation, tidal energy absorbed, and transformed deep earth heat energy. Total solar emergy supporting global processes is estimated as 9.460×10^{24} sej/yr (calculations are given as footnotes to Figure 6). From these independent sources, weather systems are formed from coupled environmental flows. The chemical and physical work of rainfall, along with energies of wind and sunlight serve as source inputs for regional and local production subsystems. Other co-products from global flows include convergent energies of stream flows, waves absorbed on shore driven from oceanic and atmospheric systems, and the cycle of earth materials from

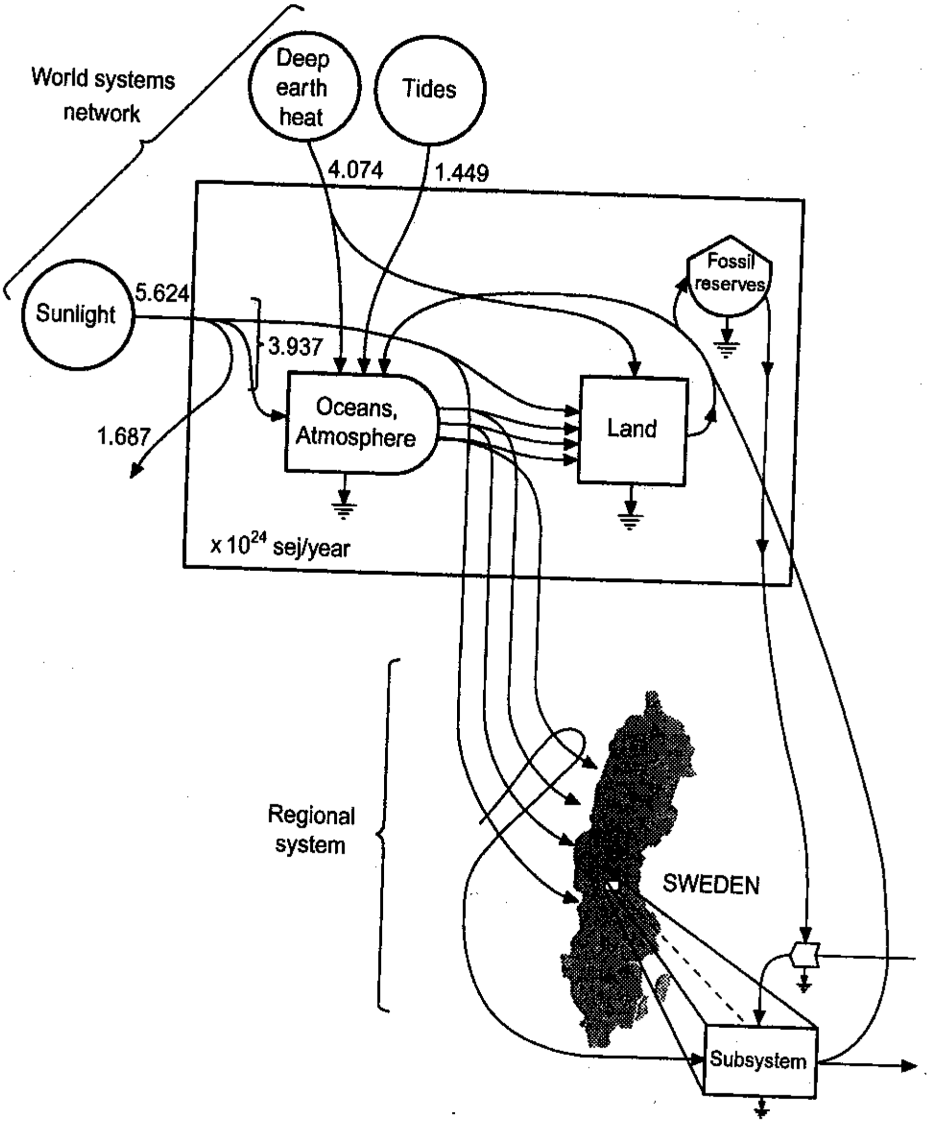


Figure 6. Annual solar emergy basis for the geobiosphere and the byproduct environmental and meteorological contributions to Sweden and its forestry subsectors (adapted from Odum *et al.* 1983; revised in Odum 1996).

Footnotes to Figure 6:

Calculations of energies driving global processes, before advent of fossil fuel use (solar emergy operating the geobiosphere) considered the sum of 1) solar, 2) geologic deep heat, and 3) tidal sources:

1. SOLAR INSOLATION
   Solar constant: 20 kcal/m^2/min
   Earth cross section (facing sun): 1.278×10^{14} m^2
   Average albedo: 30 %
   a) Total incident sunlight = (20 kcal/m^2/min)(525.6×10^3 min/yr)(1.278×10^{14} m^2)(4 186 J/kcal) = 5.624×10^{24} J/yr

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b) Solar transformity of sunlight, by definition = 1 sej/J; therefore
   total absorbed sunlight (considered 100%−reflected albedo = 70%);
   = $(5.624\times10^{24}$ sej/yr)(0.7) = 3.937×10^{24} sej/yr

2. EARTH HEAT (data from Sclater *et al.* 1980)

Total heat coming up through crust = $(10.02\times10^{9}$ kcal/s/earth)$(3.154\times10^{7}$ s/yr)(4186 J/kcal)
   = 13.229×10^{20} J/yr

Sources of deep earth heat are as follows:

a) residual heat from earth formation, moving from the mantle to the crust:
   = 4.744×10^{20} J/yr

b) heat from radioactive disintegrations (considered 15%):
   $(13.229\times10^{20}$ J/yr)(0.15) = 1.984×10^{20} J/yr

c) remainder (heat processes that are solar driven such as compression of sedimentary deposits in river deltas and the chemical potentials in these deposits which are later released under higher temperatures and pressures):
   13.229×10^{20} J/yr−$(4.744 + 1.984)\times10^{20}$ J/yr = 6.501×10^{20} J/yr

Total from deep earth processes, independent of solar based flows:
   = (a) + (b) = $(4.744+1.984)\times10^{20}$ J/yr = 6.728×10^{20} J/yr

Solar transformity of deep earth processes: the ratio of solar energy used in the biosphere (item 1b) to the actual heat component in the crust due to solar input (item 2c):
   $(3.937\times10^{24}$ sej)/$(6.501\times10^{20}$ J/yr) = 6056 sej/J

Therefore the contribution of deep heat energy to annual, global processes is:
   $(6.728\times10^{20}$ J/yr)(6056 sej/J) = 4.074×10^{24} sej/yr

3. TIDAL ENERGY

a) tidal energy received by the earth; 0.27×10^{20} ergs/s (Munk and MacDonald 1960);
   $(0.27\times10^{20}$ ergs/s)$(31.536\times10^{6}$ s/yr)/$(10^{7}$ ergs/J) = 0.8515×10^{20} J/yr

b) tidal energy transformed into ocean currents; 0.165×10^{20} ergs/s (Miller 1966);
   $(0.165\times10^{20}$ ergs/s)$(31.536\times10^{6}$ s/yr)/$(10^{7}$ ergs/J) = 0.520×10^{20} J/yr

Solar emergy contributed by tides = $(0.520\times10^{20}$ J/yr)(27850 sej/J) = 1.449×10^{24} sej/yr (solar transformity of tidal currents assumed equal to that for stream currents, see item e, table 1, page 24)

Solar transformity of tidal energy received by shoreline calculated as the solar emergy of tidal currents divided by the energy received = $(1.447\times10^{24}$ sej/yr)/$(0.8515\times10^{20}$ J/yr) = 16993 sej/J

TOTAL, ANNUAL EMERGY BASIS OF THE GEOBIOSPHERE = (1) + (2) + (3)
   = $(3.937+4.074+1.449)\times10^{24}$ sej/yr = 9.460×10^{24} sej/yr

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isostatic adjustments of land through erosion processes. Fossil carbon reserves are shown as by-products of environmental production primarily through sequestration of atmospheric carbon. The extraction, processing and burning of fossil fuels drive main production sectors in the global economy and their use results in CO_2 release and other "greenhouse gases" which impact global atmospheric systems. This is shown as a feedback loop from local production systems.

Global solar transformities for each flow were obtained by dividing the annual solar emergy supporting the global system network by estimates of the global energy flow of each process (Odum 1996). These solar transformities, ranging from 1500 sej/J for kinetic wind energy to almost 50000 sej/J for chemical potential energy of stream flows (Table 1), were used in this study as the basis for converting environmental energy sources to common units of solar emergy. Because these are by-product flows, each requiring the total annual budget of global solar emergy, they are coupled and cannot be directly added in emergy summations of environmental contributions to local production subsystems. Thus, source inputs must be identified as independent, and consideration must be taken to avoid double counting of dependent or coupled inputs.

Solar emergy basis for primary fuels

In order to convert fossil fuel energy into solar emergy, estimates of solar transformities were generated based on energy conversion efficiencies between fuel types[1]. A solar emergy value for coal of 29000 sej/J (Odum 1996) based on sedimentary cycles was used as the basis for estimating the solar emergy of each fuel type. Values ranged from 35000 sej/J for natural gas to 48 000 sej/J for refined fuel oils. An estimate of electricity of 125000 sej/J was made based on an equivalence of 2.6 joules of fossil fuel directly used in the production of 1 electricity joule (Swedish Power Association 1981). Odum (1996) calculated a solar transformity for electricity which includes human services of 200 000 sej/J based on an analysis of a wood powered electric plant in Jari, Brazil. Thus, the solar transformities used herein are considered approximations of solar emergy requirements for fuel production, excluding human services, which are measured separately in proportion to the monetary cost of production and transport as defined next.

Estimate of the solar emergy support base of human services

The money paid for machinery, fuels and other goods necessary in a production sector pays for the human services involved in the refinement, manufacture and delivery of the commodity. By summing the total solar emergy input to Sweden in 1988, including environmental sources, fuels and foreign purchases, the amount of solar emergy supporting the gross national product was estimated, measured as solar emjoules per unit currency (sej/SEK or sej/USD) for that year. This relation was used to assign a solar emergy value to human services in proportion to the money paid for the service, assuming that each SEK paid for a product or service represents a proportional amount of solar emergy supporting the direct and indirect human labor requirements. By multiplying the monetary cost of a commodity or labor hour by this index of annual solar emergy flow to monetary flow, an estimate of solar emergy supporting labor inputs and indirect human services was assigned.

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[1] Solar transformities for primary fuels calculated as follows: 1) sedimentary coal; 29000 sej/J (Odum 1984, revised 1996); 2) natural gas 20% more efficient in boilers than coal (Cook 1976) thus (29 000 sej/coal J)(120%) = 34 800 sej/J natural gas; 3) 1.65 coal J/J liquid motor fuel (Slesser 1978) thus (29 000 sej/ coal J)(1.65 coal J/motor fuel J) = 47 850 sej/J refined fuel; 4) 19% crude oil used in refinement and transport of motor fuel (Cook 1976) thus (47 850 sej/ motor fuel)/(119%) = 40210 sej/J crude oil; 5) electricity; (2.6 fuel J)/(electric power J) (Swedish Power Assoc. 1981) thus (2.6 fuel J/J electricity)(47 850 sej/J) = 124450 sej/J electricity. These values are estimates of solar transformities without associated human services, which are assessed separately in proportion to the money paid.

Since money is only paid to people for their contributions and not for environmental work, this estimate was derived so that human services could be equivalently evaluated along with other inputs to the forest sector. An average solar emergy base for wages earned is an estimate of the lifestyle support requirements of both direct forest laborers in Sweden as well as the associated human services that produce and deliver imported commodities. This method of assigning resources supporting labor in proportion to the money paid is used in other ecological economic accounting methods such as input-output matrix algebra (Costanza 1980, Hannon *et al.* 1985) and is not without its limitations (Odum 1996). Other methods are possible. For example, the solar emergy supporting labor can be estimated using an average solar transformity of human metabolism for a given socio-economic class. While the method used here is an approximation, some measure of total contributions to human work is necessary if the real requirements to system production is to be assessed.

Table 1. *Solar transformities of environmental and meteorological flows based on annual global solar emergy flows, 9.46x10^{24} solar emjoules/year (from Odum et al. 1983; revised in Odum 1996).*

Note	Item	Energy flux (10^{20} J/yr)	Solar transformity (sej/J)
b)	Surface wind	63.1	1 500
c)	Physical energy, rain on land	9.0	10500
d)	Chemical energy, rain on land	5.2	18200
e)	Physical stream energy	3.4	27850
f)	Waves absorbed on shore	3.1	30650
g)	Earth sedimentary cycle	2.8	34450
h)	Chemical stream energy	2.0	48550

Footnotes to Table 1:

Solar transformities are calculated as the ratio of total biosphere input (a) to the transformed environmental flow (items b–h)

a) Total, annual emergy basis of the geobiosphere (see Figure 6 for calculations)
= solar emergy (1) + deep heat emergy (2) + tidal emergy (3)
= $(3.94+4.07+1.45) \times 10^{24}$ solar emjoules per year = 9.46×10^{24} sej/yr

b) Wind used at surface of the earth estimated as 10% of total flux of wind energy, 2×10^{12} kW (Monin 1972):
$(2 \times 10^{12}$ kW$)(1$ J/s/W$)(1\,000$ W/kW$)(31.54 \times 10^{6}$ s/yr$)(10\,\%) = 63.1 \times 10^{20}$ J/yr;
Solar transformity of surface wind energy = (a)/(b) =
= $(9.46 \times 10^{24}$ sej/yr$)/(63.1 \times 10^{20}$ J/yr$) = 1\,500$ sej/J

c) Physical energy in rain on elevated land:
world's rain over land = 105 000 km^3/yr; average elevation of land = 875 m (Ryabchikov 1975);
$(105 \times 10^{3}$ $km^3)(1 \times 10^{12}$ kg/$km^3)(9.8$ m/$s^2)(875$ m$) = 9.0 \times 10^{20}$ J/yr;

Footnotes to Table 1, continued.

Solar transformity of physical energy in rain = (a)/(c) =
= (9.46x10^{24} sej/yr)/(9.0x10^{20} J/yr) = 10504 sej/J

d) Chemical potential energy in rain: world's rain over land = 105000 km^3/yr;
average salinity of rain = 10 ppm;
average salinity of seawater = 35000 ppm;
Gibbs free energy (F) per gram H_2O = (nRT) $\log_e(C_1/C_2)$; where:
n = 1 g H_2O/atomic wgt. of H_2O = 1 g/(18 g/mole)
R = universal gas constant = 0.00199 kcal/K/mole
T = temperature, Kelvin = 300 K
C_1 = seawater concentration = 100000–35000 = 965000 ppm
C_2 = rainwater concentration = 100000–10 = 999990 ppm
Gibbs free energy (F) = (0.00199 kcal/K/mole)(300 K)/(18 g/mole H_2O) *
* ln(999990/965000)(4186 J/kcal) = 4950 J/kg;
(105x10^3 km^3/yr)(10^{15} g/km^3)(4.95 J/g Gibbs free energy) = 5.187x10^{20} J/yr;
Solar transformity of chemical potential energy in rain
= (a)/(d) = (9.46x10^{24} sej/yr)/(5.187x10^{20} J/yr) = 18234 sej/J

e) Physical energy in stream flow:
global runoff = 39.6x10^3 km^3/yr (Todd 1970);
average elevation of land = 875 m (Ryabchikov 1975):
(39.6x10^3 km^3/yr)(1x10^{12} kg/km^3)(9.8 m/s^2)(875 m) = 3.395x10^{20} J/yr;
Solar transformity of the physical energy in stream flow
= (a)/(e) = (9.46x10^{24} sej/yr)/(3.395x10^{20} J/yr) = 27852 sej/J

f) Wave energy absorbed at shore:

estimated as the energy of an average wave coming ashore multiplied by the length of the receiving shorelines; average wave energy = 168x10^6 kcal/m/yr (Kinsman 1965);
global shoreline = 439x10^6 m;

(168x10^6 kcal/m/yr)(439x10^6 m)(4186 J/kcal) = 3.09x10^{20} J/yr;
Solar transformity of wave energy = (a)/(f) = (9.46x10^{24} sej/yr)/(3.09x10^{20} J/yr) = 30550 sej/J

g) Earth cycle is considered the work of earth uplift replacing erosion without net change in elevation, indicated by continental heat flow, 2.746x10^{20} J/yr (Sclater *et al.* 1980);
Solar transformity of earth cycle = (a)/(g) = 9.46x10^{24} sej/yr)/(2.746x10^{20} J/yr) = 34377 sej/J

h) Chemical potential energy in rivers.
Rivers represent concentration of dispersed rainwater over land. Global average given based on: global runoff = 39.6x10^3 km^3/yr (Todd 1970); typical dissolved solids = 150 ppm; Gibbs free energy (F) = (8.33 J/mole/deg)(300 K)/(18 g/mol H_2O)*ln(999850/965000) = 4.92 J/g;
(0.396x10^{20} cm^3/yr)(0.99985 g/cm^3)(4.92 J/g) = 1.948x10^{20} J/yr;
Solar transformity of chemical potential energy in streams
= (a)/(h) = (9.46x10^{24} sej/yr)/(1.948x10^{20} J/yr) = 48460 sej/J

Objectives and research plan

The first step was to undertake an analysis of the annual solar emergy flows supporting the Swedish economy in order to place forests in perspective of the combined ecologic-economic national system. This national overview included an assessment of renewable and non-renewable resources from the environmental support base within the country as well as imported goods, fuels and related human services. Export commodities were also evaluated to better understand trade and national support.

Detailed subsystems analyses were then made of different sectors of the forest industry. These included silvicultural management of coniferous (spruce/pine) forest production, harvesting and transport. Forest resources were then evaluated for their use as district heating fuels; these technologies included wood chipping and wood powder development as alternative fuels. Short rotation energy forestry operations were also evaluated and compared with spruce/pine forest management systems for emergy requirements and net yields. An overview of Sweden's pulp and paper industries was also undertaken. The results of these subsystem analyses were then used to address the role of the nations' forests to its welfare, its energy supply systems and foreign trade. By starting with a national overview analysis, forests and related industries could be synthesized and better understood relative to Sweden's larger, combined ecologic-economic system.

Determining benefits of forest applications and alternatives

Measurements of solar emergy are used in this study to address issues of resource use. Solar transformities for forest products are compared to identify resource allocations, requirements and efficiencies. Two ratios were used to help determine the feasibility of using forest products as primary sources to fuel Sweden's economy. First, the origins of emergy flows required to transform a product or process are identified as to whether they are inputs from nature such as sun, rain, wind and soil, or whether they are human derived inputs such as upgraded fuels, goods and services. The net yield ratio, NYR, a measure comparing the solar emergy of a product or process to the solar emergy inputs received from the economy, was used to investigate benefits due to an activity. If the ratio is close to unity (1:1) then the investor (in this case the Swedish economy) is putting in as much into the process as is received in the product; the free inputs from nature are trivialized compared to purchased inputs.

Another index, the investment ratio, IR, relates the amount of purchased inputs to those from the environment. If there is more solar emergy input from the economy then contributed from environmental sources, the investment ratio is greater than unity (1:1). It is theorized that in order to be competitive with other systems in the market place, an activity's investment ratio should not be any greater than the regional average. This measure can also than be thought of as a measure of loading on the environment; as inputs from society increase (the more emergy intensive the process) so does the product's ability to impact the resource it's dependent upon.

The systems analysis procedure is designed to evaluate the flows of energy, information, materials and money in common units that enables one to compare environmental and economic aspects of systems. This study is based on these thermodynamic principles common to all systems; that each component of a self-organized system is coupled to lower and higher levels and all components contribute to system performance commensurate to their position, transformity and emergy. Usually questions of development policy and resource-use involve environmental impacts that must be weighed against economic gains. Often impacts and benefits are quantified in different units resulting in a paralysis of the decision-making process because there is not a common means of evaluating the trade-offs between environment and development. Emergy provides a common basis; the energy of one type that is required by all productive processes.

Methods

For overview, to determine the relation between resource use and the gross national product and to better understand forest sector analyses in perspective of the national trends, the combined ecologic-economic system of Sweden was first synthesized. Subsystems analyses were then conducted of Sweden's energy and forest sectors. Included as subsystems were 1) silvicultural spruce/pine production, 2) short rotation willow cultivation, 3) harvesting and wood delivery systems, 4) wood fuel development including both chips and wood powder, 5) district heating systems, and 6) the pulp and paper sector. The results of these analyses were then used to address critical public policy questions concerning energy delivery systems, sustainable use of forest resources and trade alternatives. Each system or subsystem was studied with a similar methodology (steps A–E) as follows:

(A) First a detailed energy systems diagram of Sweden and each of the forestry sectors studied was drawn as a way to gain an initial network overview, combine information of participants, and organize data-gathering efforts. This was done for the entire country and each of the forestry subsectors that were investigated.

(B) Next, aggregated diagrams were generated from the detailed ones by grouping components into those conceived important to system trends, those of particular interest to current public policy questions, and those to be evaluated as line items in resource evaluation tables.

(C) Resource evaluation tables were set up to facilitate calculations of main sources and contributions to each system studied. Resource inputs and yields are reported in each table as general accounting units (tons, joules, SEK, etc.) and also evaluated in solar emergy units (solar emjoules) and macro-economic terms to facilitate comparisons and public policy inferences.

(D) Indices of solar emergy-use and source origin were calculated to compare systems, predict trends, to suggest alternatives, identify system efficiencies, and assess which will be successful.

(E) Models and evaluations were used to consider which alternatives generate more real contributions to the unified economy of humanity and nature. In particular, forest alternatives were considered in light of Sweden's energy needs, to determine their relative contributions and the optimal development of forest systems under sustainable harvests that will most benefit the Swedish economy.

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Detailed energy systems diagram

For understanding, for evaluating, and for simulating, our procedures start with diagramming the system of interest, or a subsystem of particular interest. This initial diagramming is done in detail with anything put on paper that can be identified as a relative influence to the system of interest, even though it is thought to be minor. The first complex diagram is like an inventory. Since the diagram usually includes environmental and economic components, it might be considered an organized impact statement.

The following are the steps in the initial diagramming of a system to be evaluated:

1. The boundary of the system is defined.
2. A list of important sources (external causes, external factors, forcing functions) is made.
3. A list of principal component parts conceived important, considering the scale of the defined system, is made.
4. A list of processes (flows, relationships, interactions, production and consumption processes, etc.) is made. Included in these are flows and transactions of money conceived to be important.
5. With these lists agreed on as the important aspects of the system and the question under consideration, the diagram is drawn using the following conventions of energy language diagramming (from Odum 1971, 1996):

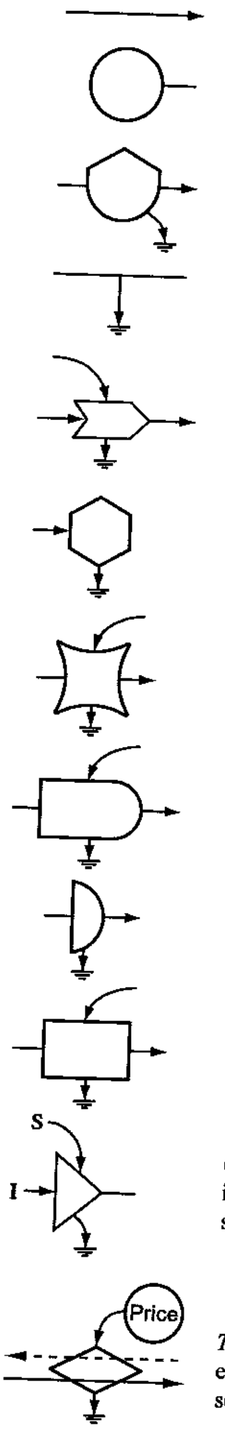
   Symbols: The symbols each have rigorous energetic and mathematical meanings (Figure 7). An example of a system diagram is given in Figure 3 as an overview of the combined environmental-economic system of Sweden.

   System Frame: A rectangular box is drawn to represent the boundaries that are selected.

   Arrangement of Sources: Any input that crosses a boundary is a source, including pure energy flows, materials, information, the genes of living organisms, human services, as well as inputs that are destructive. All of these inputs are given a circular symbol. Sources are arranged around the outside border from left to right in order of their ability to influence the system (*i.e.*, their solar transformities) starting with sunlight on the left and information and human services on the right.

   Pathway Line: Any flow is represented by a line including pure energy, materials and information. Money is shown with dashed lines flowing in opposite direction of energy flows. Lines without arrows to indicate direction of flow, may flow in either direction dependent on the difference between two forces.

   Outflows: Any outflow which still has available potential energy, material more concentrated than the environment, or usable information is shown as a pathway from either of the three upper system borders, but not out of the bottom.



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 7. Symbols and definitions of the energy language diagramming used to represent systems (from Odum 1971, 1983 and 1996, p 5).

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Degraded Energy: Energy that has lost its ability to do work in its present surrounding, according to the second law of thermodynamics, is represented as pathways converging to a heat sink at the bottom center of the diagram. Included is heat energy as by-products of processes and the dispersed energy from depreciation of storages.

Adding Pathways: Pathways add their flows when they join or when they go into the same the storage tank. Every flow in or out of a tank must be the same type of flow and measured in the same units.

Interactions: Two or more flows that are different, but are both required for a process are drawn to an interaction symbol. The flows to an interaction are connected from left to right in order of their solar transformity; the lower transformity flow connecting to the notched left margin of the symbol (refer to Figure 7 for details).

Counterclockwise Feedbacks: High-quality outputs from consumers such as information, controls, and scarce materials are fed back from right to left in the diagram. Feedbacks from right to left represent a loss of concentration because of divergence, the service usually being spread out to a larger area.

Material Balances: Since all inflowing materials either accumulate in systems storages or flow out, each inflowing material such as water or money needs to have outflows drawn.

Aggregated systems diagrams

Aggregated diagrams were simplified from the detailed diagrams, not by leaving things out, but by combining them in aggregated categories. Simplified diagrams have: the source inputs (cross boundary flows) to be evaluated; environmental inflows (sun, wind, rain, rivers, and geological processes, etc.); the purchased resources (fuels, minerals, electricity, foods, fiber, wood); human labor and indirect services; money and exchanges; and information flows. Export flows were also drawn. Initial evaluations were useful in deciding what was important enough to retain as a separate unit in the diagram.

Components inside the system boundary included: the main land use areas; large storages of fuel, water, and soil; the main economic interfaces with environmental resources; and final consumers. Interior circulation of money was not drawn, but all the major flows of money in and out of the systems were included.

Resource evaluation tables

All systems studied, including the national overview analysis and subsystems evaluations of forest production, development and use are summarized using **resource evaluation tables** with calculations of inputs and summaries of solar emergy indices given as footnotes. Each table is presented similarly, with 6 columns, each with the following headings:

1	2	3	4	5	6
Note	Item	Basic data (J, tons, $ cost)	Solar transformity (sej/unit)	Solar emergy (sej/quantity/time)	Macro-economic value (USD, 1988)

Column One is the line item number, which is also the number of the footnote in the table where the source of the raw data is cited and calculations shown.

Column Two is the name of the item being evaluated, which is also shown on the aggregated diagram.

Column Three is the resource inputs to production, given in units reported by industry accounting or obtained from environmental and statistical abstracts. These are reported as average annual flows (joules, grams or dollars) per unit volume or area, derived from various sources and identified as footnotes (column 1). Forest production figures are reported here as wood volume (solid cubic meters; m^3f) per hectare per year.

Column Four is the solar transformity or solar emergy per unit for each input, measured in solar emjoules per joule, sej/J (or sej/g; or sej/dollar, see definitions below). These are obtained from previous, independent studies (updated from Odum *et al.* 1983; McClanahan and Brown 1991, Odum and Arding 1991, and Odum 1996).

Column Five is the solar emergy of the resource input, measured in solar emjoules per year per production output (generally per hectare or per solid cubic meter wood, m^3f). It is the product of columns 3 and 4.

Column Six is the macro-economic value, reported in macro-economic dollars, for 1988. This was obtained by dividing the solar emergy (column 5) by the relation of annual solar emergy-use to Sweden's GNP in 1988. See definitions below for solar emergy per dollar index and macro-economic value.

Aggregations of environmental inputs are identified as (I) and each set of purchased inputs associated with a particular process step is summed as (F_i). For example, the inputs evaluated for harvesting wood include motor fuel, machinery, direct labor, human services and capital investment. The solar emergy of these items are summed and referred to as F_2 throughout the report. All other inputs from the economy are reported similarly, such as transportation, wood chipping, wood powder production and final combustion. Product yields are identified on each resource evaluation table and in the text and footnotes similarly; (Y_3) identifies the yield of wood chips, (Y_4) identifies wood powder yield and so on. The solar transformities for each forest product yield (standing biomass, harvested wood, chips, powder, domestic heat) that are derived from these evaluations are indexed in the tables by lower case letters a, b, c, d, and e, given as footnotes. This was done in order to separate solar transformities derived from other, referenced independent studies and those that were calculated as a result of this study.

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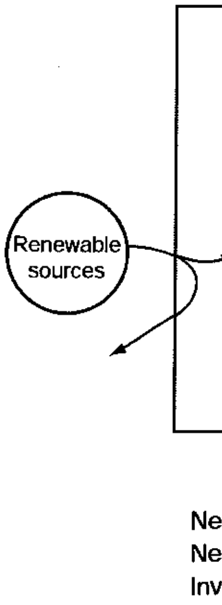

Figure 8. Systems
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Footnotes for each resource evaluation table begin with a summary of the solar emergy yields, solar transformities, net yield and investment ratios tabulated for the forest product being evaluated for each process step or transformation. This is followed by the actual calculations for each resource input, referenced from column one.

Solar emergy indices

The following are comparative indices of solar emergy origins, allocations, exchange, and relations to macro-economic valuation used in this study to draw inferences from the resource evaluations. They are reported below each resource evaluation table along with summaries of inputs, yields and solar transformities.

Net yield ratio

The **net solar emergy yield ratio** is the solar emergy of an output divided by the solar emergy of those inputs to the process that are purchased and fed back from the economy (Figure 8). This ratio indicates whether the process can compete in supplying a primary energy source for an economy. Typical competitive fuel sources have been about 4–6 to 1, though these favorable ratios are declining as fossil reserves decline increasing extraction and processing costs. Processes yielding less than those available may not be currently economic as primary sources.

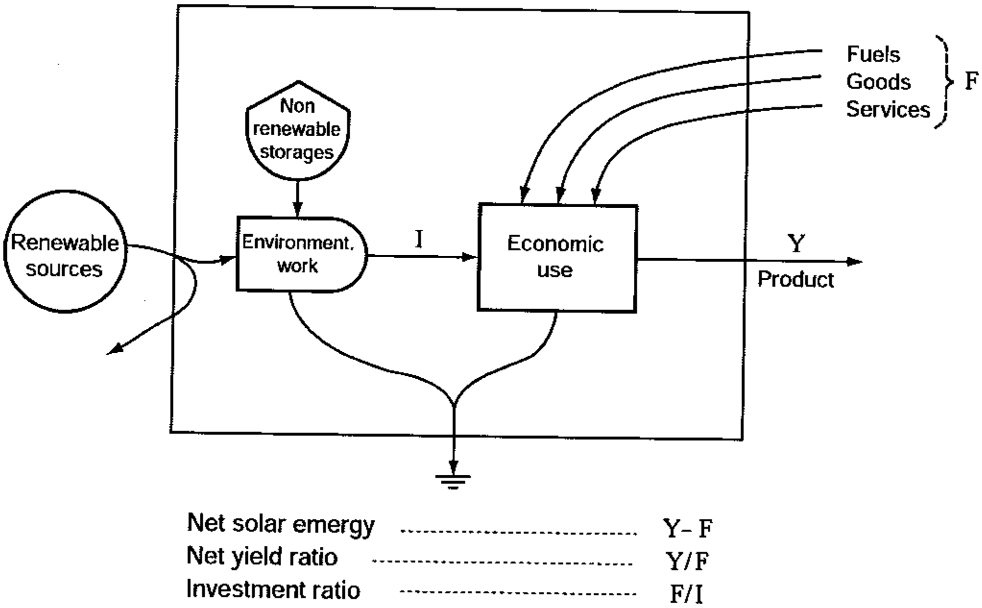

Figure 8. Systems diagram showing calculation of net solar emergy, net solar emergy yield ratio (NYR), and solar emergy investmaent ratio (IR) calculated for an agro-ecosystem.

Investment ratio

The **solar emergy investment ratio** is the ratio of solar emergy derived from the economy to the solar emergy delivered free from environmental sources (Figure 8). This ratio indicates if the process is economical as a utilizer of the economy's investments in comparison with alternatives. To be economical, the process should have a similar ratio to its competitors. If it receives less from the economy, the ratio is less and its prices are less so that it will tend to compete in the market place. Its prices are less when it is receiving a higher percentage of its useful work free from environmental inputs than its competitors.

However, operation at a low investment ratio uses less of the attracted investment than is possible. The tendency may be to increase the purchased inputs so as to process more output and generate more cash flow. The tendency is towards optimum resource use. This suggests that operations above or below the current regional investment ratio will tend to change towards the investment ratio common for that region.

Exchange ratio

The **solar emergy exchange ratio** is the ratio of solar emergy received to solar emergy delivered in a trade or sales transaction. If the market transaction is trade, for example a trade of grain for oil, the ratio can be expressed as the relation of solar emergy supporting each commodity (Figure 9a). If the exchange is a sale of a commodity in order to generate revenue to purchase necessary goods or services,

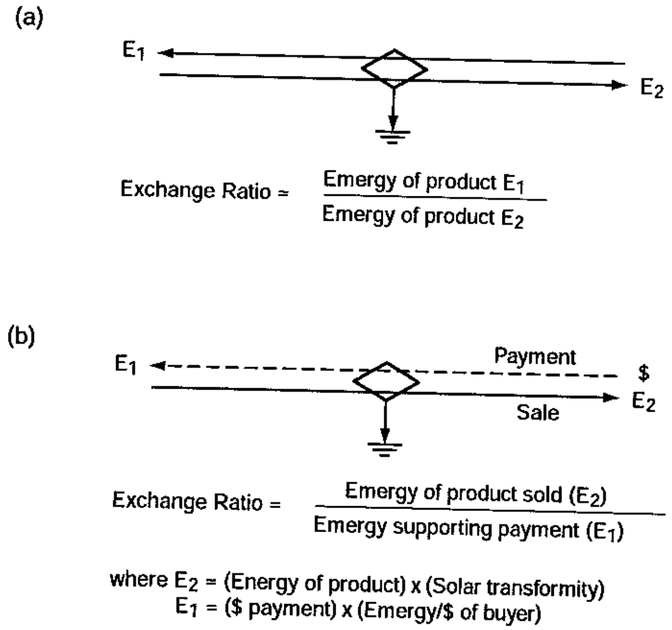

Figure 9. Solar emergy exchange of an economic transaction: (a) trade of two commodities; (b) sale of a commodity.

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the exchange ratio can be calculated as the solar emergy of the product sold divided by the solar emergy that could be purchased with the earned revenue (9b). This is estimated using the solar emergy/dollar index for the buyer nation or region.

A central theorem investigated here is that the area receiving the more solar emergy due to the market transaction has its economy stimulated more. Previous studies have indicated that raw products such as minerals, rural products from agriculture, fisheries, and forestry generally tend to have high exchange ratios when sold at market price (Doherty *et al.* 1991, Odum and Arding 1991). This is a result of money being paid for human services and not for the extensive work of nature that went into these products.

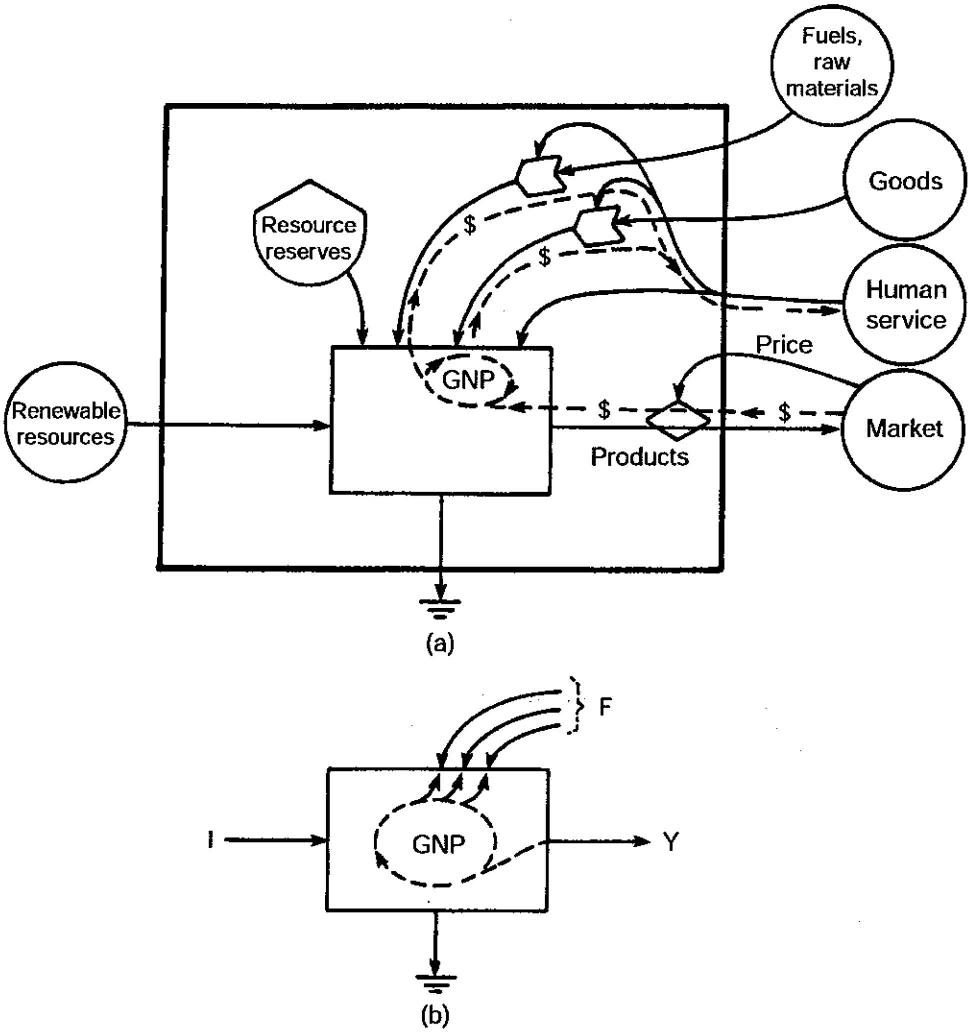

Figure 10. Overview systems diagram of a nation, its environmental resource base, economic component, imports and exports (from Odum *et al.* 1983): (a) main flows of money and solar emergy; (b) procedure for summing solar emergy inflows and outflows.

Relation of solar emergy support base and economic product

The relation of annual solar emergy-use to the gross national product of a country was considered an estimate of the solar emergy supporting each unit of currency circulating in the economy for a particular year (Figure 10). As the diagram shows, it includes renewable environmental sources such as sunlight, wind and rain, non-renewable resources used such as fossil and mineral reserves and soil, imported fuels, goods and services. In general, rural countries tend to have higher solar emergy/dollar indices because more of their economy involves direct environmental resource inputs that are not paid for (Odum *et al.* 1983, Doherty *et al.* 1991, Odum and Arding 1991).

In this study, the solar emergy to dollar index calculated for Sweden in 1988 is used to estimate the amount of direct and indirect resources supporting each unit of currency. This is used to address all inputs and all costs to forest production sectors, including an estimate of solar emergy supporting life-styles of workers discussed below.

Macro-economic value

The term macro-economic value refers to the total amount of monetary flow generated in the entire economy supported by a given amount of solar emergy input. It is calculated by dividing the solar emergy of a product or process by the solar emergy/monetary unit index for the economy to which it contributes. This is a way of putting a monetary value on services and storages not traditionally accounted for in economics such as transpired rainfall, photosynthetic production, forest biomass, volunteer labor, parenting and information. This is not a market value, but instead a value for public policy inferences and directives.

Public policy questions

Various policy questions were examined by comparing solar emergy contributions of forest alternatives evaluated in this study. Alternative products and services with higher solar emergy flows represent solutions that may tend to prevail because their contribution to the ecological-economic system is greater, provided there are sectors designed to use them. The presumption is that through trial and error as well as through rational argument, alternatives are tried so that their utility can be observed by the public decision process. By evaluating the solar emergy basis for proposed alternatives in advance, it may be possible to predict what will eventually be the accepted policy.

Ecological-economic support base of Sweden

The biophysical resource support base of Sweden was evaluated in order to place in perspective the role of forests in the national economy and to evaluate international trade and alternate uses of forest products within Sweden. The relation of Sweden's solar emergy base and its gross national product was also calculated from this

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national overview as an estimate of the solar emergy supporting human service contributions to the forest sector, in proportion to the money paid.

Renewable sources of sunlight, precipitation, kinetic wind energy, geologic uplift, and the geopotential energy of stream flow were evaluated along with the mined indigenous mineral and metal ores within the country. Imported and exported commodities, fuels and their associated human services were also evaluated. Sweden's solar emergy support base is presented first, then indices are drawn that relate solar emergy-use to economic activity, self-sufficiency and international exchange. Comparisons with other countries are presented to place Sweden in perspective with the ecological-economic base of developed and rural nations.

Synthesis of annual solar emergy contributions to ecosystem life-support and national welfare

The solar emergy incoming to Sweden from external, independent sources is figured as the sum of the inputs of free, renewable and mined, nonrenewable environmental resources and the solar emergy contribution from imports. The solar emergy of exports, byproducts of internal production are a source of exchange with external markets that enable Sweden to purchase fuels, raw materials and commodities that are necessary to national welfare, but not internally available.

Indigenous renewable and non-replenishable environmental sources

The indigenous resource base of Sweden includes the renewable sources of sunlight, kinetic wind energy, rainfall, stream flow and the energies from a portion of the Baltic Sea, including tides and the surface winds driving waves and currents. Major indigenous production systems are forestry, agriculture, fisheries and hydroelectricity generation. Sweden has an active and rich mineral and metal ore extractive industry. Iron ores, copper, lead, zinc, and other mineral rocks are annually extracted. These indigenous environmental and meteorologic inputs are evaluated in Table 2. See also overview maps in Appendix A.

Annual rainfall (a mean of 800 mm/yr) was estimated to be the major renewable solar emergy source in Sweden. Through transformations, precipitation is used in two ways: (1) as chemical potential energy created by differentials in salt concentrations between the incoming rain and the transpired water from respiration of photosynthetic plants after the rainfall has moved through plants; and (2) as hydro-geopotential energy from the concentration of runoff and transport of sediments and dissolved nutrients in river channels due to elevational gradients across the landscape. Using a mean elevation of 345 meters above sea level for Sweden, the geopotential solar emergy of dispersed rainfall was calculated at 60×10^{20} sej/yr, about 10% of Sweden's renewable resource base. Forests, through uptake and transpiration of water (considered 49% of incoming rainfall, runoff averaging 405 mm/yr), account for almost 100×10^{20} sej/yr, approximately 21% of the solar emergy from renewable sources. The gross hydropotential thermal energy of stream flow, estimated based on topography and runoff (200 TWh/yr, Swedish

Power Association 1981) was indirectly estimated at 270×10^{20} sej/yr (footnote 4, Table 2).

A solar transformity for physical stream flow was calculated at 37500 sej/J, corresponding to a second order stream (Diamond 1987). This measurement was used as an estimate of the environmental work associated with concentrated and elevated water. A total solar emergy inflow from annual rainfall was estimated at roughly 366×10^{20} sej/yr.

Direct solar insolation (85 kcal/cm^2/yr, 37% reflected albedo) and the kinetic energy of wind (average wind speed, 2.7 m/s) comprised 13% of Sweden's renewable base. Southern Sweden has a small net uplift of its land mass due to icemelt following retreating glaciers on the order of magnitude of 5 mm/yr (Atlas of Sweden). Using an estimated solar transformity of 32×10^9 sej/J (footnote 5, Table 2), solar emergy of net land uplift was calculated as roughly 43×10^{20} sej/yr.

The solar emergy supporting the part of the Baltic Sea that comprises Sweden's exclusive economic zone (roughly 40%, Wulff *et al.* 2001) was estimated as the waves driven by wind and tidal energy and absorbed at the shore. These Baltic flows are part of Sweden's renewable solar emergy base, totalling about 43×10^{20} sej/yr, contributing about 9% of the annual renewable input. Figure 11 shows the contributions of environmental and meteorologic sources, forming the renewable resource base in Sweden.

Indigenous renewable production systems were also evaluated for overview (items 12–16, Table 2). The solar emergy associated with these production outflows range from over 300×10^{20} sej/yr for hydroelectricity generation to 40×10^{20} sej/yr for fisheries production. Forest industry output was estimated as 180×10^{20} sej/yr based on a solar transformity for wood products calculated in this study. Although these solar emergy flows are generated from indigenous production, the driving energies are independent sources (environmental and imported inputs evaluated as part of this study). Therefore, to avoid double counting inputs, they are not added to the overview of Sweden's solar emergy base; they are presented here for perspective.

Mining of stored minerals, unrefined metals and other geologic materials (items 17–23, Table 2) contributed about 258×10^{20} sej to Sweden's annual emergy base in 1988. Iron ores represent about 65% of the solar emergy attributed to this nonrenewable extractive sector. Transformation indices of sej/g (Odum 1996), used to convert extracted mass to solar emergy, are based on geologic earth-based processes, not including societal energies of extraction, so that the solar emergy estimates represent only free, indigenous contributions. Human services and materials involved in the mining of mineral and metal ores were accounted for separately to avoid double counting. All extracted minerals and metal ores in Sweden are at least partially transformed (processed) within the country before being exported. Together, the indigenous renewable and nonrenewable resource inputs contribute about 700×10^{20} sej/yr to Sweden's solar emergy base, approximately 28% of the total.

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Table 2. *Solar emergy support for Sweden's indigenous resource base. All flows are based on annual contributions, using 1988 data. Calculations for basic data are given as footnotes to this table (referenced in column 1).*

Note	Item	Annual flows raw units/yr (J, g)	Solar transformity 1) (sej/unit)	Solar emergy (10^{20} sej/yr)	Macro-economic value 2) (10^9 USD, 1988)
RENEWABLE RESOURCES:					
Physical energy received over land:					
1	Solar insolation	1.05×10^{21} J	1	10.51	0.72
2	Wind, kinetic energy	3.17×10^{18} J	1500	47.48	3.27
3	Evapo-transpired rain	5.31×10^{17} J	18200	96.64	6.66
4	Hydro-geopotential energy	7.20×10^{17} J	37500	270.04	18.61
5	Net uplift	1.33×10^{11} J	3.23×10^{10}	43.13	3.24
Physical energy over the Baltic Sea:					
6	Solar insolation	5.68×10^{20} J	1	5.68	0.39
7	Surface wind absorbed	1.98×10^{18} J	1500	29.75	2.05
8	Rain, chemical	6.32×10^{16} J	18200	11,52	0.79
9	Runoff, chemical	1.40×10^{17} J	48500	67.95	4.68
10	Tidal energy	6.56×10^{15} J	16850	1.10	0.08
11	Waves received	1.40×10^{17} J	30550	42.68	2.94
INDIGENOUS RENEWABLE PRODUCTION:					
12	Hydroelectricity	2.59×10^{17} J	125000	324.00	22.33
13	Agricultural crops	2.11×10^{17} J	68000	143.56	9.89
14	Livestock, dairy	1.65×10^{16} J	2.0×10^{6}	329.67	22.74
15	Fisheries	1.16×10^{15} J	3.5×10^{6}	40.73	2.81
16	Forest harvest	5.59×10^{17} J	32400	181.12	12.48
NONRENEWABLE STORAGES MINED WITHIN SWEDEN:					
17	Iron ore	1.91×10^{13} g	8.6×10^{8}	163.99	11.32
18	Gold, silver	2.66×10^{8} g	5.0×10^{9}	0.01	0.00
19	Copper	8.31×10^{10} g	4.5×10^{9}	3.74	0.26
20	Lead	6.26×10^{10} g	9.2×10^{8}	0.58	0.04
21	Zinc	3.92×10^{11} g	4.5×10^{9}	17.64	1.22
22	Other mineral rock	1.35×10^{13} g	5.0×10^{8}	67.71	4.67
23	Sedimentary material	3.89×10^{11} g	1.0×10^{9}	3.89	0.27

1) Mineral and metal ore resources are evaluated using solar emergy per mass (sej/g).

2) Solar emergy value divided by annual solar emergy-use/GNP for Sweden, 1988 (1.45×10^{12} sej/USD).

Footnotes to Table 2:

Derivation of annual energy flows of environmental contributions and principle production systems in Sweden, circa 1988. 1 joule = 1 kg*m²/s².

RENEWABLE RESOURCES:

1. Solar insolation received over inland areas:
   a) Energy over land = (land area)(avg. insolation)(1–albedo)
   $= (0.412 \times 10^{6}\ \text{km}^2)(85\ \text{kcal/cm}^2/\text{yr})(10^{10}\ \text{cm}^2/\text{km}^2)(1-0.37)(4186\ \text{J/kcal}) = 9.23 \times 10^{20}$ J/yr

Footnotes to Table 2, continued.

b) Energy over lakes = (area of lakes)(avg. insolation)
$= (35.9\times10^3\ \text{km}^2)(85\ \text{kcal/cm}^2/\text{yr})(10^{10}\ \text{cm}^2/\text{km}^2)(4\,186\ \text{J/kcal}) = 1.28\times10^{20}\ \text{J/yr}$

Total solar insolation $= 9.28\times10^{20}\ \text{J/yr} + 1.37\times10^{20}\ \text{J/yr} = 1.06\times10^{21}\ \text{J/yr}$

2. Wind, kinetic energy: wind speed, 2.7 m/s (Lansberg 1976); (Vertical gradient of wind)^2*(height of atmospheric boundary)(area of Sweden)(density of air)(eddy diffusion coefficient)(s/yr);
$= [(2.7\ \text{m/s})/(1\,000\ \text{m})]^2\,(1\,000\ \text{m})$(land area, $411.0\times10^3\ \text{km}^2$ + lakes, $35.9\times10^3\ \text{km}^2$)
$(10^6\ \text{m}^2/\text{km}^2)(1.23\ \text{kg/m}^3)(25\ \text{m}^2/\text{s})(31.54\times10^6\ \text{s/yr}) = 3.17\times10^{18}\ \text{J/yr}$

3. Rain, chemical potential energy = transpired rain over forest and agriculture lands, (below tree line);
= (forest land + agricultural land)(rainfall)(evapotranspiration rate)(Gibbs free energy)
$= (23.6\times10^6\ \text{ha} + 3.6\times10^6\ \text{ha})(10\,000\ \text{m}^2/\text{ha})(0.8\ \text{m})$(49%; 1−runoff)$(1\,000\text{kg/m}^3)(4\,940\ \text{J/kg})$
$= 5.31\times10^{17}\ \text{J/yr}$

4. Stream hydro-geopotential energy; 200 TWh/yr gross hydropotential estimate based on topography and runoff (Swedish Power Assoc. 1981); $= (200\ \text{TWh/yr})(3.6\times10^{15}\ \text{J/TWh}) = 0.72\times10^{18}\ \text{J/yr}$;
Catchment area of 13 largest rivers in Sweden = 315 100 km^2 (76% of total land area);
total mean flow $= (4\,395\ \text{m}^3/\text{s})(3.154\times10^7\ \text{s/yr}) = 138.6\times10^9\ \text{m}^3/\text{yr}$;
therefore mean runoff $= (138.6\times10^9\ \text{m}^3/\text{yr})/(315\times10^{12}\ \text{m}^2) = 0.44\ \text{m/yr}$;
estimate of mean elevation of catchments $= (0.72\times10^{18}\ \text{J/yr})/[(138.6\times10^9\ \text{m}^3/\text{yr})(999.84\ \text{kg/m}^3)(9.8\ \text{m/s}^2)] = 530\ \text{m}$
therefore physical energy of runoff $= (138.6\times10^9\ \text{m}^3/\text{yr})(530\ \text{m})(1\,000\ \text{kg/m}^3)(9.8\ \text{m/s}^2) = 0.72\times10^{18}\ \text{J/yr}$.

Estimate of solar transformity for stream geopotential energy in Sweden: Using an estimate of 3:1 net emergy yield ratio for typical hydroelectric production, Y = 3 relative to F = 1 and I = 2 (see Figure 8, page 31). Then I/Y = 67% solar emergy requirements derived from stream geopotential emergy:

Hydropowered electricity generation (1988) = 72 TWh (259×10^{15} J), item 12; then $(259\times10^{15}\ \text{J})(1.25\times10^5\ \text{sej/J electricity}) = 324\times10^{20}\ \text{sej}$; and %I $= 2/3\,(324\times10^{20}\ \text{sej}) = 216\times10^{20}\ \text{sej}$.

If current generation of 72 TWh is 80% of gross theoretical upper limit;
$(216\times10^{20}\ \text{sej})/(0.8) = 270.0\times10^{20}\ \text{sej}$;

solar transformity for stream geopotential energy in Sweden $= 268\times10^{20}\ \text{sej}/0.72\times10^{18}\ \text{J} = 37325\ \text{sej/J}$;
corresponds to hydro/geo-potential energy flux of a third order stream (Diamond 1987).

5. Geologic uplift: (considered the net increase due to rebound following the icemelt of retreating glaciers); estimated rate: 5 mm/yr (Atlas of Sweden); density of rock: 2.65 g/cm^3 (estimate from Odum *et al.* 1983); mass lifted $= (0.005\ \text{m/yr})(0.411\times10^{12}\ \text{m}^2)(2\,650\ \text{kg/m}^3) = 5.45\times10^{12}\ \text{kg/yr}$.

Assuming that the center of gravity is 1/2 of uplift, the work done is estimated as:
Energy $= (5.45\times10^{12}\ \text{kg/yr})(0{,}005\ \text{m/yr})/2*(9.8\ \text{m/s}^2) = 1.34\times10^{11}\ \text{J/yr}$;

Estimated solar transformity for net uplift in Sweden (adapted from Odum *et al.* 1983):
The net uplift of the earth is calculated as the uplift of the continents to an average global elevation of 875m over 5 billion years. The center of gravity assumed 1/2 of mean earth elevation so that work done is:

Energy $= [(875\ \text{m})(1.5\times10^{14}\ \text{m}^2$ area of continents$)(2.6\times10^3\ \text{kg/m}^3)(9.8\text{m/s}^2)(875\text{m})/2]/5\times10^9 = 2.93\times10^{14}\ \text{J/yr}$;

Solar transformity of net earth uplift: Annual, renewable global emergy flow/energy of net uplift $= (9.46\times10^{24}\ \text{sej/yr})/(2.93\times10^{14}\ \text{J/yr}) = 3.23\times10^{10}\ \text{sej/J}$

PHYSICAL ENERGIES OF THE NORTH SEA AND BALTIC SEA COASTS:

Surface area of Baltic proper; 365 000 km^2 (Wulff *et al.* 2001)
Portion attributed to Sweden; approximately 40% ($146\times10^9\ \text{m}^2$, corresponds to exclusive economic zone).

Footnotes to Table 2, continued.

6. Direct solar insolation = 93 kcal/cm^2/yr (estimate for Baltic island of Gotland; Jansson and Zucchetto 1978)

   Energy over sea = (146 x 10^9 m^2)(10^4 cm^2/m^2)(93 kcal/cm^2/yr)(4 186 J/kcal) = 5.68 x 10^{20} J/yr

7. Kinetic wind energy transfered to Baltic surface, generating waves and driving surface currents and evaporating water, is contributed from 2 processes;

   a) lateral transfer of wind energy across Baltic surface;
      = 1/2 (density of air)(length of Baltic proper)(wind speed)(100 m hgt.)(wind speed)^2
      = 1/2 (1.3 kg/m^3)(605 000 m)(7.15 m/s)(100 m)(3.154 x 10^7 s/yr)(7.15 m/s)^2
      = 4.53 x 10^{17} J/yr

   b) vertical movement of air to surface from turbulent wind eddies;
      = 1/2 (density of air)(wind speed)^2(eddy diffusion coefficient)/(100 m height)(Baltic area)
      = 1/2 (1.3 kg/m^3)(7.15 m/s)^2(1 m^2/s)/(100 m)(3.154 x 10^7 s/yr)(1.46 x 10^{11} m^2)
      = 1.53 x 10^{17} J/yr

   Total wind energy over Sweden's exclusive economic zone portion of the Baltic Sea = 4.53 x 10^{17} J/yr + 1.53 x 10^{18} J/yr = 1.98 x 10^{18} J/yr

8. Chemical potential energy in rainfall over the Baltic Sea;
   Salinity of rainfall = 1.2 ppm; Average salinity of Baltic seawater = 6 000 ppm;
   Mean rainfall 520 mm/yr (Jansson and Zucchetto 1978)

   Gibbs energy = [(8.31451 J/K/mole)(300 K)]/(18 g/mole)[ln(10^6 – 1.2) – ln(10^6 – 6 000)] = 834 J/kg;

   Chemical potential energy = (0.52 m/yr)(146 x 10^9 m^2)(999.84 kg/m^3)(834 J/kg) = 6.3 x 10^{16} J/yr

9. Chemical potential of stream runoff into the Baltic Sea; salinity of runoff = 150 ppm; volume runoff = 430 km^3/yr

   Gibbs energy = [(0.00199 kcal/K)(300 K)]/(18 g/mole)][ln(10^6 – 150)/(10^6 – 6 000)](4 186 J/kcal) = 815 J/kg;

   Chemical potential energy = (430 x 10^9 m^3)(40%)(999.85 kg/m^3)(815 J/kg) = 140 x 10^{15} J/yr

10. Tides (50% of energy is assumed to be absorbed by shelf – only 50% received at shoreline);
    = (area of shelf)(mean tidal amplitude)^2 (tides/yr)(density of seawater)(gravity)(0.5)
    = (19.6 x 10^9 m^2)(0.31 m tidal range)^2 (706 tides/yr)(1 006 kg/m^3)(9.8 m/s^2)(0.5) = 6.56 x 10^{15} J/yr

11. Waves: length of shoreline = 2 500 km (Hammer 1991); Baltic Sea is frozen 2–3 month/yr and w/o wave action; = (1/8)(gravity)(seawater density)(mean wave height)^2 [(gravity)(mean shoaling depth)]$^{1/2}$ (s/yr)(length of shoreline) = (1/8)(9.8m/s^2)(1006 kg/m^3)(0.5 m)^2 [(9.8m/s^2)(6 m)]$^{1/2}$ (31.54 x 10^6 s/yr)(2 500 km)(1 000 m/km)(9 month/12 month/yr) = 9.3 x 10^{16} kg*m^2/s^2/yr = 1.40 x 10^{17} J/yr

INDIGENOUS RENEWABLE PRODUCTION SYSTEMS:

12. Hydroelectricity = (72 TWh/yr)(10^9 kWh/TWh)(3.6 x 10^6 J/kWh) = 2.59 x 10^{17} J/yr

13. Agricultural production: 1988 crop production; 13.1 x 10^6 t (including 4.435 x 10^6 t of hay, sillage)
    = (13.1 x 10^6 t/yr)(10^6 g/t)(3.85 kcal/g)(4 186 J/kcal) = 2.11 x 10^{17} J/yr

14. Livestock and dairy production, 1988; livestock, 0.433 x 10^6 t + wild game, 0.02 x 10^6 t + poultry, 0.165 x 10^6 t + dairy products, 3.45 x 10^6 t = 4.068 x 10^6 t/yr
    = (4.073 x 10^6 t)(10^6 g/t)(4.4 kcal/g)(4 186 J/kcal)(22% protein) = 1.65 x 10^{16} J/yr

15. Fisheries; 5 020 J/g energy content of Baltic herring (Hammer 1991);

    (0.232 x 10^6 t catch, 1988)(10^6 g/t)(5 020 J/g) = 1.16 x 10^{15} J/yr

16. Forestry: Harvested stemwood, bark and tops = 64.1 x 10^6 m^{3}f; (64.1 x 10^6 m^{3}f)(0.425 x 10^6 g/m^3)(2.052 x 10^4 J/g) = 5.59 x 10^{17} J/yr

Footnotes to Table 2, continued.

NONRENEWABLE STORAGES MINED WITHIN SWEDEN IN 1987:

17*. Iron ore = $(19.1\times10^{6}$ t/yr$)(10^{6}$ g/t$) = 1.91\times10^{13}$ g/yr

18*. Gold, 7231 kg + silver, 259087 kg = 2.66×10^{8} g/yr

19*. Copper = (83128 t/yr)$(10^{6}$ g/t$) = 8.31\times10^{10}$ g/yr

20*. Lead = (62588 t/yr)$(10^{6}$ g/t$) = 6.26\times10^{10}$ g/yr

21*. Zinc = (392000 t/yr)$(10^{6}$ g/t$) = 3.92\times10^{11}$ g/yr

22*. Other geologic materials = (pyrites, 429000 + granite, 8.3×10^{6} + marble, dolomite, 3.5×10^{6} + quartz, 1.32×10^{6}) t/yr = $(13.5\times10^{6}$ t/yr$)(10^{6}$ g/t$) = 1.35\times10^{13}$ g/yr

23*. Sedimentary materials = (limestone, 3.42×10^{5} + sandstone, 4.7×10^{4}) t = $(3.89\times10^{5}$ t/yr$)(10^{6}$ g/t$) = 3.89\times10^{11}$ g/yr

*) References to footnotes: Statistical Yearbook of Sweden (SYS) 1994, table 101: note 15. Statistical Abstract of Sweden (SAS) 1990, table 96 and 97: note 17–23.

Imported and exported goods, fuels and human services

Purchased fuels, including crude and refined petroleum products, coal, natural gas and uranium (items 24–28; Table 3) contributed about 660×10^{20} sej to Sweden in 1988. Imported uranium fuel (36600 tons, 1988) was estimated as roughly 67% of the solar emergy required for nuclear powered electricity generation [3:1 net yield ratio; Lapp (1991)], using a solar transformity for electricity generation of 200000 sej/J (Odum *et al.* 1986, updated in Odum 1996). This resulted in a value of 190×10^{20} sej/yr (item 24, Table 3), about 30% of the imported fuels for 1988.

Other imported goods, including fertilizers, refined metals, vehicles, textiles and food, collectively contributed less than 10% of the imports in 1988. Although the solar transformities used to estimate solar emergy in these commodities include both environmental energies and societal services and thus some double counting occurs, it is considered only 2–3 percent of Sweden's total solar emergy budget (using a ratio of 1:2 nature to societal energy inputs; 67%x10% imports/total solar emergy base < 3%). Human services associated with the production, refinement and delivery of imports accounted for about half of the country's import of solar emergy (item 46, Table 3). Together, imports of goods (G), fuels (F), and associated human services (P_2I) contributed the largest proportion of solar emergy supporting Sweden's combined ecological-economic system in 1988, more than twice that of free indigenous sources.

Almost 227×10^{20} sej were exported in paper and pulp products in 1988 (items 56–58, Table 3), representing its largest export items that year. Another 21×10^{20} sej were exported in sawlogs and sawn wood. Together, forest industry products represented about 16% of total exported goods and services. Products of the steel industry were also large exports; vehicles, generators, farm and office equipment, rolled iron, steel alloys, rail tracks, wire and pipes represented about 10% of exports. Fish and cereal grains were relatively small by comparison. The human services associated with the production, refinement and transport of export commodities in Sweden, estimated in proportion to the revenues received for the sale of the exports, measured 754×10^{20} sej, about 50% of all exported solar emergy. This figure is a

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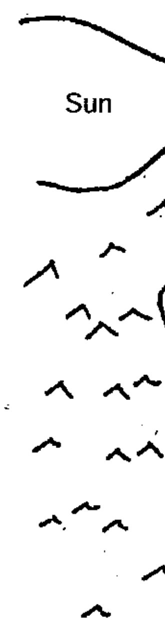


Figure 11. Sum
base including r

result, in part, of taxes and high wages paid for labor, but is indicative of high quality products made in the country.

Overview indices of Sweden's solar emergy and economic base

An aggregated systems diagram of Sweden, its resource base, imports and exports, and gross national product is given in Figure 12. Renewable sources are shown on the left, representing more dispersed, lower transformity energy inputs. Mining of minerals and metal ores are shown as a use of an internal storage. Imported fuels,

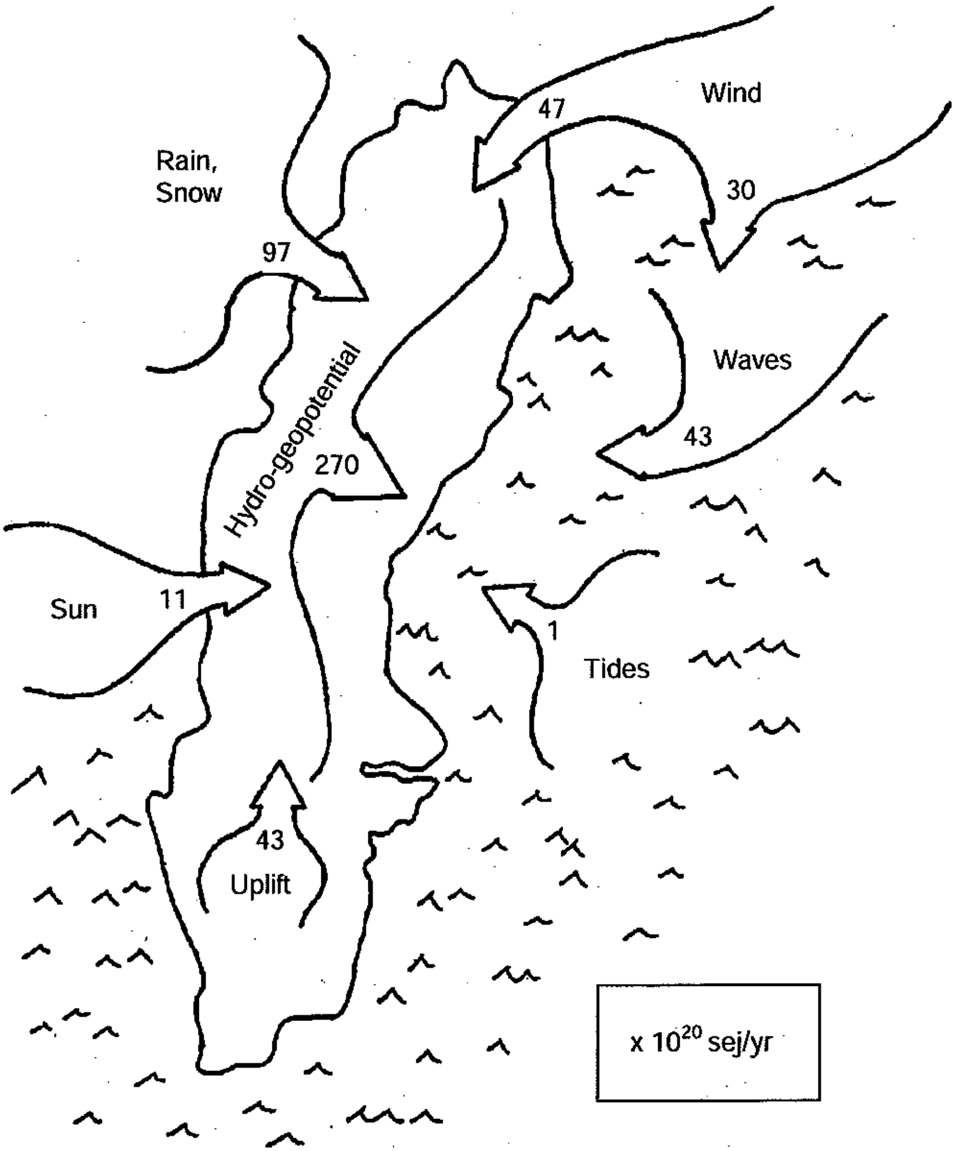


Figure 11. Summary of estimates of free environmental contributions to Sweden's resource base including meteorologic and hydrologic sources and the support base of the Baltic Sea.

goods and services are shown has higher transformity products inflowing at the right hand side of the diagram. Exports are shown leaving the system in exchange for monetary revenues inflowing as a counter current to the exported products. The solar emergy values on the pathways are totals for 1988 from the national resource evaluation (Tables 2 and 3) and summarized in Tables 4 and 5. The gross national product in 1988 was about 1 156 billion SEK (178 billion USD; 6.5 SEK/USD 1988 exchange rate). The total annual solar emergy base for the combined ecological-economic system of Sweden in 1988 ($U = R+N_1+F+G+P_2I$) was $2\,580 \times 10^{20}$ sej. By dividing the national economic product into the solar emergy-use for that year, an average amount of resources supporting circulating currency was calculated as 0.223×10^{12} sej/SEK (1.45×10^{12} sej/USD, 1988; P_1, Table 4). This was considered an estimate of the "buying power" of Swedish currency converted to international dollars for 1988, using solar emergy as the measure of resources supporting each SEK.

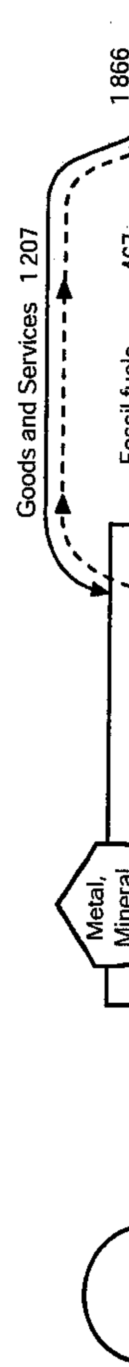
Human service employed in production and delivery of imported items was estimated using an index of solar emergy per international USD for Sweden's trade partners (considered middle Europe and the U.S.A.) of 2×10^{12} sej/$ (P_2, Table 4). This corresponds to values derived for West Germany, U.S.A., and Japan from previous studies, adjusted for 1988.

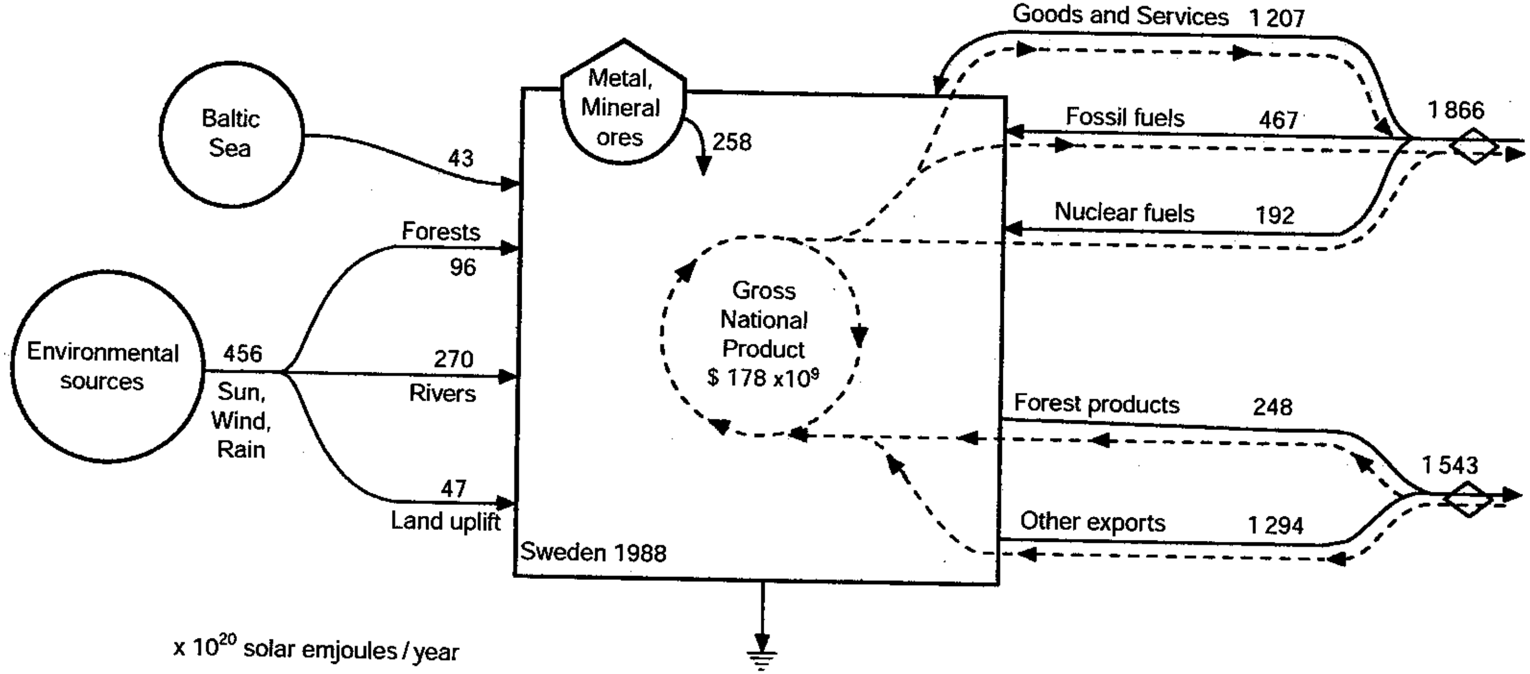
Sweden exports only transformed products (B) and associated human services (P_1E) (Table 4). All extracted natural resources, such as mineral and metal ores and timber, are upgraded to some degree before being sold to outside markets. This is indicative of large processing and industrial sectors, employing a large labor force. By not exporting raw materials, Sweden uses its resource base within the country, upgrading the "free" resources of nature through value-added economic product transformations and at the same time keeps unemployment down.

The solar emergy basis of the national economy is considered in perspective of economic and environmental contributions, self-sufficiency and trade. Indices of fuel-use, renewable and purchased solar emergy-use, imports and exports are presented to lend insight to the country's solar emergy support basis. Table 5 lists several indices comparing distribution and utilization of the emergy in resources available to Sweden. The first six items are simple aggregations of solar emergy contributions from environmental sources (R), internal storages (N_1) and imported fuels, goods and services (F, G and P_2I). Most of these indices are self-explanatory, but a few will discussed below to better understand the solar emergy basis for national welfare.

Renewable solar emergy flows of sun, wind, rain, rivers and sea account for about 18% of Sweden's solar emergy base (item 7, Table 5). Including mining of internal storages of metal ores and minerals, 28% of the solar emergy available in 1988 was derived from domestic sources (item 13). Seventytwo percent of the country's annual solar emergy used in 1988 came from purchased goods, fuels and associated services from outside the economy (item 12).

Sweden paid 350 billion SEK (54 billion USD) for imported fuels, goods, and services in 1988. Revenues received from export commodities were 370 billion





$$\frac{\text{Annual solar emergy use}}{\text{GNP}_{1988}} = \frac{2\,580 \times 10^{20}\,\text{sej}}{178 \times 10^{9}\ \$} = 1.45 \times 10^{12}\ \text{sej/\$}$$

Figure 12. Aggregated systems diagram of sweden, its solar emergy basis and gross national product. Numbers on pathways are from the national analysis, tables 2 and 3.

Table 3. *Solar emergy support for Sweden's annual imports and exports in 1988. Raw materials, commodities and human services are reported from basic trade statistics (General trade statistics for Sweden 1989), and derived in footnotes to this table.*

Note	Item	Trade quantity raw units/yr (J, g, $)	Solar transformity[1)] (sej/unit)	Solar emergy (10^{20} sej)	Macro-economic value[2)] (10^9 USD, 1988)
IMPORTS:					
24	Uranium[3)] (U_3O_8)	1.90×10^6 g	---	192.00	13.23
25	Crude petroleum	6.41×10^{17} J	40200	257.49	17.74
26	Refined fuels	3.56×10^{17} J	47900	170.56	11.75
27	Coal	1.17×10^{17} J	29000	33.89	2.34
28	Natural gas	1.44×10^{16} J	34800	5.01	0.35
29	Nitrogen	1.47×10^{15} J	1.70×10^6	25.05	1.73
30	Potassium	1.21×10^{14} J	2.60×10^6	3.15	0.22
31	Phosphorus	7.33×10^{11} J	4.10×10^7	0.30	0.02
32	Copper	6.05×10^{10} g	4.50×10^9	2.72	0.19
33	Aluminum	2.82×10^{10} g	4.50×10^9	1.27	0.09
34	Zinc	3.97×10^{10} g	4.50×10^9	1.79	0.12
35	Pig iron	2.14×10^{11} g	8.60×10^8	1.84	0.13
36	Steel	2.09×10^{12} g	1.80×10^9	37.67	2.60
37	Vehicles	3.99×10^{11} g	6.70×10^9	26.75	1.84
38	Wool	3.74×10^{13} J	3.80×10^6	1.42	0.10
39	Cotton	6.72×10^{13} J	1.90×10^6	1.28	0.09
40	Meats	1.12×10^{14} J	1.70×10^6	1.90	0.13
41	Fish	2.75×10^{14} J	3.10×10^6	8.53	0.59
42	Sugar	1.37×10^{15} J	85000	1.16	0.08
43	Other agriculture	2.08×10^{16} J	68000	14.14	0.97
44	Rubber	6.81×10^{14} J	222000	1.51	0.10
45	Other goods	3.86×10^9 \$	2.00×10^{12}	77.29	5.33
46	Services in imports	50.00×10^9 \$	2.00×10^{12}	999.30	68.86
EXPORTS:					
47	Refined fuels	3.33×10^{17} J	47900	159.51	10.99
48	Electricity	1.08×10^{16} J	125000	13.50	0.93
49	Iron ore	1.77×10^{13} g	8.60×10^8	152.41	10.50
50	Pig iron	3.64×10^{11} g	8.60×10^8	3.13	0.22
51	Steel products	2.96×10^{12} g	1.80×10^9	53.28	3.67
52	Machines	2.90×10^{11} g	6.70×10^9	19.42	1.34
53	Vehicles	7.43×10^{11} g	6.70×10^9	49.80	3.43
54	Sawlogs, roundwood	6.34×10^{15} J	32400	2.05	0.14
55	Sawn wood, plyboard	6.00×10^{16} J	32400	19.44	1.34
56	Chemical pulp	2.73×10^{12} g	1.80×10^9	49.16	3.39
57	Mechanical pulp	4.52×10^{11} g	4.45×10^9	20.11	1.39
58	Paper products	6.38×10^{12} g	2.47×10^9	157.59	10.86
59	Fish	2.92×10^{14} J	3.10×10^6	9.06	0.62
60	Cereal, grains	1.16×10^{16} J	68000	7.89	0.54
61	Other exports	5.00×10^9 \$	1.45×10^{12}	72.61	5.00
62	Services in exports	51.94×10^9 \$	1.45×10^{12}	753.74	51.94

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Footnotes to Tab

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1) Some commodities are evaluated using sej/g, services are evaluated using sej/$.

2) Solar emergy value divided by solar emergy-use/GNP for Sweden, 1988 (1.29x10^{12} sej/$).

3) Imported proportion of nuclear power is deduced from an estimate of I/Y, nuclear fuel/electricity generation for current nuclear power of 67% (net yield ratio estimated at 3:1) where I in Sweden is imported U_3O_8 .

Footnotes to Table 3:

Formulae used for calculating annual energy and monetary flows for import and export commodities in Sweden, 1988.

IMPORTED FUELS, GOODS AND SERVICES:

24. Nuclear fuels: Electricity production (1988) = (64 TWh/yr)(3.6x10^{5} J/TWh) = 2.30x10^{17} J/yr;
Imported uranium, U_3O_8 = 1.90 ton (1989); Import costs of uranium = 39.7 SEK/MWhe;
25% of cost includes waste handling;
(39.7 SEK/MWhe)(0.75)/(1 000 kWh/MWh)(64x10^{9} kWhe/yr) = 1.906x10^{9} SEK;
(1.91x10^{9} SEK)/(366 000 t) = 5 200 SEK/t;
(1.91x10^{9} SEK)/(6.5 SEK/USD, 1988) = 0.294x10^{9} USD

25*. Crude petroleum = (14 233 807 t/yr)(4.5x10^{10} J/t oil) = 6.41x10^{17} J/yr

26*. Refined fuels = [(gasoline 3 563 733)+(oils 4 701 586)+(lubricants 212 575)] t/yr = 8 477 894 t/yr; (8 477 894 t/yr)(4.2x10^{10} J/t oil) = 3.56x10^{17} J/yr

27*. Coal = (4.23x10^{6} t/yr)(6.6x10^{6} kcal/t)(4186 J/kcal) = 1.17x10^{17} J/yr

28*. Natural gas = (4 TWh/yr)(3.6x10^{15} J/TWh) = 1.44x10^{16} J/yr

29*. Nitrogen fertilizer = (678 917 t/yr)(10^{6} g/t)(2 170 J/g) = 1.47x10^{15} J/yr

30*. Potassium fertilizer = (172 497 t/yr)(10^{6} g/t)(702 J/g) = 1.21x10^{14} J/yr

31. Phosphorus fertilizer = (2 105 t/yr)(10^{6} g/t)(348 J/g) = 7.33x10^{11} J/yr

32*. Copper = (60 526 t/yr)(10^{6} g/t) = 6.05x10^{10} g/yr

33*. Aluminum = (28 191 t/yr)(10^{6} g/t) = 2.82x10^{10} g/yr

34*. Zinc = (39 718 t/yr)(10^{6} g/t) = 3.97x10^{10} g/yr

35*. Pig iron, unrefined = (213 580 t/yr)(10^{6} g/t) = 2.14x10^{11} g/yr

36*. Refined iron and steel = (ingots, 122 330 + rolled iron, 1 011 871 + steel alloys, 80480 iron, steel bars, 495 629 + railroad tracks, 7 046 + wire, 34075 + iron pipes, 341472) t/yr = 2 092 903 t/yr; (2 092 903 t/yr)(10^{6} g/t) = 2.09x10^{12} g/yr

37*. Transport vehicles = (passenger cars, 291 675 + buses, 84 586 + tractors, 22 950) t/yr = 399 211 t/yr; (399 211 t/yr)(10^{6} g/t) = 3.99x10^{11} g/yr

38*. Wool = (1 789 t/yr)(10^{6} g/t)(5 kcal/g)(4 186 J/kcal) = 3.74x10^{13} J/yr

39*. Cotton = (4 016 t/yr)(10^{6} g/t)(4kcal/g)(4 186 J/kcal) = 6.72x10^{13} J/yr

40*. Meat = (27 556 t/yr)(22% protein)(10^{6} g/t)(4.4 kcal/g)(4 186 J/kcal) = 1.12x10^{14} J/yr

41*. Fish = (54 809 t/yr)(10^{6} g/t)(5 020 J/g) = 2.75x10^{14} J/yr

42*. Sugar = (81 594 t/yr)(4x10^{6} kcal/t)(4 186 J/kcal) = 1.37x10^{15} J/yr

43*. Other agricultural imports = (grains, cereals, 187574 + fruits, nuts, 464406 + coffee, 91 290 + animal feed, 472 813 + oil seed, kernels, 76262) t/yr = 1.29x10^{6} t/yr;
= (1.29x10^{6} t/yr)(10^{6} kcal/t)(3.85 kcal/g)(4186 J/kcal) = 2.08x10^{16} J/yr

44*. Rubber (synthetic and natural) = (46 324 t/yr)(10^{6} g/t)(1.47x10^{4} J/g) = 6.81x10^{14} J/yr

45*. Other imported goods = (animal hides, 17408 t; 0.33x10^{9} SEK + clothing, 79619 t; 12.77x10^{9} SEK + cotton fabrics, 12 587 t; 0.73x10^{9} SEK + synthetic fibers, 9947 t; 0.8x10^{9} SEK + tires, 91 878 t; 2.22x10^{9} SEK + chassis, car parts, 258 027 t; 8.27x10^{9} SEK) = 25.1x10^{9} SEK/yr;
(25.1x10^{9} SEK/yr)/(6.5 SEK/USD, 1988) = 3.86x10^{9} USD/yr

46*. Imported human services = import costs 350x10^{9} SEK−25.1x10^{9} SEK (other goods, item 45) = 325x10^{9} SEK/yr; (325x10^{9} SEK/yr)/(6.5 SEK/USD, 1988) = 50.0x10^{9} USD/yr

Footnotes to Table 3, continued.

EXPORTED GOODS AND SERVICES:

47*. Refined fuels = (8 477 894 t/yr)–(net import 549 000 t/yr)(4.2×10^{10} J/t) = 3.33×10^{17} J

48*. Electricity = (3 TWh/yr)(3.6×10^{15} J/TWh) = 1.08×10^{16} J/yr

49*. Iron ore = (17 721 900 t/yr)(10^6 g/t) = 1.77×10^{13}

50*. Pig iron, unrefined = (363 700 t/yr)(10^6 g/t) = 3.64×10^{11} g/yr

51*. Refined iron and steel = (ingots, 430 400 + rolled iron, 978 000 + steel alloys, 397 600 + iron, steel bars, 803 100 + rail tracks, 38 200 + wire, 65 800 + iron pipes, 247 100) t/yr = 2 960 200 t/yr; (2.96E+6 t/yr)(10^6 g/t) = 2.96×10^{12} g/yr

52*. Machines = (power generators, 83.3×10^3 + milking machines, 3.42×10^3 + paper machines, 22.3×10^3 + pumps, centrifuges, 44.7×10^3 + mech. handling equipt., 97.3×10^3 + non-electr. hand tools, 7.67×10^3 + ball bearings, 28.1×10^3 + office machines, 3.05×10^3) t/yr = 289 900 t/yr; (0.289×10^6 t/yr)(10^6 g/t) = 2.90×10^{11} g/yr

53*. Transport vehicles = (Passenger cars, 193 494 vehicles/yr)(1.4 t/vehicle) = 0.271×10^6 t/yr; (buses, lorries, 39 360 buses/yr)(12 t/bus) = 0.472×10^6 t/yr; total = (0.271 + 0.472)*10^6 t = 0.743×10^6 t/yr; (0.743×10^6 t)(10^6 g/t) = 7.43×10^{11} g/yr

54*. Sawlogs = (727×10^3 m^3, 1988 exports)(0.425×10^6 g/m^3)(2.052×10^4 J/g) = 6.34×10^{15} J/yr

55*. Sawn wood, plyboard = (6.88×10^6 m^3, 1988 exports)(0.425×10^6 g/m^3)(2.052×10^4 J/g) = 60.0×10^{15} J/yr

56*. Chemical pulp = (2.731×10^6 t, 1988 exports)(10^6g/t)(2.052E+4 J/g) = 5.60×10^{16} J/yr

57*. Mechical pulp = (0.452×10^6 t; 1988 exports)(10^6 g/t)(2.052×10^4 J/g) = 9.27×10^{15} J/yr

58*. Paper products = (newsprint, 1.75×10^6 + kraft, paperboard, 2.09×10^6 + other paper 2.54×10^6) t = 6.38×10^6 t, 1988 export; (6.38×10^6 t)(10^6 g/t)(2.052×10^4 J/g) = 1.31×10^{17} J/yr

59*. Fish = (58194 t/yr)(10^6 g/t)(5 020 J/g) = 2.92×10^{14} J/yr

60*. Cereal, grains = (0.72×10^6 t/yr)(10^6 g/t)(3.85 kcal/g)(4 186 J/kcal) = 1.16×10^{16} J/yr

61*. Other export products = (ADP machines, 9 700 t; 4.84×10^9 SEK + ADP parts, 4 020 t; 2.67×10^9 SEK + telecomunication equipt., 17.6×10^3 t; 11.6×10^9 SEK + televisions, 2.95×10^5 units; 0.612×10^9 SEK + car parts, 278 034 t; 12.8×10^9 SEK) = 38.03×10^9 SEK/yr; (38.0×10^9 SEK/yr)/(6.5 SEK/USD, 1988) = 5.00×10^9 USD/yr

62*. Human services in export products = 370.1×10^9 SEK/yr export revenues – 38.0×10^9 SEK/yr (other exports, item 61) = 337.6×10^9 SEK/yr; (337.6×10^9 SEK/yr)/(6.5 SEK/USD, 1988) = 51.9×10^9 USD/yr

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*) References to footnotes: Statistical Abstract of Sweden (SAS) 1990, table 139: note 25–30, 32–45; SAS 1990, table 131: note 46; SAS 1990, table 140: note 49–61; SAS 1990, table 132: note 62; NUTEK Energy in Sweden 1994: note 47–48.

SEK (57 billion USD), indicating a 5% net balance of monetary payments due to international trade. Sweden, however, received 1.21 times as much solar emergy in imports as it exported (item 9, Table 5). By comparison, although Sweden had a slight net benefit from trade in monetary terms for 1988, in real resources, measured in solar emergy, it received an even greater net benefit to its economy (21% more solar emergy was received in imports than was exported). A net solar emergy benefit of 323×10^{20} sej were received due to international sales and purchases of fuels, commodities and associated human services (item 11, Table 5). This is approximately 13% of the total solar emergy received in Sweden in 1988.

From the national data, an investment ratio of solar emergy was calculated as the ratio of purchased or societal inputs a particular economic sector or local area within Sweden can, on average, support in relation to the solar emergy supplied from environmental sources. This economic/environment ratio of solar emergy contributions was measured as $(F+G+P_2I)/R = 4.7$ (item 8). This ratio suggests that typically between four and five times as much solar emergy input to a production subsector within Sweden is due to purchased inputs delivered from the main economy as is input from the environment. This ratio is used later to determine the amount of invested, purchased solar emergy that presently could be attracted due to a given use of an environmental resource such as forest. The use

Table 4. *Summary of major solar emergy flows and market economic monetary flows for Sweden, 1988. Complete analyses are given in Tables 2 and 3.*

Variable	Item	Solar emergy (10^{20} sej/yr)	Market value (10^9 USD, 1988)	sej/$
R	Renewable sources 1)	456.3		
	Sun	10.5		
	Wind over land	47.5		
	Evapo-transpired rain	96.6		
	Hydro-geopotential	270.0		
	Net land uplift	47.0		
	Waves absorbed on shore	42.7		
	Tides	1.1		
N	Nonrenewable sources within Sweden (mineral and metal ores)			
	N_1 Refined within the country	257.9		
	N_2 Export of unprocessed raw materials	0.0		
F	Imported fuels (fossil fuels, uranium)	659.0	8.88	
G	Imported goods, minerals, fertilizers	130.5	34.70	
I	Dollars paid for imports		49.96	
P_2I	Solar emergy value of service in imports	1076.6		
E	Dollars received for exports		56.94	
P_1E	Solar emergy value of service in exports	826.4		
B	Exports transformed, upgraded within country	716.4		
x	Gross National Product, 1988 (6.5 SEK/USD)		177.79	
P_2	European trade partner's solar emergy/$ index			2.00×10^{12}
P_1	Sweden's solar emergy/$ index			1.45×10^{12}

1) Renewable environmental sources (R) are corrected for double counting of byproduct solar emergy by summing all independent, over-land contributions and subtracting from that total the coupled flows since the annual global solar emergy budget was used to derive solar transformities for each source (see text and Table 1 and Table 2 for details): sun + wind + stream hydro-geopotential + chem rain + net uplift – (sun + wind) = $(270.0 + 96.6 + 47.0) \times 10^{20}$ sej/yr = 413.6×10^{20} sej/year. Physical energies in surrounding seas calculated similarly: sun + wind + waves + tide – (sun + wind + tide) = 42.7×10^{20} sej/year. R-total = land based emergy + sea based emergy = $(413.6 + 42.7) \times 10^{20}$ sej/yr = 456.3×10^{20} sej/year.

of one unit of renewable solar emergy from nature attracts 4.7 times that amount in external investment. In order for a new sector introduced to the Swedish economy to be competitive or economic under current conditions, the investment requirements of the new sector should not exceed this ratio.

Estimating the solar emergy for electricity generation, 37% of Sweden's economy was driven by electricity use (item 18). Similarly, 24% of all solar emergy used

Table 5. *Overview indices of annual solar emergy-use, origin, and economic and demographic relations for Sweden, 1988.*

	Name of Index	Derivation	Quantity
1	Renewable solar emergy flow (rain, river, Baltic Sea)	R	456×10^{20} sej/yr
2	Solar emergy flow from indigenous nonrenewable reserves	N	258×10^{20} sej/yr
3	Flow of imported solar emergy	$F+G+P_2I$	1866×10^{20} sej/yr
4	Total solar emergy, U	$U = N_1+R+F+G+P_2I$	2580×10^{20} sej/yr
5	Economic component	$U-R$	2124×10^{20} sej/yr
6	Total exported solar emergy	N_2+B+P_1E	1543×10^{20} sej/yr
7	% Locally renewable (free)	R/U	17.7 %
8	Economic/environment ratio	$(U-R)/R$	4.7
9	Ratio of imports to exports	$(F+G+P_2I)/(N_2+B+P_1E)$	1.21
10	Export to imports	$(N_2+B+P_1E)/(F+G+P_2I)$	0.83
11	Net contribution due to trade (imports minus exports)	$(F+G+P_2I) - (N_2+B+P_1E)$	323×10^{20} sej/yr
12	% of solar emergy-use purchased	$(F+G+P_2I)/U$	72.3 %
13	% of solar emergy-use derived from home sources	$(N_1+R)/U$	27.7 %
14	Solar emergy-use per unit area (0.411 million km²)	U/area	6.3×10^{11} sej/m²
15	Solar emergy-use per person (8.5 million people)	U/population	3.0×10^{16} sej/person
16	Renewable carrying capacity at present living standard	(R/U)(population)	1.50×10^{6} people
17	Index of solar emergy-use to GNP (178 billion USD)	$P_1 = U/GNP_{1988}$	1.45×10^{12} sej/$
18	Fraction electric 1) (134 TWh)	(electricity-use)/U	0.37
19	Fraction fossil fuels 2)	(fuel-use)/U	0.24
20	Fossil fuel-use per person	fuel-use/population	7.39×10^{15} sej/person

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1) Solar emergy estimate for electricity generation estimated from solar transformity which includes human services, 0.2×10^{6} sej/J (Odum 1996).

2) Emergy values for imported fuels (F) reported here are estimated using solar transformities from Odum (1996) which include associated human services (coal 40000 sej/J; natural gas 48000 sej/J; crude oil 53000 sej/J; refined petroleum 66000 sej/J) so that the full cost of these primary sources are considered. Imported uranium ore estimated as given in Table 3.

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in 1988 was direct consumption of fossil fuels (item 19). A rough estimate of imports of uranium fuel from Australia and Canada for nuclear powered electricity generation was calculated to be about 7% of Sweden's solar emergy basis. Sweden's relatively high ratio of electrical energy consumption is like that of Switzerland, New Zealand and the U.S.A. This facilitates high quality operations such as information processing which enables Sweden to be a world hierarchical center. Hydropowered electricity production, although not yet studied here in Sweden, appears to produce an inexpensive high quality energy supply. If this renewable source produces a net solar emergy in the hydropowered generation of electricity, this would support Sweden's extensive use of electricity to supplement production systems, transportation and low quality purposes such as general heating.

Solar emergy basis for Sweden compared with other nations

To place Sweden's ecological-economic system in a global context with other nations, solar emergy-use, distribution, exchange, and gross economic product were compared with other countries. Tables 6–10 compare various indices calculated in this study of Sweden with those of other nations. Sweden is like other more developed nations in being only moderately self-sufficient; in 1988, 28% of the solar emergy used came from within its border, and only about 18 percent units of these home sources were renewable. Correspondingly, more of its annual resource base was contributed from imports (72%). More rural nations such as Ecuador and Papua New Guinea receive a much greater percentage of solar emergy from within their borders (Table 6).

While annual solar emergy-use was moderate compared with some nations, solar emergy-use per capita and solar emergy per unit area (empower density) are high compared with other countries of the world (Tables 7 and 8). Population density in 1988 was around 20 persons/km^2, low compared with other countries. A combination of a large resource base developed from rainfall and snow melt in mountainous terrain, large productive forest areas, and a net benefit from international trade, Sweden has a large resource base supporting its sparse human population.

The relation of solar emergy to GNP for Sweden (1.45×10^{12} sej/USD, 1988) calculated in this study was comparable with other technologically developed nations such as Switzerland, Japan and the U.S.A. (Table 9). Countries divided on the basis of this index generally split among the rural and urban. Past studies of other countries have illustrated that rural nations have a greater annual solar emergy base per unit currency than more urban and industrialized countries (Odum *et al.* 1983, Doherty *et al.* 1991, Huang and Odum 1991, McClanahan and Brown 1991). This is a result of both a small GNP and a large environmental base supporting a large part of the economy without monetary valuation. Currency in these countries represents more total resources. This suggests that in an exchange with a country whose currency is supported with less total resources (*i.e.* solar emergy), the exchange is not equitable, and the advantage goes to the country with the lower solar emergy/\$, even if their accounting ledgers are balanced. International dollars don't purchase

Table 6. *Solar emergy self-sufficiency and trade balance for Sweden and other countries of the world.*

Nation	% solar emergy from within [1]	solar emergy imported [2] / solar emergy exported
Netherlands	23	4.3
West Germany	10	4.2
Switzerland	19	3.2
Spain	24	2.3
U.S.A.	77	2.2
India	88	1.45
Sweden	**28**	**1.21**
Taiwan	28	1.19
Brazil	91	0.98
Dominica	69	0.84
New Zealand	60	0.76
Thailand	70	0.54
Australia	92	0.39
Soviet Union	97	0.23
Ecuador	94	0.20
Liberia	92	0.15
Papua New Guinea	96	0.13

Solar emergy valuations for countries compared in Tables 6 – 10 are based on revised national analyses from Odum *et al.* (1983) except Papua New Guinea (Doherty *et al.* 1991), Thailand (McClanahan *et al.* 1990), Taiwan (Huang and Odum 1991), U.S. (Odum *et al.* 1987) and Ecuador (Odum and Arding 1991). Values for Sweden based on national analysis documented in this study.

[1] $(N_1+R)/U$; item 13, Table 5.

[2] $(F+G+P_2I)/(N_2+B+P_1E)$; item 9, Table 5.

as much in Sweden as in some countries of the world. This means that Sweden benefits from an exchange of goods and services, paid for with market dollars, with any nation which has more solar emergy supporting its currency than does Sweden. Papua New Guinea and Ecuador for example, have a greater amount of total resources representing each international dollar within their countries than Sweden or the U.S.A. (Table 9).

Comparing economic, fuel-based solar emergy-use with solar emergy received from environmental and meterological sources, Sweden appears to be intermediate of other countries (Table 10). A 4.7 to 1 ratio of economic to environmental resources, Sweden is about half as dependent on external purchases and societal resources as are other technologically developed nations such as West Germany and the U.S.A., and 2–3 times more tied to economic resources than rural countries such as Papua New Guinea and Thailand. More developed nations tend to have more of their total resource base tied to economic activities, import more solar emergy than is exported and are often less self-sufficient than more rural, developing nations. A large resource base per capita or per unit area (Tables 7 and 8) are not necessarily correlated with high per capita incomes indicative of urban or industrialized countries. Because non-market services and commodities such as solar energy capture, stream flow and forest production are accounted for on an equivalent basis of solar emergy, these contributions can be reflected in national accounts.

Table 7. *Solar emergy-use, population and per capita solar emergy-use for Sweden and other countries of the world.*

Nation	Solar emergy used[1] (x 10^{20} sej/yr)	Population x 10^6	Solar emergy-use per person[2] (x 10^{15} sej/person/yr)
Australia	8850	15	59
Papua New Guinea	1216	3.5	35
Sweden	**2580**	**8.5**	**30**
U.S.A.	66400	227	29
West Germany	17500	62	28
Netherlands	3702	14	26
New Zealand	791	3.1	26
Liberia	465	1.3	26
Soviet Union	43150	260	16
Brazil	17820	121	15
Dominica	7	0.08	13
Switzerland	733	6.37	12
Ecuador	964	9.6	10
Taiwan	1340	17.8	8
Spain	2090	134	6
Thailand	1590	50.0	3
India	6750	630	1

1) $U = N_1+R+F+G+P_2I$; item 4, Table 5.

2) Sweden's population (1988) = 8.5 million; item 15, Table 5.

Table 8. *Population density and solar emergy-use per unit area for Sweden and other countries of the world.*

Nation	Area (x 10^{10} m^2)	Population density[1] people/km^2	Solar empower density[2] (x 10^{11} sej/m^2/yr)
Netherlands	3.7	378	100.0
Taiwan	3.6	494	94.6
West Germany	24.9	247	70.4
Switzerland	4.1	154	17.7
Dominica	0.1	107	8.8
U.S.A.	940	24.2	7.0
Sweden	**41.1**	**20.7**	**6.3**
Liberia	11.1	16.1	4.1
Ecuador	28.0	34	3.4
Spain	50.5	68.5	3.12
New Zealand	26.9	11.5	2.94
Papua New Guinea	46.2	7.6	2.63
Thailand	74.0	67.6	2.15
Brazil	918	13.2	2.08
India	329	192	2.05
Soviet Union	2240	11.6	1.71
Australia	768	1.9	1.42

[1] Population divided by national area.

[2] Rate of solar emergy-use, U (item 4, Table 5) divided by national area

Table 9. *Solar emergy-use, gross national products and solar emergy/dollar indices for Sweden and other countries of the world.*

Nation	Solar emergy used [1] (x 10^{20} sej/yr)	GNP [2] (x 10^9 USD/yr)	Solar emergy-use/dollar [3] (x 10^{12} sej/USD)
Papua New Guinea	1216	2.6	48.0
Liberia	465	1.34	34.5
Dominica	7	0.08	14.9
Brazil	17820	214.	8.4
India	6750	106.	6.4
Australia	8850	139.	6.4
Thailand	1509	43.1	3.7
Soviet Union	43150	1300.	3.4
New Zealand	791	26.	3.0
West Germany	17500	715.	2.5
U.S.A.	66400	2600.	2.0
Netherlands	3702	16.6	2.2
Taiwan	1861	99.3	1.9
Spain	2090	139.	1.6
Sweden	**2580**	**178.**	**1.5**
Switzerland	733	102.	0.7

[1] $U = N_1+R+F+G+P_2I$; item 4, Table 5.

[2] Gross national product for 1988; Table 4.

[3] Solar emergy supporting a unit of currency, expressed in international USD, 1988; P_1, Table 4.

Table 10. *Environmental and economic components of annual solar emergy-use for Sweden and other countries of the world.*

Nation	Environmental component[1] (renewable solar emergy) (x 10^{20} sej/yr)	Economic component of solar emergy[2] (x 10^{20} sej/yr)	Economic/ environment ratio
West Germany	193	1 730	9.0
Switzerland	87	646	7.4
U.S.A.	8 240	58 160	7.1
Spain	255	1 835	7.2
Sweden	**456**	**2 124**	**4.7**
Dominica	2	5	2.7
Australia	4 590	3 960	1.1
Thailand	779	811	1.1
India	3 340	3 410	1.0
Soviet Union	9 110	9 110	1.0
World[3]	94 400	90 000	0.96
New Zealand	438	353	0.8
Brazil	10 100	7 600	0.7
Papua New Guinea	1 050	166	0.14
Ecuador	891	483	0.1
Liberia	427	38	0.1

[1] R = independent, renewable environmental sources; Table 4.

[2] Total solar emergy-use minus renewable environmental contribution = U – R, item 5, Table 5.

[3] Annual global solar emergy flux (Figure 6) divided by annual world fossil fuel consumption.

Emergy synthesis of Sweden's forestry sector

The following subsystems analyses of forest production, lumber, pulp and paper industries, fuelwood development and district heating were studied within the framework of the national overview. Managed forests of spruce and pine are evaluated along with natural forest regeneration and willow cultivation for energy. The results of each forest sector evaluation are then compared among forest alternatives, and perspectives are drawn of forest contribution to national welfare and competitive exchange under current trade practices, based on sustainable use of Sweden's forests.

General overview of Sweden's forests and forest industries

Spruce (*Picea abies*) and pine (*Pinus silvestris*) are the most common tree species in Sweden, both occurring almost all over the country. Birch (*Betula verrucosa*, *B. pubescens*) a mid successional species, is the most common deciduous tree in the country, inhabiting all areas and comprising between 5 and 20% of the standing stock in mixed coniferous forest complexes (Kempe and von Segebaden 1990). Annual growth ranges from 0–2 forest cubic meters per hectare (m^3sk/ha) in northern and mountainous areas to 7–9 m^3sk/ha in Southern Sweden, in relation to increasing rainfall, mean temperature and longer growing seasons (Eriksson and Odin 1990). The average volume of wood in Sweden's forests varies from under 60 m^3sk per hectare (stem and bark, exclusive of branches, stump and roots) in the far north to over 160 m^3sk/ha in the south (Kempe and von Segebaden 1990) and can reach 400 m^3sk/ha and more in old growth forests. Stumps, tops and other logging residues generally left in the field account for between 25 and 40% of growing biomass stock, depending on harvesting goals. Nilsson (1990) gives a thorough overview of Sweden's forests, environmental conditions affecting production, growing stock estimates, historical uses, present utilization, current industry trends, and projections for the future.

Sweden harvested 57 million solid cubic meters (m^3f) of wood from its forests in 1988 (Figure 13). Eighty-eight percent of this annual harvest was used in the forest industry sectors for sawn timber, pulp and paper products. Of the wood resources developed in the forest industry, 48% was sold as export, and 52% (30 million m^3f) was used within Sweden (Table 11). Almost 40% of the annual harvest (equivalent to 22 million m^3f) was used as a fuel, mainly in the form of lyes (black liquer) in the sulphate pulp mills (equivalent to about 10 million m^3f). Other by-products as saw dust, bark, shavings etc. were also used as a fuel in the forest industry (equivalent to about 6 million m^3f). The remaining 6 million m^3f were used for domestic heating, mainly as traditional fuel wood in one family houses in the coutryside, but also as a district heating fuel.

The potential wood fuel for the future is logging residues, including branches, tops and some of the needles. Other sources are wood from thinnings in young stands and low grade trees and lumps from clear cuttings.

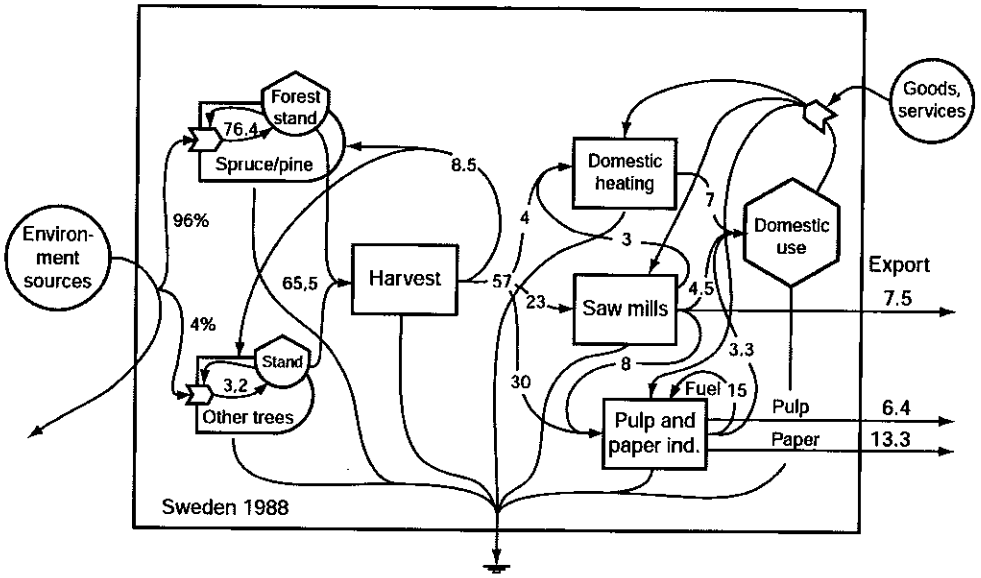

Figure 13. Systems diagram showing distribution and utilization of harvested forest biomass within sectors of Sweden's national economy for 1988. Numbers on pathway are volume of solid wood (million m^{3}f/year). See Table 11 for detailed breakdown of total harvested wood (57×10^6 m^{3}f).

Table 11. *Distribution of annual forest harvest (57 million solid cubic meters) between different sectors of Sweden's economy, 1988 (from Statsistical Yearbook of Forestry). Values are 10^6 m^{3}f.*

	Fuel	Sawlogs	Pulp	Pulp and paper	Total
Wood harvest distribution:	4	23	15	15	
By-products in saw-mills	3 ←		→ 8		
				38	
By-products and lyes used in pulp and paper industy	15 ←	↓		↓	
Product totals:	22	12	23		57×10^6 m^{3}f
Final consumption of forest products:					
Domestic use (52%):	22	4.5	3.3		29.8
Export sales (48%):		7.5	6.4	13.3	27.2
					57×10^6 m^{3}f

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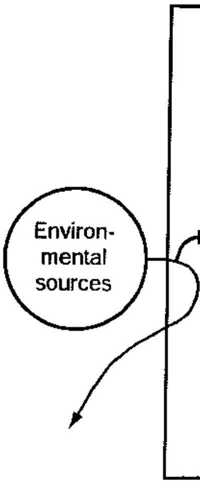

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Footnotes to Figure 1

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Mixed coniferous forest growth and maintenance

Average net primary production of woody biomass in a spruce/pine forest in Southern Sweden measured 8.989 m^3f/ha/yr (Danielsson *et al.* 1990). "Southern Sweden" is here defined as the area south of an imaginary line between Stockholm and Göteborg (Gothenburg). Using an energy conversion factor of 8.72×10^9 J/m^3f (specific wood density, 425 kg/m^3f; and an energy content of 20.52 MJ/kg) the average annual net primary production is calculated as 8.989 m^3f/ha = 78.4×10^9 J/ha/yr. This area receives about 800 mm precipitation annually (Eriksson and Odin 1990). Mature forests were estimated to evapo-transpire 49% of incoming rainfall, the remainder leaves as surface water runoff.

Forest production under natural regeneration

Growing stock of coniferous forests under natural regenaration in Southern Sweden average 283 m^3f/ha (Danielsson *et al.* 1990). Sixty percent of standing stock (170 m^3f/ha) is stemwood, bark and tops; stumps and logging residues make up the

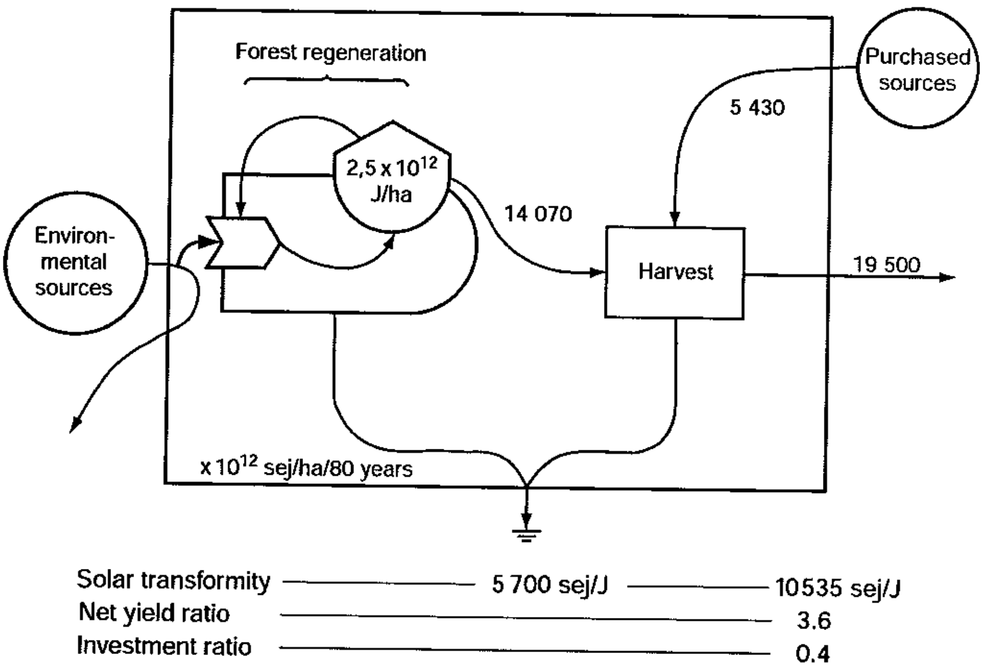

Figure 14. Solar emergy basis for environmental contributions to net forest production in Southern Sweden under natural regeneration. Values were derived using average standing volume of mature forest stands (283 m^3f/ha) at steady state production.

Footnotes to Figure 14:

Growing stock: (283 m^3f/ha)(425 kg/m^3f)(20.52×10^6 J/kg) = 2.47×10^{12} J/ha
Harvested volume: (75% of growing stock) = 211 m^3f/ha = 1.85×10^{12} J/ha
Environmental emergy ($I = Y_1$): (351.7×10^{12} sej/ha/yr; Table 12, page 58)(80 yr rotation)(50% used) = = 14069×10^{12} sej/ha

Footnotes to Figure 14, contimued.

Harvest subsidies (F_2): (211 m^3f/ha)(435 kg/m^3f)(20.52x10^6 J/kg)[(173.5x10^{12} sej; item 7–10,Table 12)/(58.5x10^9 J; Y_2, Table 12, page 58)] = 5460x10^{12} sej/ha
System inputs: I + F_2 = 19529x10^{12} sej/ha
Solar transformity for growing stock (Y_1): (14069x10^{12} sej/ha)/(2.47x10^{12} J/ha) = 5700 sej/J
Solar transformity for harvested yield (Y_2): (Y_1+F_2)/(1.85x10^{12} J/ha) = 10550 sej/J
Net yield ratio: Y_2/F_2 = (19529x10^{12} sej/ha)/(5460x10^{12} sej/ha) = 3.6
Investment ratio: F_2/I = (5460x10^{12} sej/ha)/(14069x10^{16} sej/ha) = 0.4

Estimate for old growth spruce/pine forests:
Y_1 = (425 m^3f/ha)(425 kg/m^3f)(20.52x10^6 J/kg) = 3.71x10^{12} J/ha
I = (351.7x10^{12} sej/ha/yr)(200 yrs)(50% used) = 3.517x10^{16} sej/ha
Solar transformity for growing stock (Y_1) = (3.517x10^{16} J/ha)/(3.71x10^{12} sej/ha) = 9490 sej/J

Table 12. *Annual resource flows associated with production of one hectare of spruce and pine forest under silvicultural management in Southern Sweden, 1988. All values are given as annual inputs and yield per hectare for average annual production.* [1]

Note	Item	Average annual flows raw units/ha (J, g, $)	Solar transformity [2] (sej/unit)	Solar emergy (10^{12} sej/ha/yr)	Macro-economic value [3] (USD, 1988)
I	ENVIRONMENTAL INPUTS:				
1	Sunlight	25.7x10^{12} J	1	25.7	17.74
2	Wind, kinetic	87.3x10^9 J	1500	130.9	90.21
3	Rain, transpired	19.5x10^9 J	18200	351.7	242.36
F_1	SILVICULTURAL INPUTS:				
4	Motor fuel	55.9x10^6 J	47900	2.7	1.84
5	Tractors, trucks	66.7 g	6.7x10^9	0.5	0.31
6	Human services	18.70 $	1.45x10^{12}	27.1	18.70
Y_1	Spruce/pine production (8.989 m^3f/ha/yr)	78.4x10^9 J	4873	382.0	263.21
F_2	HARVESTING:				
7	Motor fuel	89.0x10^6 J	47900	4.3	2.94
8	Feller, forwarder	187.7 g	6.7x10^9	1.3	0.87
9	Human services	101.26 $	1.45x10^{12}	147.0	101.28
10	Capital investment	14.44 $	1.45x10^{12}	21.0	14.44
Y_2	Spruce/pine yield (6.704 m^3f/ha/yr harvested)	58.5x10^9 J	9500	555.4	382.74

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[1] Analysis based on an average production of 8.989 m^3f of spruce and pine, and harvesting 74.6% of production (6.704 m^3f/ha/yr) in Southern Sweden (based on an 80 year, steady state rotation).

[2] Inputs reported as mass are converted to solar emergy using sej/g; monetary inputs use 1.45x10^{12} sej/USD_{1988} . (Sweden's solar emergy to dollar index minus 4% of national solar emergy basis attributed to forest production to avoid double counting of forest sector).

[3] Solar emergy value of input or yield divided by the relation 1.45x10^{12} sej/USD for Sweden's economy of 1988.

Summary of resource inputs, yields, solar transformities, and net yield and investment ratios for Table 12.

Environmental inputs:

I = Note 3 = 351.7×10^{12} sej/ha/yr

Inputs fed back from society (*i.e.* purchased):

F_1 = Notes 4+5+6 = $30,1 \times 10^{12}$ sej/ha/yr

F_2 = Notes 7+8+9+10 = 172.7×10^{12} sej/ha/yr

Solar emergy yields of products:

Y_1 = Standing biomass = 381.9×10^{12} sej/ha/yr

Y_2 = Harvested wood = 554.5×10^{12} sej/ha/yr

Solar transformities:

(a) Standing biomass = Y_1 sej / Y_1 J = 4 873 sej/J

(b) Harvested wood = Y_2 sej / Y_2 J = 9 500 sej/J

Net solar emergy yield ratio = solar emergy yield / solar emergy invested:

I. Standing biomass = $Y_1/F_1 = 12.6$

II. Harvested wood = $Y_2/(F_1+F_2) = 3.2$

Solar emergy investment ratio = solar emergy invested / free solar emergy from environment:

I. Standing biomass = $F_1/I = 0.09$

II. Harvested wood = $(F_1+F_2)/I = 0.49$

Footnotes to Table 12:

I Environmental inputs:

1. Solar energy = (area)(avg insolation)(1 – albedo) = (10 000 m^2/ha)(85.4 kcal/cm^2/yr)(10 000 cm^2/m^2)(4 186 J/kcal)(1 – 0.28) = 2.57×10^{13} J/ha/yr

2. Wind, kinetic energy = (Vertical gradient of wind)^2 (hgt of atmospheric boundary)(density of air)(eddy diffussion coefficient)(1 ha)(s/yr) = [(3.0 m/s)/(1 000 m)]^2 (1 000 m)(1.23 kg/m^3)(25 m^2/s)(10 000 m^2/ha)(3.154×10^7 s/yr) = 8.73×10^{10} J/ha/yr

3. Rain, chemical potential energy = (area)(rainfall)(% evapotrans)(Gibbs free energy) = = (10 000 m^2/ha)(0.80 m)(0.49)(1 000 kg/m^3)(4.94×10^3 J/kg) = 1.93×10^{10} J/ha/yr

F_1 Inputs to silvicultural management:

	fuel (liters/ha/yr)	machines (g/ha/yr)
scarification:	0.28	19.0
planting:	0.04	3.5
stand regulation:	0.35	8.8
ditching:	0.52	3.4
roads:	0.38	31.7
Total:	1.57 l/ha/yr	66.4 g/ha/yr

4. Motor fuel = (1.57 l/ha/yr)(35.6×10^6 J/l) = 5.59×10^7 J/ha/yr

5. Machinery depreciation [given as weight (g)] = (0.1 operating hrs/ha/yr)/(15 000 hrs useful life)(10 t trucks, tractors)(10^6 g/t) = 66.7 g/ha/yr

6. Human services (total cost of production) = 13.52 SEK/m^3f; (13.52 SEK/m^3f)(8.989 m^3f/ha/yr)/(6.50 SEK/USD, 1988) = 18.70 USD/ha/yr

Y_1 Spruce/pine annual stemwood production =
= (8.989 m^3f/ha/yr)(0.425×10^6 g/m^3f)(2.052×10^4 J/g) = 7.84×10^{10} J/ha/yr

Footnotes to Table 12, continued.

F_2 Harvesting expenditures:

7. Motor fuels = (2.5 liters/ha/yr)(35.6 x 10^6 J/liter) = 8.90 x 10^7 J/ha/yr

8. Feller and forwarder depreciation [given as weight (g)]: (0.07 operating hrs/m^3f)/(15000 hrs useful life)(6 t)(10^6 g/t)(6.704 m^3f/ha/yr) = 187.7 g/ha/yr

9. Human services = [(Direct costs 85.6 SEK/m^3f) – (silv. prod. costs 13.5 SEK/m^3f)] + (indirect costs 12.1 SEK/m^3f) + (depreciation 14.0 SEK/m^3f) = 98.2 SEK/m^3f; (98.2 SEK/m^3f)(6.704 m^3f/ha/yr)/(6.50 SEK/USD, 1988) = 101.28 USD/ha/yr

10. Capital cost of machines = (6.704 m^3f/ha/yr harvest)(0.07 hrs/m^3f) = (0.47 hrs/ha/yr); (0.47 hrs/ha/yr)(200.0 SEK/hr capital costs) = 93.9 SEK/ha/yr; (93.9 SEK/ha/yr)/(6.50 SEK/USD, 1988) = 14.44 USD/ha/yr

Y_2 Spruce/pine harvest, wood still in the field [note: calculation based on 1 hectare spruce/pine forest, using only harvested stemwood (5.587 m^3f/ha/yr) and 1/2 of logging residues (1.117 m^3f/ha/yr) which is chipped (74.6% of total 8.989 m^3f/ha/yr = 6.704 m^3f/ha/yr)].

= (74.6%)(8.989 m^3f/ha/yr)(0.425 x 10^6 g/m^3f)(2.052 x 10^4 J/g) = 5.85 x 10^{10} J/ha/yr

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remainder (113 m^3f/ha). Figure 14 shows the net yield and solar transformities associated with self-thinned spruce/pine forest regeneration on 80 year harvest schedules. Environmental emergy in the standing stock was estimated by multiplying the emergy of rainfall used annually through forest transpiration by 80 years. Production is related to transpiration; young stands with low LAI's and biomass storage, and older aged, mature forests with minimal net production, don't transpire (*i.e.* use) as much sunlight and rainfall as forests under maximum production (the steepest point on a typical sigmoidal growth curve). Therefore, an estimate of environmental emergy that was used up during the production cycle of a forest was approximated by multiplying the incoming sources by half (see footnotes to Table 12; harvesting requirements follow those calculated for silviculturally produced wood analyzed in Table 12).

A solar transformity for growing stock of naturally regenerated wood measured 5700 sej/J or 49.7 x 10^{12} sej/m^3f. With no silvicultural management, societal subsidies included only harvesting requirements (25.9 x 10^{12} sej/m^3f) – about 28% of emergy yield of cut wood, resulting in a net yield ratio of 3.6. An investment ratio of 0.4 indicates that two and a half times more emergy is delivered from environmental sources than from societal sources. A solar transformity for harvested wood (considered 75% of standing stock) measured 10550 sej/J. A solar transformity for old growth forests (standing stock, uncut) of 9490 sej/J was estimated based on maximum forest volume of 425 m^3f/ha produced over 200 years (see Figure 14 footnotes for derivations). These values will be compared with silviculturally produced spruce/pine and cultivated willow in the following sections of this report.

Silvicultural forest production

Annual production, distribution and use of forest resources are diagrammed in Figure 15. Currently, (1988 harvest schedule) about 75% of the net tree biomass production in a typical southern mixed coniferous forest system is harvested annually (7.8 m^3f/ha/yr). Of the harvested volume, about 5.6 m^3f is stemwood and bark for sawn timber and pulp. The remaining 2.25 m^3f is logging residues. About half of the logging residues (just over one solid cubic meter of biomass) may be chipped at the roadside and delivered as a fuel resource for district heating. This fuel wood volume represents roughly 17% of the total, average annual harvest per hectare.

The forests considered in this study are managed silviculturally in order to shorten the rotation time between harvestable yields of forest biomass. A forest stand is clear cut on average 80 year rotations, the cleared land is often scarified, seedlings are planted, the stands are thinned about four times during each rotation, and access roads and drainage ditches are built and maintained. Thinning operations act to reduce competition for resources by selectively removing a number of the smaller trees at various intervals during the rotation period of the stand. More resources of sunlight, precipitation and soil nutrients are available for each remaining tree, which can develop a higher stem volume and better quality than otherwise, making the trees of the final harvest more commercially valuable. The productivity of the stand is generally reduced by ca. 10 percent compared with unthinned stands. On the other hand each thinning delivers a yield that would be lost in a self-thinned stand.

The average annual biomass production of 9 m^3f/ha for mixed coniferous forests in Southern Sweden used in this study is for silviculturally managed forests as described here.

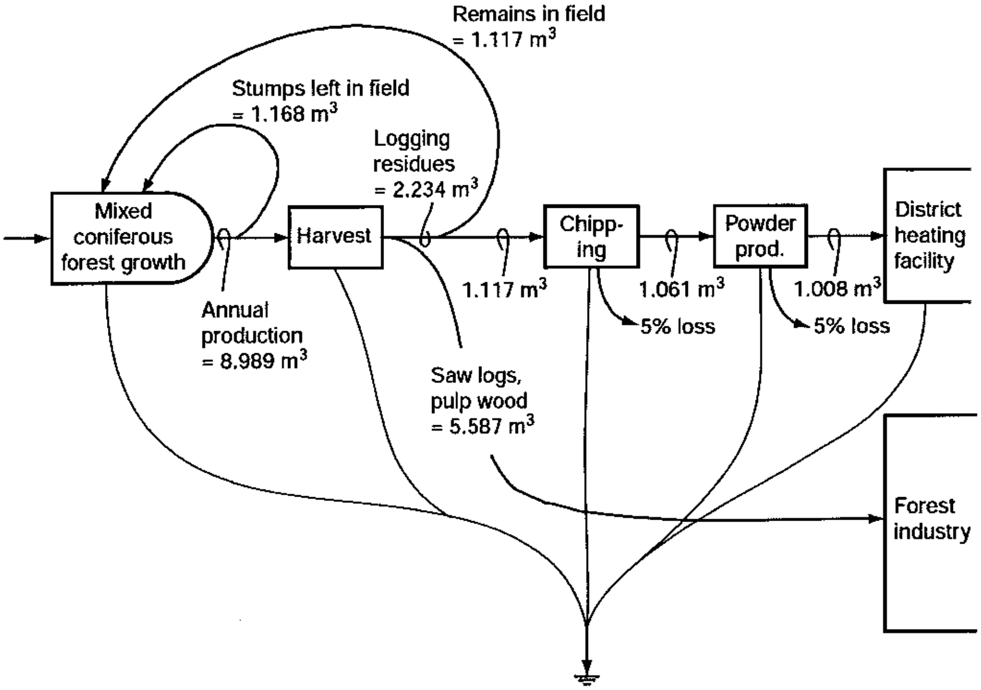


Figure 15. Systems diagram of annual production, distribution and use of one hectare of coniferous forest under current silvicultureal management. Numbers on pathways are reported for average steady-state net forest production in Southern Sweden, given as m^3f/ha/year.

Managed forest production is based on inputs from environmental sources as well as inputs purchased or supported outside the immediate forest system (Table 12). The environmental contributions (I) measured in this study included 1) direct solar insolation, 2) the kinetic energy of wind over the forest canopy driving evapotranspiration, and 3) the chemical potential energy of transpired water created by the salt differential of rainfall as it moves through the plants of the forest system. The silvicultural inputs (F_1) included 4) motor fuel, 5) depreciation of fellers and forwarders due to use, and 6) direct human labor in the forest and the indirect human services supporting the forestry operation. All unit inputs were measured from average annual flows and converted to solar emergy values using solar transformities, solar emergy per unit mass, or solar emergy per SEK for human services.

Measured in direct energy, sunlight provides the greatest input (26×10^{12} J/ha/yr compared with 56×10^{6} J/ha/yr for the 1.6 liters of fuel directly consumed on average). By accounting for the direct and indirect energies supporting or "embodied" in each of the independent inputs (*i.e* correcting for energy contributions using solar transformities), the chemical potential energy of transpired rain constitutes the largest input to standing crop biomass production (352×10^{12} sej/ha/yr compared with 26×10^{12} solar joules of direct sunlight and 3×10^{12} sej from consumed fuel). Silvicultural inputs (F_1) totalled about 30×10^{12} sej/ha/yr.

A solar transformity for silviculturally managed forest production, with the wood still in the field (standing crop biomass) was calculated as 4 873 sej/J. This was the total amount of solar emergy from all inputs used in relation to the direct caloric heat energy value of 9 m^3f of annual spruce/pine forest production. The net yield ratio of total solar emergy input (Y_1) to that invested from society (F_1) measured 12.6, suggesting silvicultural forest production has a yield twelve times greater than the required investments. An investment ratio of solar emergy contributions from purchased sources (F_1) to environmental sources of 0.09 is another way of illustrating the yield; the net contribution to Sweden's ecological-economic system from forest management is due to resources delivered free from the environment.

Harvesting requirements

The spruce/pine forests are generally clear cut on 80 year rotations, however, average annual harvesting requirements were calculated to compare with the evaluation of average annual net production. About 75% of the average annual net production is harvested per hectare (6.7 m^3f). The additional inputs necessary to harvest the standing crop (F_2, Table 12) were calculated on a per cubic meter basis for the 6.7 m^3f of stemwood, tops, branches and needles harvested. These include 7) motor fuel, 8) use of fellers and forwarders, 9) associated human services and 10) capital costs of machinery.

Inputs from environmental sources, silvicultural management, forest cutting and the associated yields are diagrammed in Figure 16 with all inputs reported as solar emergy/ha/yr for average production and operations. The accompanying solar transformities, net yield and investment ratios for standing forest biomass and

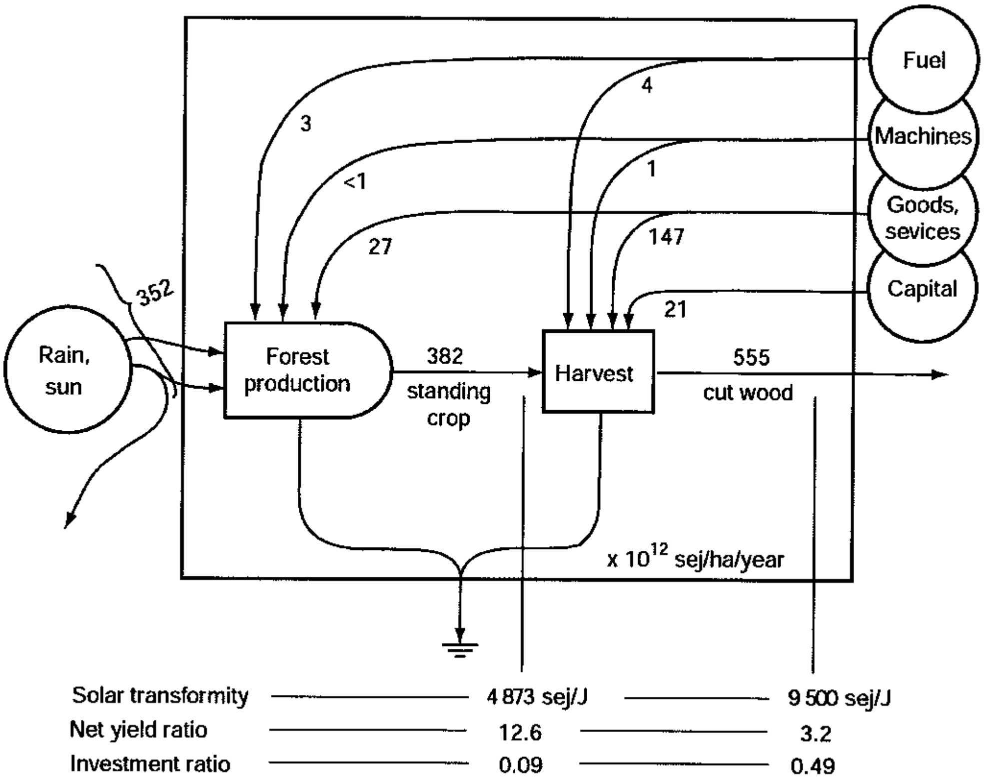


Figure 16. Systems diagram of spruce/pine silvicultural growth and harvest. Pathway values are solar inputs associated with each process step (10^{12} sej/ha/yr), based on average steady-state production. See Table 12 for calculations, raw units of each input, and the derivations of solar transformities and net solar emergy.

roadside harvest are given below each yield. Human services, estimated from the monetary costs of direct and indirect operations and depreciation (item 9, Table 12), was the largest solar emergy input to harvesting operations. Together these harvest inputs (F_2) total 173 x 10^{12} sej/ha/yr. The total solar emergy supporting the harvested biomass (Y_2), calculated as the sum of environmental sources (I) plus silvicultural management (F_1) and the inputs for the harvest (F_2), was 555 x 10^{12} sej/ha/yr for average production. The aggregated sum of environmental sources (I_{total}) contributes the greatest portion of solar emergy to the production and harvest of forest biomass.

A solar transformity of harvested forest wood, stacked at roadside of 9 500 sej/J indicates that twice as much solar emergy is necessary to make the resource available for consumer use than is required for actual forest production. A net solar emergy yield ratio of 3.2, a reduction from 12.6 for standing forest biomass (Y_1), suggests that almost four times less emergy is yielded per unit purchased input once harvesting operations are accounted for in the tabulations. The investment ratio correspondingly increases five fold to 0.5. Although there is a reduction in net contribution, these inputs are necessary as a process step in making the forest resources available for other economic transformations and consumption.

Short rotation willow cultivation

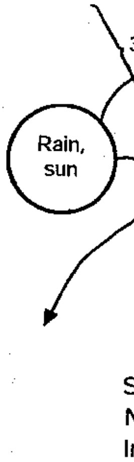
Cultivation of willow (Salix spp.) as a fuel wood source is part of the Energy Forestry Project at the Swedish University of Agricultural Sciences. Energy forestry is targeted for agricultural lands, both abandoned and marginal, peat lands and possibly existing forest lands in Southern Sweden. Principles of energy forestry include site preparation, planting shoots or cuttings form existing stock, site management (fertilization, mechanical and chemical weed control, irrigation), and harvesting on 4–5 year rotations (Sennerby-Forsse 1986). Approximately six harvests from planted sprigs generally can be taken from a site over an estimated 24 year cycle period before the site must be prepared and new shoots planted. In controlled field experiments willow production reaches 36–60 tons/ha every rotation (21.8–36.5 m^3sk/ha/yr). In practice lower yields can be expected. Other species, including nitrogen fixing alder (Alnus spp.) and poplar (Populus spp.) may be considered in the future.

Solar emergy requirements for short-rotation energy forestry

The environmental sources supporting short rotation willow farming were considered the same as those contributing to average spruce/pine forest production since both operations are located in Southern Sweden. The silviculture and maintenance operations include planting the willow cuttings, fertilization and herbicide application, tractor fuel consumption, direct labor and associated human services (Table 13). The largest inputs delivered from the main economy were nitrogen and phosphorus fertilizers, about 300 and 150×10^{12} sej/ha/yr, respectively. Often, irrigation is necessary in short rotation willow agro-forestry, though this input was not accounted for in this evaluation. It should be noted, however, that a previous study of irrigation and irrigated agriculture showed large investments of purchased resources from the main economy, reducing the net contribution of such operations to the larger ecological-economic system (Odum *et al.* 1987).

On average, 48 tons of wood (dry matter, TS) is cut from each hectare of planted willow every 4–5 years, producing approximately 11.5 ton annually per hectare This translates into an energy yield of around 224×10^{9} J/ha/yr, see Y_1, Table 13. Solar emergy inputs ($I+F_1$) totalled $1\,075 \times 10^{12}$ sej/ha/yr. A resultant solar transformity [(a), Table 13] for willow production was calculated at 4 794 sej/J. When calculating the solar emergy of willow cuttings (item 4, Table 13), the contribution from environmental sources and societal inputs were apportioned based on the investment ratio for willow calculated from this analysis (the derivations, calculated through multiple spreadsheet iterations, are described as a footnote to item 4, Table 13). This was necessary so that all environmental sources within Sweden contributing to the production of willow were accounted for in tabulations (this same technique was used in other forest product evaluations reported later in this study).

Willow production, harvest, and the resource inputs are diagrammed in Figure 17 with all flows reported in solar emergy. After the inputs necessary for harvesting the woody biomass ($F_2 = 332 \times 10^{12}$ sej/ha/yr) were accounted, a solar transformity



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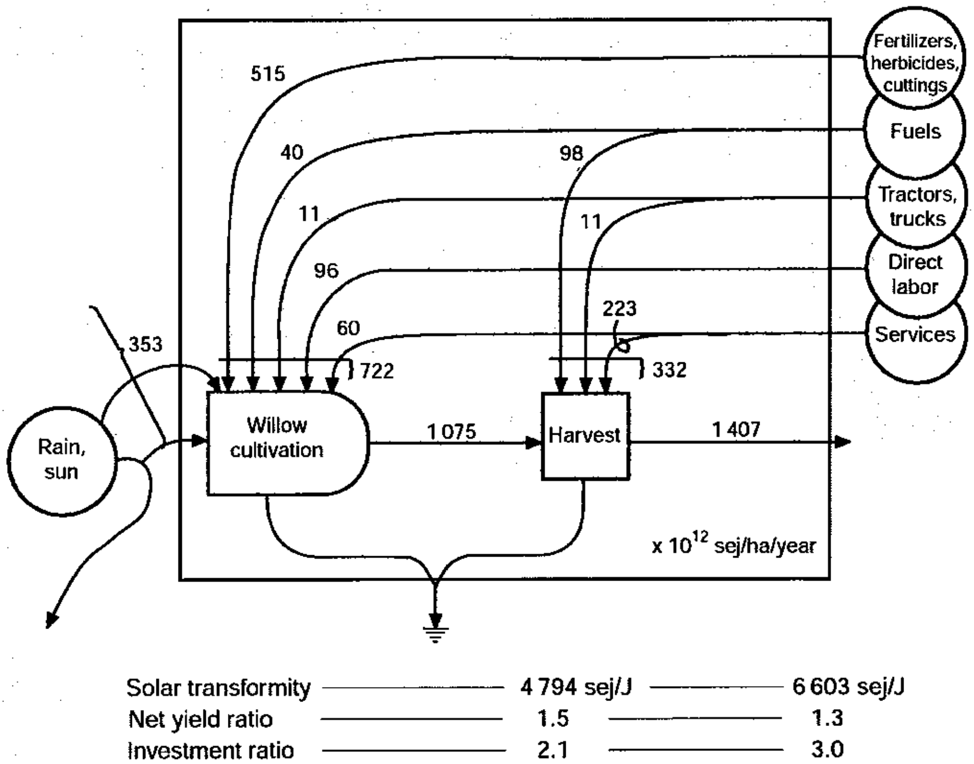

Figure 17. Systems diagram of short rotation willow farming and fuelwood harvest. Pathway values are annual solar emergy flows associated with each process step (x 10^{12} sej/ha/yr), based on average steady-state production. See Table 13 for calculations, raw units of each input, and the derivations of solar transformities and net solar emergy indices.

for harvested willow stalks was 6 603 sej/J. The net yield ratio decreased from 1.49 for standing crop biomass production to 1.34 after harvest, a 10% reduction. The investment ratio increased from 2.05 to 2.99 for harvested stalks, a 46% increase in the ratio of purchased inputs to those from environmental sources.

Comparisons with forest rotations

Using a wood density of 394 kg dry matter/m^3 solid wood for 4 year old willow plantings (Sennerby-Forsse 1986), about 29 m^3sk fresh wood is produced on average each year from a hectare of intensively managed willow cultivation, three times the volume of wood production of a managed spruce/pine forest.

The amount of solar emergy input into willow production ($Y_1 = I + F_1$) measured 93 x 10^9 sej/kg TS, compared with 100 x 10^9 sej/kg for silvicultured spruce/pine (the solar transformities for biomass production were correspondingly similar, 4 794 sej/J and 4 873 sej/J respectively). The calculations for short rotation forestry are based on yields from controlled experiments. In practical production the yield can be expected to be about two thirds of that in experiments. In this case the

Table 13. *Annual resource flows associated with production of one hectare of short rotation willow in Southern Sweden, 1988. All values are given as annual inputs and yields per hectare for average annual production.* [1]

Note	Item	Avg. annual flows, raw units/ha (J, g, $)	Solar transformity [2] (sej/unit)	Solar emergy (10^{12} sej/ha/yr)	Macro-economic value [3] (USD, 1988)
I	ENVIRONMENTAL INPUTS			352,8	243.12
F_1	SILVICULTURE:				
4	Willow cuttings [4]	650×10^6 J	6603	3,2	2.20
5	Fertilizers:				
	Nitrogen	73.3 kg	4.19×10^{12}	307.3	211.72
	Potassium	24.6 kg	1.84×10^{12}	45.2	31.16
	Phosphorus	7.9 kg	20×10^{12}	158.4	109.15
6	Herbicides	12×10^6 J	66000	0.8	0.54
7	Motor fuel	848×10^6 J	47900	40.6	28.00
8	Tractors	1.6 kg	6.7×10^{12}	10.6	7.34
9	Direct labor	65.97 $	1.45×10^{12}	95.7	65.97
10	Indirect services	41.51 $	1.45×10^{12}	60.2	41.51
Y_1	Willow production	224×10^9 J	4794	1075	740.72
F_2	HARVESTING:				
11	Motor fuel	2.05×10^9 J	47900	98.1	67.56
12	Tractors, trucks	1.5 kg	6.7×10^{12}	10.3	7.08
13	Human services	153.92 $	1.45×10^{12}	223.4	153.92
Y_2	Willow yield	213×10^9 J	6603	1407	969.29

[1] Analysis based on an average willow production of 11.5 t/ha/yr dry matter, TS (about 29 m^3f/ha/yr), harvested every 4–5 years and replanted with willow cuttings on a 24 year rotation.

[2] Inputs reported as mass are converted to solar emergy using sej/kg; monetary inputs use the relation of solar emergy and GNP 1988 for Sweden (1.45×10^{12} sej/USD).

[3] Solar emergy input divided by the relation 1.45×10^{12} sej/USD for Sweden, 1988.

[4] The solar emergy contributions for willow cuttings was derived from the solar transformity for harvested willow (b) calculated in this table. Environmental contributions (I) and societal energies (F) for cuttings were separated in spreadsheet iterations and accounted for in net yield and investment ratios to avoid any double counting.

Summary of resource inputs, yields, solar transformities and net yield and investment indices for Table 13.

Environmental sources (same as items 1, 2 and 3, Table 12)

$I = 351.7\times10^{12}$ sej/ha/yr

I (cuttings) = 1.1×10^{12} sej/ha/yr

Inputs fed back from society:

F (cuttings) = 3.2×10^{12} sej/ha/yr

F_1 = silviculture = items 5...10 + F(cuttings) = 722×10^{12} sej/ha/yr

F_2 = harvesting = items 11 + 12 + 13 = 332×10^{12} sej/ha/yr

Solar emergy yields:

Y_1 = Standing crop biomass = 1075×10^{12} sej/ha/yr

Y_2 = Harve

Solar transformi

(a) Standi

(b) Harves

Net solar emerg

I. Standi

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Footnotes to Table

I Environmen items 1, 2 a year planting

F_1 Inputs to sho
4. Willow harvests/24 = 0.80 t cutti

Note: us

5. Fertilize
a. Nit
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6. Herbicid J/kcal) = 2.8

Note: th the heat val the herbicid petroleum pr

7. Motor f 460 l = 572 l

8. Tractors 1.0 hrs + sta hrs/ha/yr)/(1

9. Direct l planting 94 S planting 94 S + other 90 SI = 65.97 USD

10. Indirect (herbicide, a yr; fertilizer SEK) = 647

Y_1 Willow prod (276 t TS/ha/

F_2 Harvesting e
11. Motor f

Y_2 = Harvested willow crop = 1 405x10^{12} sej/ha/yr

Solar transformities:

(a) Standing crop biomass = Y_1 sej / Y_1 J = 4 794 sej/J
(b) Harvested willow crop = Y_2 sej / Y_2 J = 6 603 sej/J

Net solar emergy yield ratios:

I. Standing crop biomass = Y_1/F_1 = 1.49
II. Harvested willow crop = $Y_2/(F_1+F_2)$ = 1.34

Solar emergy investment ratio:

I. Standing crop biomass = F_1/I = 2.05
II. Harvested willow crop = $(F_1+F_2)/I$ = 2,99

Footnotes to Table 13:

I Environmental inputs: same annual energy values per hectare as those for Southern Sweden forests; items 1, 2 and 3, Table 12, plus the environmental input to willow cuttings (item 4) used in first year planting.

F_1 Inputs to short rotation willow farming:

4. Willow cuttings = (20 000 cuttings/ha planted)/(60 cuttings/stool)(20000 stools/harvest)/(5.75 harvests/24 yr rotation) = 0.29% of total harvested biomass; (0.29)(276 t TS prod./ha/24 yrs) = 0.80 t cuttings; (800 kg salix cuttings/ha)(19.5x10^6 J/kg)/(24 yrs/rotation) = 650x10^6 J/ha/yr

Note: use solar transformity for harvested willow calculated in this analysis.

5. Fertilizers:
   a. Nitrogen; 1 760 kg/ha/24 yr = 73.33 kg/ha/yr
   b Potassium; 590 kg/ha/24yr = 24.58 kg/ha/yr
   c. Phoshorus;190 kg/ha/24yr = 7.92 kg/ha/yr

6. Herbicides; (4 liters/ha/24 yr Roundup + 3 l/ha/24 yr Gardoprim)(9800 kcal/liter)(4186 J/kcal) = 2.87x10^8 J/ha/24 yr rotation = 12x10^6 J/ha/yr

Note: the heat of formation of the organic compounds in the herbicides was estimated using the heat value of petroleum, since herbicides are oil based derivatives. The caloric value of the herbicide was converted to a solar emergy estimate using the solar transformity for refined petroleum products. These are considered conservative estimations.

7. Motor fuels; Stand establ 100 liters + herbicide appl 2 l + planting 10 l + stand management 460 l = 572 liters/24 yrs = 23.8 l/ha/yr; (23.8 l)(35.6x10^6 J/l) = 8.5x10^8 J/ha/yr

8. Tractors [(given as weight (g)]: (stand establ. 10.0 hrs + hebicide appl. 0.2 hrs + planting 1.0 hrs + stand mgt 46.0 hrs)/ha/24 yr rotation = 57.2 hrs/ha/24 yr = 2.4 hrs/ha/yr; (2.4 operating hrs/ha/yr)/(15000 hrs useful life)(10 t)(10^3 kg/t) = 1.59 kg/ha/yr

9. Direct labor: stand establishment/ha/24 yr rotation; planning 180 SEK + spraying before planting 94 SEK + plowing 576 SEK + tilling 414 SEK + planting 7960 SEK + spraying after planting 94 SEK + stand mgt/ha/24 yr; fertilizer spreading 258 SEK + herbicide spraying 626 SEK + other 90 SEK = 10292 SEK/ha/24 yr rotation = (429 SEK/ha/yr)/(6.5 SEK/USD, 1988) = 65.97 USD/ha/yr

10. Indirect human services: stand establ/ha/24 yr; (herbicide, before planting 660 SEK) + (herbicide, after 318 SEK) + (fuel, item 7 above, 112 lx6.5 SEK/l = 728 SEK) + (stand mgt/h/24 yr; fertilizer 1530 SEK) + (herbicide 250 SEK) + (fuel, item 7 above; 460 lx6.5 SEK/l = 2990 SEK) = 6476 SEK/ha/24 yr = (270 SEK/ha/yr)/(6.5 SEK/USD, 1988) = 41.51 USD/ha/yr

Y_1 Willow production (annual growth) = (48 t TS/harvest)(5.75 harvests/24 yr) = 276 t TS/ha/24 yr; (276 t TS/ha/24 yr)(10^3 kg/t)(19.5x10^6 J/kg)/24 yrs = 224x10^9 J/ha/yr

F_2 Harvesting expenditures:

11. Motor fuel = (1380 liters/ha/rotation)(35.6x10^6 J/liter)/(24 yrs/rotation) = 2.05x10^9 J/ha/yr

Footnotes to Table 13, continued.

12. Tractors, trucks [given as weight (g)] = (48 t TS/harvest)/(3 t harvested/hr)(5.75 harvests/rotation)/(24 yrs/rotation) = 3.83 hrs/ha/yr; (3.8 operating hrs/ha/yr)/(15 000 hrs useful life)(6 000 kg avg. wgt.) = 1.53 kg/ha/yr

13. Human services: (87 SEK/t harvest costs)(48 t TS/harvest)(5.75 harvests/ rotation)/(24 yrs/rotation) = 1001 SEK/ha/yr)/(6.5 SEK/USD, 1988) = 153,92 USD/ha/yr

Y_2 Willow yield (calculated as production minus 5% loss) = (276 t TS/ha/24 yr)(0.95)(1.95x10^{10} J/t)/24 yrs = 213x10^9 J/ha/yr

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solar transformity would be based on a yield of approximately 7.7 ton annually per hectare. The emergy input would increase to 140x10^9 sej/kg, and the solar transformity to 7 190 sej/J.

Comparing the harvesting inputs (F_2) for each agro-forestry operation, short rotation willow required 11x10^{12} sej/m^3 dry matter harvested; managed spruce/pine required 26x10^{12} sej/m^3. The solar emergy inputs drawn from the main economy for intensive willow farming are in this case less than half of the inputs required for harvesting spruce/pine forest. This reduction in harvesting requirements per unit output for willow farms is due to to the differences in harvesting methods: the coniferous forests with big trees are harvested tree by tree, while the dense willow stands with many small trees are harvested by machines that cut all trees in an area, resulting in a more efficient harvest. The solar transformities for harvested biomass reflect this (6 595 sej/J for harvested willow compared with 9 500 sej/J for harvested spruce/pine). The alternative with a smaller yield from willow farming would increase the solar transformity to 9 880 sej/J, making the two compared cases rather equal.

The origins of the required solar emergy for the inputs, however, are different under the different agro-ecosystems. The harvesting inputs (F_1), measured as a percentage of the total solar emergy required for biomass production (Y_1), were 67% of the total for willow (33% contributed from the environment) compared with only 8% for spruce/pine (92% from environmental sources). This net contribution is reflected in the higher yield ratios for managed spruce/pine forests. Eight times more solar emergy is yielded for each solar emjoule invested from the economy for spruce/pine systems than for willow agro-forests (NYR_I = 12.6 for forest production compared with a NYR_I of 1.5 for willow production, each standing biomass in field). Once harvested, there is a 2.4-fold difference in net yield ratios of spruce/pine and willow. The investment ratio for harvested biomass indicates there is a six times greater investment of purchased inputs relative to environmental contributions for harvested willow than for spruce/pine (IR_{II} for harvested willow = 3.0 compared with IR_{II} for harvested spruce/pine 0.5).

These results suggest that intensively managed, short-rotation willow cultivation produces 3 times the annual wood volume of silvicultured spruce/pine forests, but at 8 times the solar emergy investment from the economy. Further, although there might be a reduction in solar emergy investments for harvesting willow, the total investment to environment ratio (IR_{II}) for willow is about 6 times greater than for harvested spruce/pine due to the subsidies required for intensive management. This means a greater net contribution of solar emergy is obtained from spruce/pine forest operations. This greater portion of solar emergy is delivered free from nature, so that the forest products can be further transformed, stimulating other sectors of the economy.

Fuel wood development

Once the forests are clearcut, the harvested stemwood (5.6 m^3f/ha/yr, about 83% of average annual harvest per hectare) is delivered to forest industries. Currently, half of the logging residues (1.12 m^3f/ha/yr, about 17% of average annual harvest per hectare) is available as a wood fuel. This volume, consisting primarily of tops, lumps, branches and needles, is chipped at the roadside of the forest clearing, then transported to a district heating plant or a wood powder facility. The wood powder is sent to a district heating plant whose boilers are modified to combust the fuel.

In the following paragraphs, solar emergy analyses of wood chip and wood powder production are reported. Each of the evaluations are based on the previous analysis of spruce/pine forest silvicultural production and harvest. Also given is a comparison of net solar emergy and investment ratios for wood powder using intensively managed willow as the wood fuel instead of forest logging residues.

Roadside chipping

The logging residues are collected and delivered to the roadside near the forest clearing before the resource is transported either to the district heating plant or to the wood powder production facility. The process steps include transport of logging residues from the field to the chipper and roadside chipping (F_3 and F_4; Table 14). Together, the purchased inputs necessary for these process steps totalled about 44×10^{12} sej/ha/yr. This amount of solar emergy was larger than both silviculture and harvesting requirements combined, due to relatively high fuel consumption and increased labor. A solar transformity for spruce/pine wood chips was calculated as 14 793 sej/J (c; Table 14), about 1.6 times higher than the harvested wood still in the field and about 3 times higher than the standing wood biomass.

The net solar emergy yield ratio for wood chips, still at the roadside, measured 1.75, indicating about 35% less yield is delivered for each unit input from the economy for the wood chips than for the previous harvesting step. About 1.33 solar emjoules are input from the economy for each solar emjoule from environmental sources – a 230% increase in investments for chipping over the investment ratio for harvesting the woody biomass. Once the logging residues are chipped, they are delivered for cumbustion, either direct to a district heating facility or via a powder production plant.

Wood powder production

Production of wood powder from chips requires transport from roadside to the plant (F_5) and wood powder production (F_6, Table 14). Transport by truck of the wood chips to the wood powder plant was based on an average round trip of 60 km. Five

Table 14. *Annual resource flows associated with wood powder and use as a district heating fuel. Values are given as resource requirements for fuelwood from 1 ha of spruce/pine annual forest production in Southern Sweden under current management practices, 1988.* 1)

Note	Item	Average annual flows, raw units/ha (J, g, $)	Solar transformity 2) (sej/unit)	Solar emergy (10^{12} sej/ha/yr)	Macro-economic value 3) (USD, 1988)
I	ENVIRONMENTAL INPUTS:	–	–	58.6	40.38
F_1	SILVICULTURAL INPUTS:	–	–	5.0	3.47
F_2	HARVESTING:	–	–	28.9	19.92
Y_2	Fuelwood yield (1.117 m^3f/ha/yr)	9.74×10^9 J	(b)	92.6	63.77
F_3	TRANSPORT FROM FIELD TO ROADSIDE CHIPPER:				
	11 Motor fuel	95.4×10^6 J	47900	4.6	3.15
	12 Forwarder	168 g	6.7×10^9	1.1	0.77
	13 Human services	9.78 $	1.45×10^{12}	14.2	9.78
F_4	CHIPPING:				
	14 Oil	111×10^6 J	47900	5.3	3.66
	15 Chipper	197 g	6.7×10^9	1.3	0.91
	16 Human services	12.29 $	1.45×10^{12}	17.8	12.29
Y_3	Wood chips (1.061 m^3f/ha/yr)	9.25×10^9 J	(c)	136.9	94.33
F_5	TRANSPORT FROM CHIPPER TO POWDER PLANT:				
	17 Motor fuel	17.8×10^6 J	47900	0.9	0.59
	18 Trucks	352 g	6.7×10^9	2.4	1.63
	19 Human services	4.96 $	1.5×10^{12}	7.2	4.96
F_6	WOOD POWDER PRODUCTION:				
	20 Wood powder 4)	740×10^6 J	29200	21.6	14.89
	21 Oil	13×10^6 J	47900	0.6	0.43
	22 Electricity	312×10^6 J	124500	38.8	26.74
	23 Machines	30 g	6.7×10^9	0.2	0.14
	24 Human services	15.82 $	1.45×10^{12}	23.0	15.82
	25 Capital investment	6.66 $	1.45×10^{12}	9.7	6.66
Y_4	Wood powder (1.008 m^3f/ha/yr)	8.79×10^9 J	(d)	241,2	166.19
F_7	TRANSPORT FROM POWDER PLANT TO DISTRICT HEATING FACILITY:				
	26 Motor fuel	17×10^6 J	47900	0.8	0.56
	27 Trucks	335 g	6.7×10^9	2.2	1.55
	28 Human services	5.06 $	1.45×10^{12}	7.3	5.06
F_8	WOOD POWDER BURNING:				
	29 Electricity	98.7×10^6 J	124500	12.3	8.47
	30 Machinery	685 g	6.7×10^9	4.6	3.16
	31 Human services	8.22 $	1.45×10^{12}	11.9	8.22
	32 Capital investment	10.74 $	1.45×10^{12}	15.6	10.74

Table 14, continued.

Y_5	High temperature heat	7.4×10^9 J	(e)	296.0	203.94
Y_6	Mechanical output	3.0×10^9 J	(f)	296.0	203.94

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[1] Analysis based on an average, sustainable input of 1.117 m^3f fuelwood per hectare, so that values given per hectare are actually 16.7% of annual forest production (9 m^3f/h/yr).

[2] Inputs reported as mass are converted to solar emergy using sej/g; monetary inputs use 1.45×10^{12} sej/USD_{1988}, a corrected solar emergy/GNP index so that the forest sector is not double counted in the estimation of human services.

[3] Solar emergy value of input or yield divided by the relation 1.45×10^{12} sej/$ for Sweden's economy of 1988.

[4] The solar emergy contribution for wood powder (item 20) as an internal fuel for drying was derived from the solar transformity calculated in this table. Environmental contributions (I_6) and societal energies (F_6) for wood powder were separated in spreadsheet iterations and accounted for in net solar emergy yield and solar emergy investment ratios to avoid any double counting as follows:

$\%I_6 = I_6/Y_4 = (24\%)(21.4 \times 10^{12}$ sej/ha/yr$) = 5.2 \times 10^{12}$ sej/ha/yr;
$F_6 = Y_4 - I_6 = (21.4 - 5.2) \times 10^{12}$ sej/ha/yr $= 16.2 \times 10^{12}$ sej/ha/yr.

Summary of resource inputs, yields, solar transformities and net yield and investment ratios for Table 14.

Environmental inputs:

I = item 1 = 58.6×10^{12} sej/ha/yr (rain available for transpiration)
I_6 = item 20 = 5.2×10^{12} sej/ha/yr (environmental component of wood powder fuel)[1]
$I_{total} = I + I_6 = 63.8 \times 10^{12}$ sej/ha/yr

Inputs fed back from society (purchased):

F_1 = 16.7% of items 4+5+6, Table 12 = 5.0×10^{12} sej/ha/yr (silviculture)
F_2 = 16.7% of items 7+8+9+10, Table 12 = 28.9×10^{12} sej/ha/yr (harvesting)
F_3 = items 11+12+13 = 19.9×10^{12} sej/ha/yr (transfer of wood to roadside chipper)
F_4 = items 14+15+16 = 24.5×10^{12} sej/ha/yr (wood chipping)
F_5 = items 17+18+19 = 10.4×10^{12} sej/ha/yr (transport of chips to powder plant)
F_6 = items 21+22+23+24+25+F (item 20) = 88.7×10^{12} sej/ha/yr (wood powder production)
F_7 = items 26+27+28 = 10.4×10^{12} sej/ha/yr (transfer of powder to heating plant)
F_8 = items 29+30+31+32 = 44.4×10^{12} sej/ha/yr (burning of wood powder)

Solar emergy yields of products:

Y_2 = Harvested wood = $I+F_1+F_2 = 92.5 \times 10^{12}$ sej/ha/yr
Y_3 = Wood chips = $Y_2+F_3+F_4 = 136.9 \times 10^{12}$ sej/ha/yr
Y_4 = Wood powder = $I+I_6+F_1+..+F_6 = 241.25 \times 10^{12}$ sej/ha/yr
Y_5 = High temperature heat = $Y_4+F_7+F_8 = 296.0 \times 10^{12}$ sej/ha/yr
Y_6 = Mechanical heat output = $Y_5 = 296.0 \times 10^{12}$ sej/ha/yr

Solar transformities calculated for different production stages of sector:

(a) Standing biomass = Y_1 sej/Y_1 J; evaluated in Table 12 = 4 873 sej/J
(b) Harvested wood = Y_2 sej/Y_2 J; evaluated in Table 12 = 9 500 sej/J
(c) Wood chips = Y_3 sej/Y_3 J = 134×10^{12} sej/9.25×10^9 J = 14 793 sej/J

Summaryof table 14, continued.

(d) Wood powder = Y_4 sej / Y_4 J = 241×10^{12} sej / 8.79×10^{9} J = 27 437 sej/J

(e) High temp heat = Y_5 sej / Y_5 J = 296×10^{12} sej / 7.40×10^{9} J = 40 023 sej/J

(f) Mechanically usuable heat = Y_6 sej / Y_6 J = 296×10^{12} sej / 3.00×10^{9} J = 98 832 sej/J

Net solar emergy yield ratio:

II. Harvested wood = $Y_2/(F_1+F_2) = 2.73$

III. Wood chips = $Y_3/(F_1+F_2+F_3+F_4) = 1.75$

IV. Wood powder = $Y_4/(F_1+F_2+F_3+F_4+F_5+F_6) = 1.36$

V. High temp heat = $Y_5/(F_1+F_2+F_3+F_4+F_5+F_6+F_7+F_8) = 1.27$

VI. Mechnically usuable heat = $Y_6/(F_1+F_2+F_3+F_4+F_5+F_6+F_7+F_8) = 1.27$

Solar emergy investment ratio:

II. Harvested wood = $(F_1+F_2)/(I) = 0.58$

III. Wood chips = $(F_1+F_2+F_3+F_4)/(I) = 1.34$

IV. Wood powder = $(F_1+F_2+F_3+F_4+F_5+F_6)/(I+I_6) = 2.78$

V. High temp heat = $(F_1+F_2+F_3+F_4+F_5+F_6+F_7+F_8)/(I+I_6) = 3.64$

VI. Mechanically usuable heat = $(F_1+F_2+F_3+F_4+F_5+F_6+F_7+F_8)/(I+I_6) = 3.64$

Footnotes to Table 14:

I Environmental inputs: [(1.117 m^3f/ha/yr fuelwood)/(6.704 m^3f harvested)][environmental inputs (I) from spruce/pine analysis, Table 12] = (16.7%)(351.7×10^{12} sej/ha/yr) = 58.6×10^{12} sej/ha/yr

F_1 Silvicultural inputs to fuelwood production: [(1.117 m^3f/ha/yr fuelwood)/(6.704 m^3f harvested)][purchased inputs (F_1) from spruce/pine analysis, Table 12] = (16.7%)(30.13×10^{12} sej/ha/yr) = 5.04×10^{12} sej/ha/yr

F_2 Harvesting inputs to fuelwood: [(1.117 m^3f/ha/yr fuelwood)/(6.704 m^3f harvested)][purchased inputs (F_2) from spruce/pine analysis, Table 12] = (16.7%)(172.65×10^{12} sej/ha/yr) = 28.9×10^{12} sej/ha/yr

Y_2. Fuelwood harvest, wood still in the field [1.117 m^3f/ha/yr of wood (1/2 of logging residues) = 12.4% of annual production, 16.7% of average annual harvest]; (16.7%)(6.704 m^3f/ha/yr)(425 kg TS/m^3f)(20.52×10^6 J/kg) = 9.74×10^9 J/ha/yr

F_3 Transport from field to roadside chipper:

11 Motor fuel = (16 liters/hr)(0,15 hrs/m^3f)(1.117 m^3f/ha/yr)(35.6 J/l) = (2.68 l/ha/yr)(35.6 J/l) = 9.54×10^7 J/ha/yr

12 Machinery depreciation [given as weight (g)] = [(0.15 hrs/m^3f)(1.117 m^3f/ha/yr)]/(12 000 hrs useful lifetime)(12 t)(10^6 g/t) = 168 g/ha/yr

13 Human services (total cost of production) = (56.9 SEK/m^3f)(1.117 m^3f fuelwood/ha/yr harvested) = 63.56 SEK/ha/yr; (63.56 SEK/ha/yr)/(6.5 SEK/USD, 1988) = 9.78 USD/ha/yr

F_4 Roadside chipping:

14 Oil = (1.117 m^3f/ha)(0,093 hrs/m^3f)(30 l/hr)(35.6 J/l) = 1.11×10^8 J/ha/yr

15 Machinery depreciation [given as weight (g)] = [(1.117 m3f/ha)(0.093 hrs/m^3f)]/(10000 hrs useful life)(19 t)(10^6 g/t) = 197 g/ha/yr

16 Human services = (71.5 SEK/m^3f)(1.117 m^3f/ha/yr)/(6.50 SEK/USD, 1988) = 12.29 USD/ha/yr

Y_3 Wood chips [considered 95% of annual input/hectare (*i.e.* 5% loss)] = (0.95)(1.117 m^3f/ha/yr) = 1.061 m^3f/ha/yr (used in calculations of steps 17–25) = (95%)(1.117 m^3f/ha/yr)(425 kg/m^3f)(20.52×10^6 J/kg) = 9.25×10^9 J/ha/yr

Footnotes to Table 14, continued.

F_5 Transport of wood chips from roadside to district heating or wood powder plant (based on 60 km average roundtrip distance).

17 Motor fuel = (1.11 l/t TS)(425 kg TS/m^3f)(1.061 m^3f/ha/yr)(35.6 J/l) = 1.78x10^7 J/ha/yr

18 Machinery depreciation [given as weight (g)] = (0.093 hrs/m^3f)(1.061 m^3f/ha/yr)/(14 000 hrs)(50 t, truck and trailor)(10^6 g/t) = 352 g/ha/yr

19 Human services = maintenence + labor costs; maint. costs = 11.80 SEK/m^3f and labor costs = (0.093 driving hrs/m^3f)(200 SEK/hr) = 18.6 SEK/m^3f; 11.80+18.6 = 30.4 SEK/m^3f; (30.4 SEK/m^3f)(1.061 m^3f/ha/yr)/(6.5 SEK/USD,1988) = 4.96 USD/ha/yr

F_6 Powder production:

20 Wood powder fuel (for drying); 0.08 m^3f wood for powder per 1 m^3f wood processed into powder; (0.08 m3f wood powder)(425 kg TS/m3f)(1.061 m^3f/ha/yr)(20.52x10^6 J/kg) = 7.40x10^8 J/ha/yr

21 Oil = (8 kWh/t TS)(3.6 10^6 J/kWh)(1.061 m^3f/ha/yr)(425 kg TS/m^3f) = 1.30x10^7 J/ha/yr

22 Electricity consumption = (192 kWh/t TS)(3.6E+6 J/kWh)(1.061 m^3f/ha/yr)(425 kg TS/m^3f) = 3.12x10^8 J/ha/yr

23 Machinery depreciation [given as weight (g)] = [(6500 hr/yr)/(100000 t powder/yr processed)(425 kg TS/m^3f)(1.061 m^3f/ha/yr) = 0.03 hrs/ha/yr]/[(6500 hr/yr)(15 yrs) = 97500 hrs useful lifetime] [(100 t)(10^6 g/t) machines] = 30 g/ha/yr

24 Human services = (228 SEK/t TS)(0.425 t TS/m^3f) = 97 SEK/m^3f; (97 SEK/m^3f)(1.061 m^3f/ha/yr)/(6.50 SEK/USD, 1988) = 15.82 USD/ha/yr

25 Capital investment = (96 SEK/t powder prod.)(0.425 t TS/m^3f) = 40.8 SEK/m^3f; (40.8 SEK/m^3f)(1.061 m^3f/ha/yr)/(6.5 SEK/USD, 1988) = 6.66 USD/ha/yr

Y_4 Wood powder (considered 95% of volume of wood chips): (0.95)(1.06m^3f/ha/yr) = 1.008 m^3f/ha/yr (used in calculations of steps 25–31); (1.008 m^3f/ha/yr) (425 kg/m^3f)(20.52x10^6 J/kg) = 8.79x10^9 J/ha/yr

F_7 Transport from powder plant to district heating facility: (based on 60 km roundtrip distance, same inputs/m^3f as F_5):

26 Motor fuel = (1.11 l/t TS)(425 kg TS/m^3f)(1.008 m^3f/ha/yr)(35.6 J/l) = 1.69x10^7 J/ha/yr)

27 Machinery depreciation [given as weight (g)] = [(0.093 hrs/m^3f/yr)(1.008 m^3f/ha/yr)/(14000 hrs)](50 t)(10^6 g/t) = 335 g/ha/yr

28 Human services = (1.6 öre/kWh heat produced)/(100 öre/SEK)(4795 kWh heat/t TS)(0.425 t TS/m^3f)(1.008 m^3f/ha/yr)/(6.5 SEK/USD, 1988) = 5.06 USD/ha/yr

F_8 Wood powder burner:

29 Electricity consumption = (64 kWh/t)(3.6x10^6 J/kWh)/(2.35 m^3f solid/t TS)(1.008 m^3f fuelwood/ha/yr) = 9.87x10^7 J/ha/yr

30 Machinery depreciation [given as weight (g)] = (0.48 hrs/t)/(2.35 m^3f/t TS) = 0.20 hrs/m^3f; (0.20 hrs/m^3f)(1.008 m^3f/ha/yr)/(30000 hrs)(100 t)(10^6 g/t) = 685 g/ha/yr

31 Human services = (2.6 öre/kWh heat produced)/(100 öre/SEK)(4795 kWh heat/t TS) = 125 SEK/t TS; (125 SEK/t TS)/(2.35 m^3f/t TS)(1.008 m^3f/ha/yr)/(6.5 SEK/USD, 1988) = 8.22 USD/ha/yr

32 Capital costs = (3.4 öre/kWh heat produced)/(100 öre/SEK)(4795 kWh heat/t TS) = 163 SEK/t TS; (163 SEK/t TS)/(2.35 m^3f/t TS)(1.008 m^3f/ha/yr)/(6.50 SEK/USD, 1988) = 10.74 USD/ha/yr

Wood powder combustion:

Y_5 High temperature heat: 1 ton of dry matter yields 4795 kWh at 1473 Kelvin = (4795 kWh heat/t TS)(3.6x10^6 J/kWh) = 1.73x10^{10} J heat/ton TS

Footnotes to Table 14, continued.

Heat produced from 1 ha of harvested annual production of fuelwood: (1.008 m^3 solid wood/ha/yr)(0.425 t TS/m^{3}f)(1.73x10^{10} J heat/t dry matter) = 7.4x10^9 J heat output/ha/yr

Y_6 Mechanical heat (that fraction of total heat produced that can be used mechanically): Average winter temp. Sweden = 7 degrees C, then 273 K + 7 K = 280 K; Mech. usuable heat = (High Temp. Heat)(Carnot Ratio)(delta T/T) = (7.4E+09 J/ha/yr)(0.5)[(1473−280)/1473)] = 2.99x10^9 J/ha/yr

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percent of the wood volume was assumed lost during transport of wood chips and development of wood powder (inputs were evaluated as those necessary for about 1 m^{3}f of wood powder, Y_4, Table 14). Total solar emergy invested in transportation (items 17, 18 and 19, Table 14) measured 10.4x10^{12} sej/ha/yr, or about 5% of the all purchased inputs for wood powder production (F_1 + ... F_6). Resource inputs for production of wood powder from chips measured 88.7x10^{12} sej/ha/yr (items 21–25) for 1 m^{3}f of logging residues.

A solar transformity for wood powder using spruce/pine logging residues was calculated at 27437 sej/J. Roughly twice as much solar emergy is required to produce a joule of wood powder than a joule of wood chips, with all of the additional resources being input from society. About 1.36 solar emjoules are yielded from wood powder production for every one solar emjoule invested from the economy; about 2.8 times more solar emergy is invested than is contributed without cost from environmental sources.

In the production of wood powder, about 8 m^{3}f of wood powder fuel is used in drying operations for every 100 m^{3}f produced (Marks 1990). The solar emergy basis for this wood fuel input was derived using the solar transformity for wood powder fuel calculated in this analysis (item d, Table 14). Here, the environmental contributions supporting the internal use of this wood powder fuel was subtracted from the total in order that only services, fuels and goods from the economy were counted, thereby not attributing that portion of Sweden's environmental support to purchased inputs from outside (see calculations for item 20, Table 14). Environmental sources accounted for about 24% of the solar emergy of the wood powder fuel used for drying, which amounted to only about 1.5% of the total inputs necessary through process steps to make wood powder.

Combustion of wood fuels for district heating

The final process steps in the development and use of forest resources as alternative district heating fuels include transport to the district heating facility and combustion of the wood fuels. Included here are evaluations of both wood powder and wood chip combustion. When burned, one ton of wood powder yields about 17.3 GJ of high temperature heat (4795 kWh at 1473 K; see footnotes for Y_5, Table 14), compared with 15.1 GJ of 1273 K heat delivered from combustion of the same mass of wood chips (Y_5, Table 15).

Wood chip co

In the case of u
steps evaluated
15). Transport
the district heat
10.4x10^{12} sej/h
required solar e
and combustion
sej/m^{3}f.

Table 15. *Annu*
heating fuel. Va
of spruce/pine a
practices, 1988. [1]

Note	Item
I	ENVIRONM
F_1	SILVICULT
F_2	HARVESTIN
Y_2	Fuelwood yi (1.117 m^{3}f/ha
F_3	TRANSPOR
F_4	CHIPPING:
Y_3	Wood chips (1.061 m^{3}f/ha
F_5	TRANSPOR
F_6	WOOD CHI
	20 Oil
	21 Electrici
	22 Machine
	23 Human s
	24 Capital i
Y_5	High tempera
Y_6	Mechanical c (usable heat)

[1] Analysis base
given per hect

[2] Inputs reporte
sej/$, a correc
estimation of

[3] Solar emergy
sej/$).

Wood chip combustion

In the case of using wood chips directly in district heating facilities, the additional steps evaluated after chipping include only delivery and burning (F_6 and F_7, Table 15). Transport was assumed 60 km average round trip distance from the field to the district heating facility. Total solar emergy supporting transportation measured 10.4×10^{12} sej/ha/yr for about 1.1 solid cubic meters of logging residues. The required solar emergy investment from the economy for maintenance of the burner and combustion of the wood chips (F_6) measured 82×10^{12} sej/ha/yr or 80×10^{12} sej/m³f.

Table 15. *Annual resource flows associated with wood chip production and use as a district heating fuel. Values are given as resource requirements for fuelwood from one hectare of spruce/pine annual forest production in Southern Sweden under current management practices, 1988.* 1)

Note	Item	Average annual flows raw units/ha (J, g, $)	Solar transformity 2) (sej/unit)	Solar emergy (10^{12} sej/ha/yr)	Macro-economic value 3) (USD, 1988)
I	ENVIRONMENTAL INPUTS:	–	–	58.6	40.38
F_1	SILVICULTURE INPUTS:	–	–	5.0	3.47
F_2	HARVESTING:	–	–	28.9	19.92
Y_2	Fuelwood yield (1.117 m³f/ha/yr)	9.74×10^9 J	(b)	92.6	63.77
F_3	TRANSPORT TO CHIPPER:	–	–	19.9	13.70
F_4	CHIPPING:	–	–	24.5	16.86
Y_3	Wood chips (1.061 m³f/ha/yr)	9.25×10^9 J	(c)	136.9	94.33
F_5	TRANSPORT TO DISTRICT HEATING FACILITY:	–	–	10.4	7.18
F_6	WOOD CHIP BURNING:				
	20 Oil	13.0×10^6 J	47 900	0.6	0.43
	21 Electricity	170×10^6 J	124 500	21.2	14.62
	22 Machinery	721 g	6.7×10^9	4.8	3.33
	23 Human services	10.48 $	1.45×10^{12}	15.1	10.40
	24 Capital investment	27.95 $	1.45×10^{12}	40.3	27.73
Y_5	High temperature heat	6.82×10^9 J	(e)	229.3	158.03
Y_6	Mechanical output (usable heat)	2.66×10^9 J	(f)	229.3	158.03

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1) Analysis based on an average, sustainable harvest of 1.117 m³f fuelwood per hectare, so that values given per hectare are actually 16.7% of annual production (9 m³f/ha/yr).

2) Inputs reported as mass are converted to solar emergy using sej/g; monetary inputs use 1.45×10^{12} sej/$, a corrected solar emergy/GNP index so that the forest sector is not double counted in the estimation of human services.

3) Solar emergy value of input or yield divided by emergy-use/GNP for Sweden in 1988, (1.45×10^{12} sej/$).

Summary of resource inputs, yields, solar transformities, and net yield and investment ratios for Table 15.

Environmental inputs: I = 58.6×10^{12} sej/ha/yr (Table 14)

Purchased inputs from economy: $F_6 = 82.0 \times 10^{12}$ sej/ha/yr (combustion of of wood chips)

Solar emergy yield of products:

Y_2 evaluated in Table 12 and Table 14; Y_3 evaluated in Table 14.
Y_5 = High temp. heat $= Y_3 + F_5 + F_6 = 229.3 \times 10^{12}$ sej/ha/yr
Y_6 = Mechanically usable heat $= Y_5 = 229.3 \times 10^{12}$ sej/ha/yr

Solar transformities:

(a) Standing biomass = 4 873 sej/J (Table 12)
(b) Harvested wood = 9 500 sej/J (Table 12)
(c) Wood chips = 14 793 sej/J (Table 14)
(e) High temperature heat = Y_5 sej / Y_5 J = 33 661 sej/J
(f) Mechanical, usable heat= Y_5 (sej) / Y_6 (joules) = 86 305 sej/J

Net solar emergy yield ratio:

II. Harvested wood = 2.73 (Table 14)
III. Wood chips = 1.75 (Table 14)
IV. High temperature heat = $Y_5/(F_1+F_2+F_3+F_4+F_5+F_6) = 1.34$
V. Mechanical, usable heat = $Y_6/(F_1+F_2+F_3+F_4+F_5+F_6) = 1.34$

Solar emergy investment ratio:

II. Harvested wood = 0.58 (Table 12 and Table 14)
III. Wood chips = $(F_1+F_2+F_3+F_4)/I = 1.34$ (Table 14)
V. High temperature heat = $(F_1+F_2+F_3+F_4+F_5+F_6)/I = 2.91$
VI. Mechanical, usable heat = $(F_1+F_2+F_3+F_4+F_5+F_6)/I = 2.91$

Footnotes to Table 15:

Inputs I and F_{1-5} are evaluated as 16.7% of annual production (1.117 m^3f/ha/yr). I, F_1 and F_2 (steps 1–10) are evaluated in Table 12 and Table 14; F_3, F_4, and F_5 (steps 11–19) are evaluated in the analysis of wood powder production (Table 14).

F_6 Wood chip burner:

20 Oil = (8 kWh/t TS)(3.6×10^6 J/kWh)(1.061 m^3f/ha/yr)(425 kg TS/m^3f) = 1.30×10^7 J/ha/yr

21 Electricity = (105 kWh/t TS)(1.061 m^3f/ha/yr)(425 kg TS/m^3f)(3.6×10^6 J/kWh) = 1.70×10^8 J/ha/yr

22 Machinery depreciation [given as weight (g)] = (0.48 hrs/t TS)(425 kg TS/m^3f) = 0.20 hrs/m^3f; (0.20 hrs/m^3f)(1.061 m^3f/ha/yr)/(30000 hrs)(100 t) (10^6 g/t) = 721 g/ha/yr

23 Human services = (3.6 öre/kWh)/(100 SEK/öre)(4 197 kWh heat/t TS) = 151 SEK/t TS; (151 SEK/t TS)(425 kg TS/m^3f)(1.061 m^3f/ha/yr)/(6.5 SEK/USD, 1988) = 10.48 USD/ha/yr

24 Capital costs = (9.6 öre/kWh)/(100 SEK/öre)(4197 kWh heat/t TS) = 403 SEK/t TS; (403 SEK/t TS)(425 kg TS/m^3f)(1.061 m^3f/ha/yr)/(6.5 SEK/USD, 1988) = 27.95 USD/ha/yr

Combustion of wood chips:

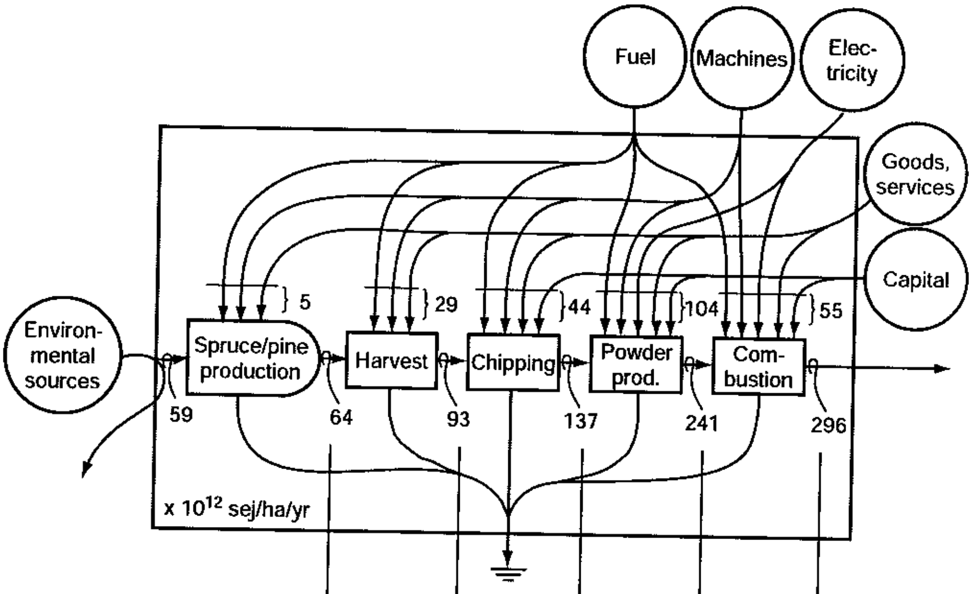
Y_5. High temperature heat: 1 ton of dry matter yields 4 197 kWh at 1 273 Kelvin = (4 197 kWh heat/ton dry matter)(3.6×10^6 J/kWh) = 1.51×10^{10} J heat/t dry matter.
Heat produced from wood chips from 1 ha of harvested annual production fuelwood: (1.061 m^3f fuelwood/ha/yr)(425 kg TS/m^3f)(1.51×10^{10} J heat/t TS) = 6.81×10^9 J heat output/ha/yr

Y_6. Mechanical heat (that fraction of total heat produced that can be used): Average winter temp. in Sweden = 7 degrees C, then 273 K + 7 K = 280 K.
Mechanically usuable heat = (High Temp. Heat)(Carnot Ratio)(delta T/T) = (6.82×10^9 J/ha/yr)(0.5)[(1273–280)/1273] = 2.66×10^9 J/ha/yr

Wood powder combustion

In the case of wood powder, the solar emergy supporting transport from the powder plant to the district heating facility and the maintenance and direct operation of the burner (F_7 and F_8, Table 14) are evaluated. Transport to the district heating facility was considered the same as transport from the field to the wood powder plant, an average round trip distance of about 60 km. Total solar emergy input for transport (F_7) was about 10.3×10^{12} sej/ha/yr, about 5% of all purchased inputs to wood powder combustion. The solar emergy invested for maintenance of a district burner and direct combustion of 1 m^3f of wood powder measured 44.4×10^{12} sej, the second largest of all purchased inputs (about 20%).

The values given in Figure 18 are aggregated from Tables 12 and 14. The total solar emergy yield (from production and combustion of 1 solid cubic meter of wood powder from logging residues ($Y_5 = I + F_1 + ... F_8$) measured 296×10^{12} sej/ha/yr. A solar transformity for high temperature heat from wood powder measured 40 023 sej/J. The net solar emergy yield ratio for high temperature heat was about 1.27, down roughly 6% from wood powder itself. The investment ratio of purchased inputs to those contributed from the environment was 3.6, up 30% from unburned wood powder. Based on these ratios, the purchased inputs increased a lttle bit more



Solar transformity (sej/J):	4 873	9500	14 793	27 473	40 023
Net yield ratio:	12.7	2.7	1.8	1.4	1.3
Investment ratio:	0.1	0.6	1.3	2.8	3.6

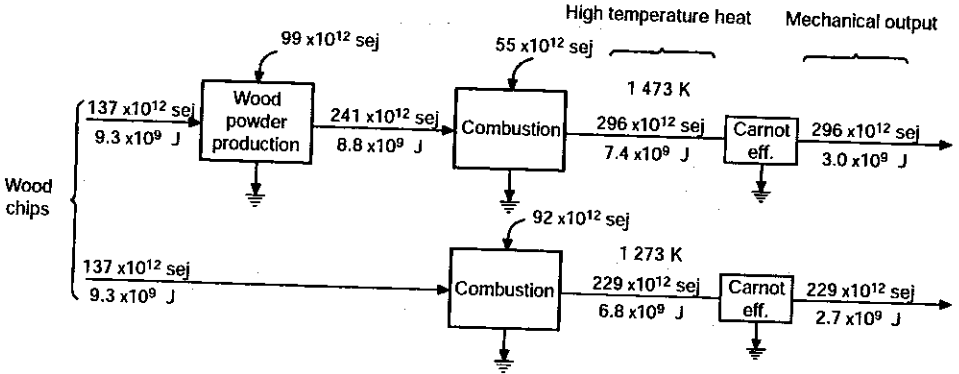
Figure 18. Systems diagram of wood powder production and use as a district heating fuel, based on current forest practices in Southern Sweden. Numbers on pathways are reported as 10^{12} sej/ha/year, assuming a steady-state production of 9 m^3f/ha/year, of which about 1 m^3f/ha of wood residues are used as fuelwood annually from forests in Southern Sweden. See Table 14 for calculations, raw units of each input and the derivations of solar transformities and net solar emergy indices.

than 6 times in relation to those delivered from environmental sources from the time the wood is harvested to its final combustion. The net yield in relation to total investment declined about 50% between harvest and final combustion of wood powder.

An estimate of possible mechanical work that could be derived from the high temperature heat was estimated using the Carnot cycle calculation for conversion of heat to mechanical work, assuming the slowest most efficient rate possible. Less "usable" energy is delivered, an amount that is available for mechanical work (about 60% less, see Y_6, Table 14). Although no additional inputs were calculated for this estimate, other resources such as technology, services and facilities would be required to use this mechanical output. The solar transformity for mechanical heat energy derived from the combustion of wood powder measured 98 832 sej/J, approaching the solar transformities presently calculated for electricity generation.

Comparisons of heat delivered from wood fuel alternatives

Comparison of heat derived from combustion of wood chips and wood powder is given in Figure 19. A solar transformity of 33 661 sej/J was calculated for high temperature heat delivered from wood chip combustion, about 16% lower than the heat produced from combustion of wood powder. Similarly, a solar transformity



Burning wood powder		
Solar transformity	40 023 sej/J	98 832 sej/J
Net yield ratio		1.27
Investment ratio		3.64
Burning wood chips		
Solar transformity	33 661 sej/J	86 305 sej/J
Net yield ratio		1.34
Investment ratio		2.91

Figure 19. Comparison of district heating alternatives from wood chips and wood powder. Pathways have both solar emergy and actual energy flows given for steady-state fuelwood harvest from southern forests (9 m³f/ha/year of forest biomass production yields approximately 1 m³f fuelwood to end user).

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for mechanical heat measured 86 305 sej/J, about 13% lower than mechanical heat energy derived from wood powder.

The net solar emergy yield ratio for heat from wood chip combustion was slightly higher than that for heat from wood powder (1.34 compared with 1.27). Fifteen percent more heat is derived from wood powder combustion compared with wood chips (17.3 GJ/t at 1 473 K compared with 15.1 GJ/t at 1 273 K; see Y_5, Tables 14 and 15). When comparing ratios of solar emergy invested from the economy relative to that delivered from the environment, use of wood powder requires about 30% greater investments of purchased resources (Investment ratios for heat delivered from powder and chips 3.6 and 2.9, respectively). These results show that although wood powder has less net solar emergy yield than chips, it produces a greater direct output of high temperature heat, though at a greater investment of solar emergy from Sweden's main economy. This investment of resources, although diverted from other competing sectors, transforms the forest resource to an upgraded fuel, allowing it greater application, ease of transport and greater combustion temperature than chipped wood.

Pulp and paper industry overview

Sweden's wood pulp and paper production sectors were evaluated for resource requirements supporting each industry. Industry data for 1986 (Skogsstyrelsen 1987 and Alsefelt 1989) were used to determine resource inputs and production output for both the pulp and paper industries (Figure 20). Estimates of solar emergy and transformities for products from each sector were calculated using this data as the most current and detailed consumption and production figures. These solar transformities were then applied to production figures for 1988, the baseline year of this study.

Chemical pulp production

In order to produce chemical pulp, the fibers of the wood cellulose (50% by volume; lignin, etc. comprise the remainder) is freed by boiling the wood chips with chemicals at high pressures. There are two basic boiling techniques: the sulphate method uses a basic liquid to produce unbleached pulp; in the sulphite method, the chips are boiled in an acid-base liquid (generally SO_4 and Ca) to produce bleached pulp. Currently, sulphate pulp is the predominant form produced in Sweden (about 3.6 million tons of sulphate pulp and 567 thousand tons of sulphite pulp were produced in 1986). About 2.7 million tons of chemical pulp was exported in 1988; this figure was used to evaluate solar emergy exported during 1988 (Table 3, item 56), using a solar transformity for chemical pulp derived from this subsystem analysis. Resource requirements for pulp production and industry output from both methods are combined in this analysis for overview.

Average, direct consumption of raw forest materials for chemical pulp production was estimated at about 4.7 m^3f ub per ton pulp produced for the entire country in 1973 (Skogsstyrelsen 1987). Using actual wood consumption and pulp production figures for 1986, about 4.15 m^3f ub/ton was determined as an industry average for chemical

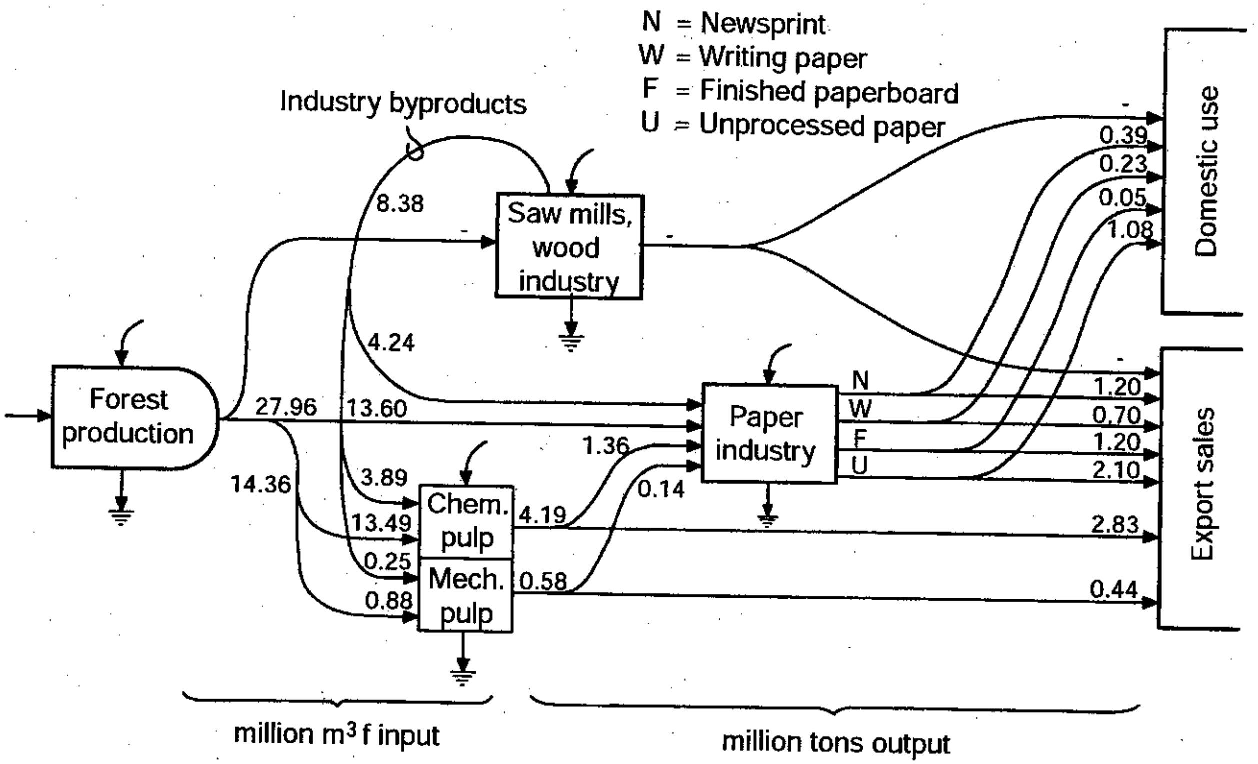

Figure 20. Overview diagram of Sweden's pulp and paper industry. Values on pathways are reported as basic consumption and production data summarized from Skogsstyrelsen (1989) and P. Alsefelt (1989).

Figure 20. Overview diagram of Sweden's pulp and paper industry. Values on pathways are reported as basic consumption and production data summarized from Skogsstyrelsen (1989) and P. Alsefelt (1989).

Footnotes to Figure 20:

Estimates of wood volume (solid cubic meters, m^3f) consumed per ton of pulp production:

chemical pulp production (sulphate and sulphite methods are combined here for overview):
wood volume input/chemical pulp produced = 17.38×10^6 m^3f/4.188×10^6 t chemical pulp
= 4.15 m^3f ub/t chemical pulp

mechanical pulp production:
wood volume input/mechanical pulp prod. = 1.129×10^6 m^3f/0.582×10^6 t mech. pulp
= 1.93 m^3f wood/t mech. pulp

Estimates of direct consumption of raw materials in pulp production:

Treatment method	Actual wood consumption[1]	Industry averages[2]
chemical pulp	4.15 m^3f ub/ton	4.7 m^3f ub/ton
mechanical pulp	1.92 m^3f ub/ton	2.4 m^3f ub/ton

m^3f ub = cubic meters of solid wood, under bark

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[1] based on calculations made above; total industry volume input divided by total pulp production.

[2] based on averages for industry consumption of raw materials for 1984 (Skogsstyrelsen 1987).

Allocation of wood resources used in overview analyses of the pulp and paper industries:

Production figures for 1984:	Mechanical pulp	Sulphite pulp (bleached)	Sulphate pulp (unbleached)
used in paper industry	138 000 t	183 000 t	1 177 000 t
exported	444 000 t	384 000 t	2 444 000 t
total production	582 000 t	567 000 t	3 621 000 t

Estimates of total wood input to pulp industry (including both forest and industry byproducts):
mechanical pulp: $(582 \times 10^3\ t)(1.92\ m^3f/t) = 1.12 \times 10^6\ m^3f$ (6% of total volume)
chemical pulp: $(4.19 \times 10^6\ t)(4.15\ m^3f/t) = 17.38 \times 10^6\ m^3f$ (94% of total volume)
total volume: $1.12 \times 10^6\ m^3f + 17.38 \times 10^6\ m^3f = 18.5 \times 10^6\ m^3f$

Percent contribution directly from forests (14.36 million cubic meters):
mechanical pulp: $(14.36 \times 10^6\ m^3f)(0.06) = 0.875 \times 10^6\ m^3f$
chemical pulp: $(14.36 \times 10^6\ m^3f)(0.94) = 13.49 \times 10^6\ m^3f$

Percent contribution from industry byproducts (4.14 million cubic meters):
mechanical pulp: $(4.14 \times 10^6\ m^3f)(0.06) = 0.253 \times 10^6\ m^3f$
chemical pulp: $(4.14 \times 10^6\ m^3f)(0.94) = 3.889 \times 10^6\ m^3f$

pulp production. This later figure was used in this study for evaluating resource requirements since this figure was based on more recent data and presumably reflected changes due to technological development in Sweden's forestry and wood pulp industries.

Direct use of fuels in chemical pulp production includes wood fuels, oil, electricity and "other" intermediate fuels. The solar emergy for intermediate fuels, oil and electricity requirements were estimated using independent solar transformities; the solar emergy for wood fuels and direct consumption of raw materials were determined using solar transformities derived in this study. The solar emergy of the raw material for chemical pulp included both environmental contributions (I) as well as solar emergy supporting silviculture, harvesting and wood chipping (F_1). Using a solar transformity for spruce/pine wood chips of 16000 sej/J (including transport) determined in this study, the environmental and societal contributions were estimated using a net yield ratio of 1.75 for transported wood chips (values from Table 14).

The direct energy inputs and monetary production costs for chemical pulp production are given in Figure 21a. As shown in this traditional energy input/output diagram, environmental contributions are not identified. Raw forest material inputs are given as an industry average of 4.15 cubic meters of wood *under bark* equivalent

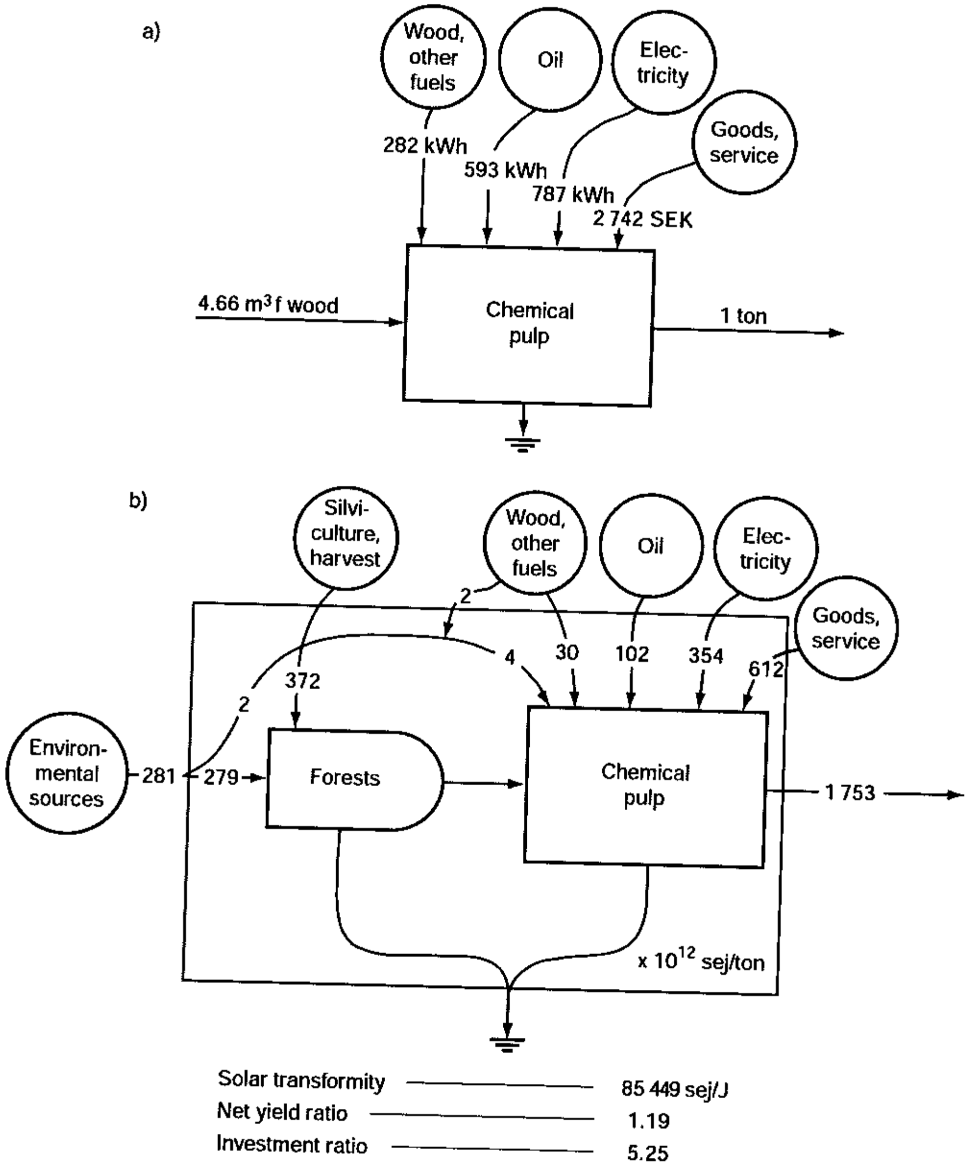

Figure 21. Systems diagram of resource requirements for production of one ton of chemical pulp; (a) inputs reported as given by paper industry; (b) flows reported as solar emergy (see footnotes for derivations of resource flows).

Footnotes to

Calculations
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J/kWh)

F_3 other, ir
kWh/t; (

F_4 oil: [(0.
J/kWh) =

F_5 electricit
(3.6x10⁶

F_6 producti
(sulphite

Solar emergy

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Footnotes to Figure 21:

Calculations are based on one ton of wood pulp production using chemical treatment (sulphate and sulphite methods are combined here for overview):

$4.66\ m^3f$ wood/ton chem. pulp; $(4.66\ m^3f/t)(8.72 \times 10^9\ J/m^3f) = 40.8.2 \times 10^9\ J/t$

Energy/economic calculations:

F_2 wood fuels (evaluated using solar transformity for wood fuels estimated from this study): $(0.3 \times 10^9\ kWh)/4.188 \times 10^6$ ton chemical pulp production = 71.6 kWh/t; 71.6 kWh/t)$(3.6 \times 10^6\ J/kWh) = 0.26 \times 10^9\ J/t$

F_3 other, intermediate fuels: $[(0.94)(0.3 \times 10^9\ kWh) + 0.6 \times 10^9\ kWh]/4.188 \times 10^6$ t ch. pulp = 210.5 kWh/t; $(210.5\ kWh/t)(3.6 \times 10^6\ J/kWh) = 0.76 \times 10^9\ J/t$

F_4 oil: $[(0.94)(0.3 \times 10^9\ kWh) + 2.2 \times 10^9\ kWh]/4.188 \times 10^6\ t = 592.6\ kWh/t$; $(592.6\ kWh/t)(3.6 \times 10^6\ J/kWh) = 2.13 \times 10^9\ J/t$

F_5 electricity: $[(0.94)(0.1 \times 10^9\ kWh) + 3.2 \times 10^9\ kWh]/4.188 \times 10^6\ t = 786.5\ kWh/t$; $(786.5\ kWh/t)(3.6 \times 10^6\ J/kWh) = 2.83 \times 10^9\ J/t$

F_6 production costs: estimated as export value less 10%; (sulphate 2 989 SEK/t)(86.5% tot. ch. pulp) + (sulphite, 3 415 SEK/t)(13.5% total ch. pulp) = 3 045 SEK/ton; (3 045 SEK/t)(0.90) = 2 741 SEK/t

Solar emergy calculations:

I environmental contribution to direct wood input (I_1) + environmental contrib. to wood fuels (I_2);

$I_1 + I_2 = (278.8 + 1.8) \times 10^{12}\ sej/t = 280.6 \times 10^{12}\ sej/t$

F_1 direct wood input: $(40.7 \times 10^9\ J/t)(16000\ sej/J) = 651 \times 10^{12}$ sej/t chemical pulp; where net yield ratio for transported wood chips = 1.75:1, then

$F_1 = (1/1.75)(651 \times 10^{12}\ sej/t) = 372 \times 10^{12}\ sej/t$

$I_1 = (Y - F) = (651 - 372) \times 10^{12}\ sej/t = 279 \times 10^{12}\ sej/t$

F_2 wood fuels: $(0.26 \times 10^9\ J/t)(16000\ sej/J) = 4.1 \times 10^{12}$ sej/t; then

$F_2 = (1/1.75)(4.1 \times 10^{12}\ sej/t) = 2.3 \times 10^{12}\ sej/t$

$I_2 = (Y - F) = (4.1 - 2.3) \times 10^{12}\ sej/t = 1.8 \times 10^{12}\ sej/t$

F_3 other fuels (using an intermediate solar transformity for coal): $(0.76 \times 10^9\ J/t)(40000\ sej/J) = 30.3 \times 10^{12}\ sej/t$

F_4 oil: $(2.13 \times 10^9\ J/t)(47900\ sej/J) = 102 \times 10^{12}\ sej/t$

F_5 electricity: $(2.83 \times 10^9\ J/t)(125000\ sej/J) = 354 \times 10^{12}\ sej/t$

F_6 production costs: (2741 SEK/t)/(6.5 SEK/USD)$(1{,}45 \times 10^{12}\ sej/USD) = 612 \times 10^{12}\ sej/t$

Summary inputs, indices and solar transformity for chemical pulp:

$I = 281 \times 10^{12}\ sej/t$; $F = 1473 \times 10^{12}\ sej/t$; $Y = I + F = 1753 \times 10^{12}\ sej/t$

Solar transformity = $(1753 \times 10^{12}\ sej/ton)(20.52 \times 10^9\ J/t) = 85499\ sej/J$
Net solar emergy yield ratio = 1.19
Solar emergy investment ratio = 5.25

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to 4.66 solid cubic meters *with bark*, per ton of chemical pulp produced. Fuels, given as direct use required per ton of chemical pulp, are reported as calorimetric heat due to combustion. Associated human services are estimated as total production costs.

In Figure 21b, the solar emergy base for these inputs are given and environmental contributions are identified and separated from societal resource inputs in order to estimate net contribution and environmental support. The largest inputs to chemical pulp production are here identified as human services (F_6), electricity (F_5), silviculture and harvesting (F_1) and environment (I). The solar emergy required to grow, harvest and deliver the raw material (4.15 m^3f ub/t) accounts for about 37% of the total resource base supporting the production of chemical pulp. The total environmental contribution, including the solar emergy embodied in the raw materials (I_1) as well as the wood fuel (I_2), accounted for about 16% of the total solar emergy necessary to produce chemical pulp, with societal, upgraded fuels, goods and human services accounting for the remaining 84%. This is reflected in the investment ratio for chemical pulp of 5.25. A solar transformity for chemical pulp was calculated at 85 500 sej/J or about $1\,750 \times 10^{12}$ sej/ton (Figure 21b).

Mechanical pulp production

Mechanical pulp is produced by grinding or refining and contains practically all parts of the wood (Skogsstyrelsen 1987). Ground pulp is produced from grinding whole logs under pressure against rotating grindstones. Refined pulp is produced from wood chips, and thus much of the solar emergy input is incurred in previous process steps. In this subsystems analysis, all raw materials are evaluated as wood chips, and grinding and refining mechanical methods are combined for overview. 582 000 tons of mechanical pulp were produced in 1984 with about one-fourth of the production used as raw material for the paper industry and about three-quarters exported. In 1988, 0.45 million tons of mechanical pulp was exported. This figure was used in the national analysis (Table 3, item 57) based on a solar transformity derived in this subsystem analysis.

About 1.93 m^3f ub equivalent to 2.17 m3f with bark per ton mechanical pulp produced was estimated based on actual wood consumption and pulp production data in 1986 [an industry average of 2.4 m^3f ub/ton is given by Skogsstyrelsen (1989)]. Again the lower figure is used in this study as a more recent assessment that presumably reflects changes in production technology. Figure 22a shows the direct inputs of fuels and associated production costs. In mechanical methods, upgraded energy sources of electricity and fuel oil are used more extensively than intermediate wood fuels. Almost ten times more electricity is used per ton of pulp using mechanical methods than in chemical production. Monetary production costs for mechanically produced pulp are about 70% of chemical pulp, reflecting the combination of low input of wood per ton pulp and low cost of electricity in Sweden due to the high, unmonied contribution from nature in hydroelectric and generation. The wood consumption per ton pulp is only half of that in chemical pulp.

As measured by direct, calorimetric heat energy, electricity consumption accounts for 93% of the fuels used (intermediate fuels, oil and electricity combined). In contrast, by estimating the solar emergy of each of these three inputs, electricity accounts for over 97% of the fuels consumed directly (Figure 22b). However, from a systems view, accounting for all inputs equally using solar emergy, electricity use accounts for about 80% of the total resource contribution, including environmental and purchased sources. Using traditional input/output methods of energy analysis, electricity is only compared with other direct fuel-use; the other contributions of raw materials, environment and labor are not evaluated, nor are the indirect fuels, goods and services supporting the sector.

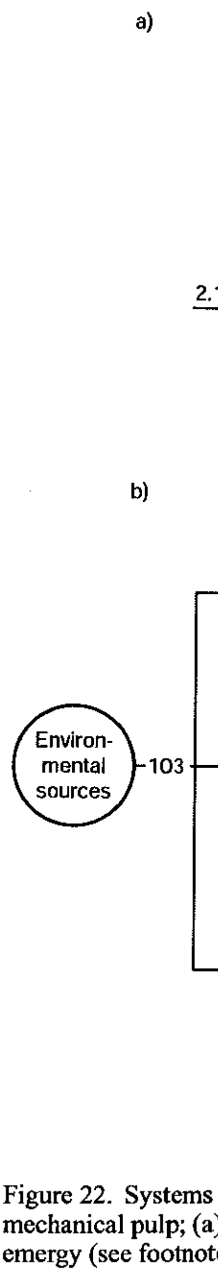

Figure 22. Systems
mechanical pulp; (a)
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Footnotes to Figure 22:

Calculations are based
2.17 m^3f wood wi

Energy/economic calcu

F_2 wood fuels: none
F_3 other fuels: [(0.06
kWh/t)(3.6×10^6 J
F_4 oil: [(0.06)(0.3 x
J/kWh) = 1.35x1

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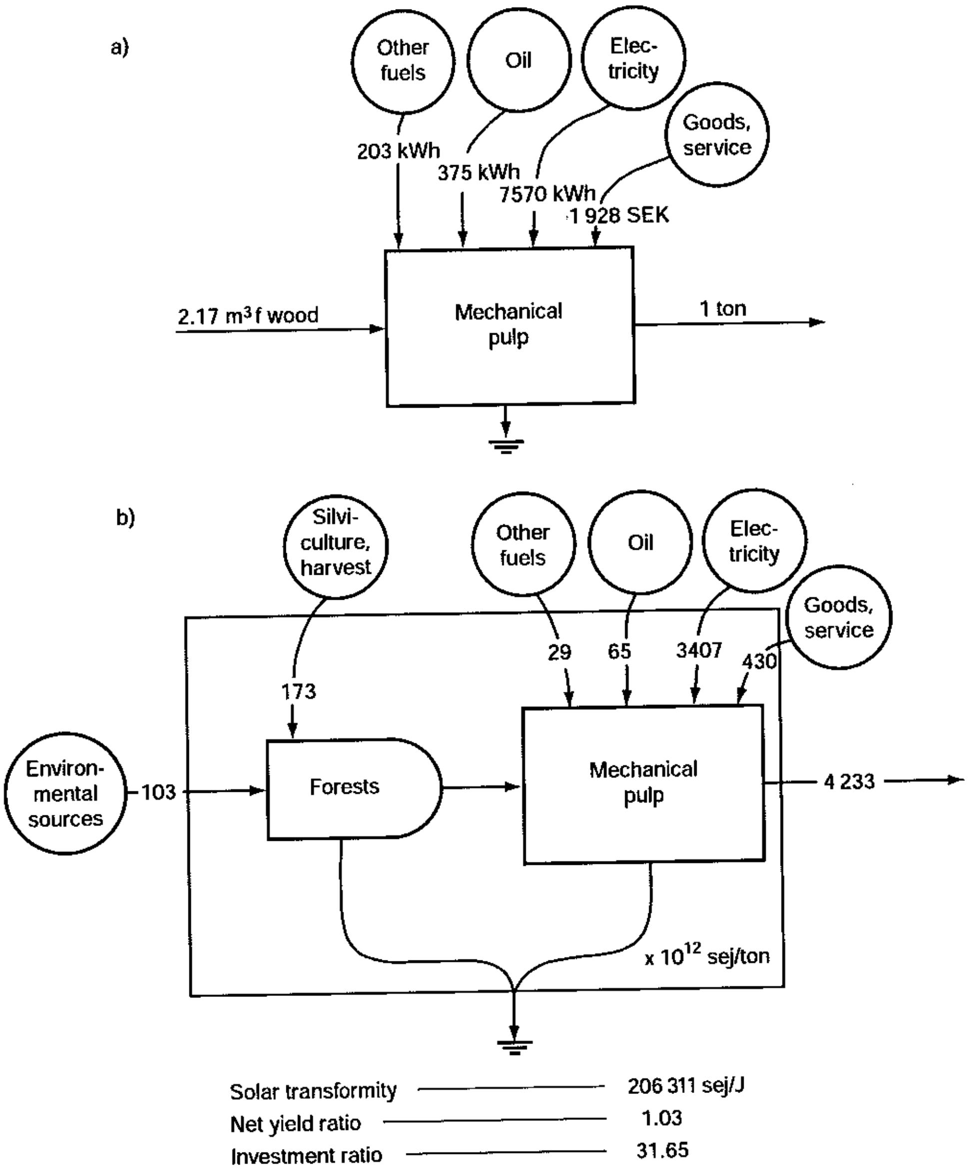


Figure 22. Systems diagram of resource requirements for production of one ton of mechanical pulp; (a) inputs reported as given by paper industry; (b) flows reported as solar emergy (see footnotes for derivations of resource flows).

Footnotes to Figure 22:

Calculations are based on one ton of wood pulp production using mechanical grinding methods:
2.17 m^{3}f wood with bark/ton mech. pulp; (2.17 m^{3}f/t)(8.72x10^9 J/m^{3}f) = 18.9x10^9 J/t

Energy/economic calculations:

F_2 wood fuels: none

F_3 other fuels: [(0.06)(0.3x10^9 kWh) + 0.1x10^9 kWh]/0.582x10^6 t mech. pulp = 202.7 kWh/t; (202.7 kWh/t)(3.6x10^6 J/kWh) = 0.730x10^9 J/t

F_4 oil: [(0.06)(0.3x10^9 kWh) + 0.2x10^9 kWh]/0.582x10^6 t = 374.6 kWh/t; (374.6 kWh/t)(3.6x10^6 J/kWh) = 1.35x10^9 J/t

Footnotes to Figure 22, continued.

F_5 electricity: $[(0.06)(0.1\text{x}10^9\text{ kWh}) + 4.4\text{x}10^9\text{ kWh}]/0.582\text{x}10^6\text{ t} = 7570\text{ kWh/t}$; $(7570\text{ kWh/t})(3.6\text{ x}10^6\text{ J/kWh}) = 27.3\text{x}10^9\text{ J/t}$

F_6 production costs (human services): estimated as export value less 10%; (2142 SEK/t)(0.90) = 1928 SEK/t

Solar emergy calculations:

F_1 direct wood input: $(18.91\text{x}10^9\text{ J/t})(16000\text{ sej/J}) = 302.6\text{x}10^{12}$ sej/t mech. pulp; where net yield ratio for transported wood chips = 1.75, then

$$F_1 = (1/1.75)(302.6\text{x}10^{12}\text{ sej/t}) = 173\text{x}10^{12}\text{ sej/t}$$
$$I = (Y-F) = (303-173)\text{x}10^{12}\text{ sej/t} = 130\text{x}10^{12}\text{ sej/t}$$

F_3 other fuels (using an intermediate solar transformity for coal): $(0.729\text{x}10^9\text{ J/t})(40000\text{ sej/J}) = 29.2\text{x}10^{12}\text{ sej/t}$

F_4 oil: $(1.35\text{x}10^9\text{ J/t})(47900\text{ sej/J}) = 64.6\text{x}10^{12}\text{ sej/t}$

F_5 electricity: $(27.25\text{x}10^9\text{ J/t})(125000\text{ sej/J}) = 3407\text{x}10^{12}\text{ sej/t}$

F_6 production costs: $(1928\text{ SEK/t})/(6.5\text{ SEK/USD})(1.45\text{x}10^{12}\text{ sej/SEK}) = 463\text{x}10^{12}\text{ sej/t}$

Summary inputs, indices and solar transformity for chemical pulp:

$I = 130\text{x}10^{12}$ sej/t; $F = 4104\text{x}10^{12}$ sej/t; $Y = I + F = 4233\text{x}10^{12}$ sej/t

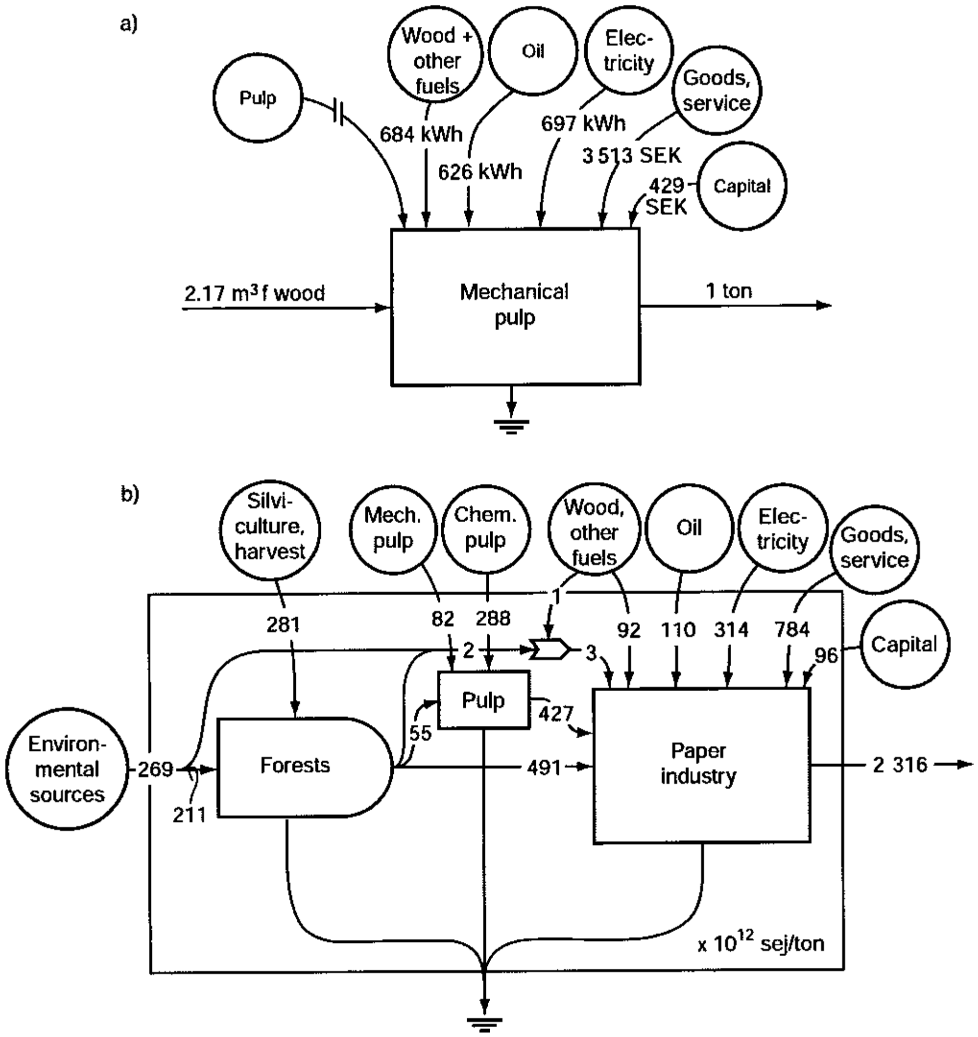
Solar transformity = $(4233\text{x}10^{12}\text{ sej/ton})/(20.52\text{x}10^9\text{ J/t}) = 206311$ sej/J
Net solar emergy yield ratio = $Y/F = 1.03$
Solar emergy investment ratio = $F/I = 31.7$

In mechanical pulp methods, environmental support of forest production contributes only about three percent of the total solar emergy. Electricity accounts for about 80% of all inputs and human services about 10%. This is reflected in an investment ratio of 31.7. A solar transformity was estimated at about 206 311 sej/J or about $4233\text{x}10^{12}$ sej/t, indicating about 2.4 times more solar emergy is necessary for mechanically produced wood pulp than for chemical pulp. It should be emphasized that byproduct emissions and chemical affluent not addressed here may result in changes in the analysis, increasing solar emergy requirements for chemical pulp, its solar transformity and net yields.

Paper products

In this analysis, all paper products, including newspaper, writing paper, kraftpaper and cardboard were combined for overview. Solar emergy of raw materials, chemical and mechanical pulp were estimated using solar transformities calculated in this study. Using 1984 production figures (Skogsstyrelsen 1987 and Alsefelt 1989), the paper industry was evaluated for resource requirements, net yield and investment ratios were calculated for the industry and an average solar transformity for paper products was estimated. This solar transformity was then used in the national analysis to evaluate the solar emergy of paper exports in 1988, the baseline year of this study.

As before, Figure 23a shows the direct inputs of raw materials, fuels, goods and services associated with an average production of one ton of paper products. In Figure 23b, the paper industry is redrawn to identify all inputs, and these inputs are expressed as solar emergy. Environmental contributions to the paper industry



Solar transformity	112 854 sej/J
Net yield ratio	1.13
Investment ratio	7.60

Figure 23. Systems diagram of resource requirements for production of one ton of paper product; (a) inputs reported as given by paper industry; (b) flows reported as solar emergy (see footnotes for derivations of resource flows). All paper products are included in this overview analysis so that the evaluation is an average for the industry.

Footnotes to Figure 23:

Calculations are based on inputs required for entire paper industry, including newspaper, writing paper, kraftpaper, cardboard production:

wood input in the form of mechanical pulp: $(0.138\text{x}10^{6}\ \text{t})(2.17\ \text{m}^3\text{f/t}) = 0.299\text{x}10^{6}\ \text{m}^3\text{f}$

wood input in the form of chemical pulp: $(1.36\text{x}10^{6}\ \text{t})(4.66\ \text{m}^3\text{f/t}) = 6.338\text{x}10^{6}\ \text{m}^3\text{f}$

direct wood input: $13.6\text{x}10^{6}\ \text{t} + 4.243\text{x}10^{6}\ \text{m}^3\text{f/t} = 17.843\text{x}10^{6}\ \text{m}^3\text{f}$

total wood volume input to paper industry: $24.480\text{x}10^{6}\ \text{m}^3\text{f}$

volume of wood input/total paper products = $24.480\text{x}10^{6}\ \text{m}^3\text{f}/6.954\text{x}10^{6}$ ton paper = average 3.52 m^{3}f wood/t paper products; $(3.52\ \text{m}^3\text{f/t})(8.72\text{x}10^{9}\ \text{J/m3f}) = 30.70\text{x}10^{9}\ \text{J/t}$

Footnotes to Fgure 23, continued.

Energy/economic calculations:

F_2 wood fuels: (0.4x10^9 kWh)/6.954x10^6 t paper = 57.52 kWh/t; (57.52 kWh/t)(3.6x10^6 J/kWh) = 0.207x10^9 J/t

F_3 other fuels: [(0.5)(0.3x10^9 kWh) + 4.2x10^9 kWh]/6.954x10^6 t paper products = 625.6 kWh/t; (625.6 kWh/t)(3.6x10^6 J/kWh) = 2.252x10^9 J/t

F_4 oil: [(0.5)(0.1x10^9 kWh) + 4.4x10^9 kWh]/6.954x10^6 t = 639.9 kWh/t; (639.9 kWh/t)(3.6x10^6 J/kWh) = 2.304x10^9 J/t

F_5 electricity: [(0.5)(0.1x10^9 kWh) + 4.8x10^9 kWh]/6.954x10^6 t = 697.4 kWh/t; (697.4 kWh/t)(3.6x10^6 J/kWh) = 2.511x10^9 J/t

F_6 production costs: (24.43x10^9 SEK)/(6.954x10^6 t) = 3513 SEK/t

F_7 capital costs: (2.98x10^9 SEK)/(6.954x10^6 t) = 428.5 SEK/t

Solar emergy calculations:

I direct wood input (I_1) – silvicultural inputs (F_1) + environmental contribution to wood fuels (I_2) + env. contr. mech. pulp (I_8) + env. contr. chem. pulp (I_9): $I_1 + I_2 + I_8 + I_9$ = (211 + 1.4 + 2.5 + 54)x10^{12} sej/t = 269x10^{12} sej/t

F_1 direct wood consumption: (30.70x10^9 J/t) (16000 sej/J) = 491x10^{12} sej/t paper products; where net yield ratio for direct wood consumption = 1.75:1, then

F_1 = (1/1.75)(491x10^{12} sej/t) = 281x10^{12} sej/t

I_1 = (Y–F) = (491.2–280.7)x10^{12} sej/t = 211x10^{12} sej/t

F_2 wood fuels: (0.207x10^9 J/t)(16000 sej/J) = 3.3x10^{12} sej/t; then

F_2 = (1/1.75)(3.31x10^{12} sej/t) = 1.9x10^{12} sej/t

I_2 = (Y–F) = (3.3–1.9)x10^{12} sej/t = 1.4x10^{12} sej/t

F_3 other fuels (using an intermediate solar transformity for coal): (2.252x10^9 J/t)(40000 sej/J) = 90x10^{12} sej/t

F_4 oil: (2.30x10^9 J/t)(47900 sej/J) = 110x10^{12} sej/t

F_5 electricity: (2.51x10^9 J/t)(125000 sej/J) = 314x10^{12} sej/t

F_6 production costs: (3513 SEK/t)/(6.5 SEK/USD)(1.45x10^{12} sej/SEK) = 784x10^{12} sej/t

F_7 capital cost: (428.5 SEK/t)/(6.5 SEK/USD)(1.45x10^{12} sej/SEK) = 96x10^{12} sej/t

F_8 mechanical pulp inputs: (0.138x10^6 t)(4232x10^{12} sej/t)/(6.954x10^6 t paper) = 84.0x10^{12} sej/t; then

F_8 = (1/1.03)(84.0x10^{12} sej/t) = 81.6x10^{12} sej/t

I_8 = (Y–F) = (84.0–81.6)x10^{12} sej/t = 2.4x10^{12} sej/t

F_9 chemical pulp inputs: (1.36x10^6 t)(1753x10^{12} sej/t)/(6.954x10^6 t paper) = 343x10^{12} sej/t; then

F_9 = (1/1.19)(343x10^{12} sej/t) = 288x10^{12} sej/t

I_9 = (Y–F) = (343–288)x10^{12} sej/t) = 55x10^{12} sej/t

Summary inputs, indices and solar transformity for paper products:

I = 269x10^{12} sej/t; F = 2047x10^{12} sej/t; Y = I + F = 2316x10^{12} sej/t

Solar transformity = (2316x10^{12} sej/t)/(20.52x10^9 J/t) = 112854 sej/J

Net solar emergy yield ratio = Y/F = 1.13

Solar emergy investment ratio = F/I = 7.60

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included forest production for raw materials (I_1), for mechanical pulp (I_2), for chemical pulp (I_3), and for wood fuels (I_4), accounting for about 12% of the total required resources. An average investment ratio of about 7.6 was calculated for the industry. A solar transformity for paper products of 112854 sej/J (2316x10^{12} sej/t) was estimated, an intermediate value between mechanical and chemical pulp.

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Forest contributions to the Swedish national economy

Using a systems measure of solar emergy to evaluate forests and the forest sector, a greater net contribution to Sweden's national economy was measured than what might be inferred from the market value of the forest products. This is because the market price only reflects the capital costs of production through money paid to forestry employees, for material goods and fuels used in the forest operations and a set margin of profit based on the consumer's willingness to pay. The actual contribution to the combined ecologic-economic system includes the contributions from environmental sources plus the attracted investments used to grow, harvest and process the forest products. Expressed as solar emergy, all inputs can be compared based on their abilities to influence production and impact the national economy. In addition to attracted investments, revenues from forest export sales can be and are used to purchase fuels, goods and services from outside that are needed to develop other economic sectors, but which are not directly available within its borders. In the following sections, overview perspectives on forest contribution to national welfare based on current and potential uses, attracted investments, and benefits due to foreign sales and purchases are discussed based on solar emergy evaluations undertaken in this study.

Macro-economic value of forest production and utilization

Forest production and use are expressed here in macro-economic dollar value, defined as the solar emergy of a resource or commodity divided by the relation of solar emergy to GNP for Sweden in 1988 (1.45×10^{12} sej/USD). Using this perspective, an environmental source, such as precipitation, or an ecological process such as forest metabolism, can be discussed as contributing to the gross national economic product, expressed as macro-economic dollars. For example, the standing crop of forest biomass in Sweden, estimated as 2.7 billion cubic meters of wood, was calculated to be worth around 76 billion dollars in 1988 (Table 16), about forty percent of the gross national economic product (178 billion USD, 1988). The contribution from forest metabolism, based on solar emergy of transpired rainfall, was estimated at 5.7 billion macro-economic dollars; the actual harvest of 57 million m^3f in 1988 measured about 3.3 billion macro-economic dollars.

The total solar emergy supporting Sweden's forest industry, including both forest input and the attracted investments from the economy was valued at 23 billion macro-economic dollars in 1988 or about 13% of the gross national economic product (Table 16, item 5). The direct forest input accounted for about 3 billion macro-economic dollars, while the purchased fuels, goods and human services (*i.e.* attracted investments) accounted for the remaining 20 billion macro-economic dollars. This suggests an industry average investment ratio of 7.9, almost twice that of the national economic/environment ratio (Table 5, item 8).

Of the total contribution, forest products used domestically accounted for about 5.7 billion macro-economic dollars, while roughly 17 billion dollars in macro-economic value was exported. In contrast, Sweden received about 8 billion USD for exported forest products in 1988. This indicates that forest products embody a greater net worth than is represented from market transactions. Further, this perspective suggests that the foreign sales of manufactured forest products, pulp and paper may not necessarily be a net benefit to Sweden's national welfare, though this analysis is dependent upon how those revenues were used. This issue of exchange is discussed in the next section.

Table 16. *Annual macro-economic contribution*[1] *of forest production and resource-use to Sweden's gross national economic product for the 1988 harvest schedule.*

Footnote	Item	Macro-economic contribution [1] billion em$, 1988
1	Standing forest (2.7 billion cubic meters)	79.1
2	Forest metabolism (based on transpiration)	5.7
3	Annual harvest (57 million m^{3}f/yr) (before processing)	3.3
4	Forest products used in domestic heating	0.4
5	Manufactured forest products:	
	a. Forest input	2.9
	b. Purchased, societal inputs	19.9
	c. Total (solar emergy yield)	22.8
6	Forest products used within Sweden	5.7
7	Exported forest products	17.1

[1] Solar emergy divided by the relation of annual solar emergy-use/GNP for Sweden in 1988 (1.45×10^{12} sej/USD).

Footnotes to Table 16:

1. Standing forest in Sweden [solar transformity of spruce/pine forest production (4873 sej/J; Table 12, item (a), page 59) is used to estimate forest contribution]: (2.7×10^{9} m^{3}f)(425 kg/m^{3}f)(20.52×10^{6} J/kg) = 23.5×10^{18} J; (23.5×10^{18} J)(4873 sej/J) = 115×10^{21} sej; (115×10^{21} sej)/(1.45×10^{12} sej/USD, 1988) = 79.1 billion macro-economic em$
2. Forest metabolism based on transpiration: (352×10^{12} sej/ha/yr, item 3, Table 12)(23.6×10^{6} ha forested land) = 8.30×10^{21} sej/yr; (8.30×10^{21} sej/yr)/(1.45×10^{12} sej/USD) = 5.7 billion macro-economic em$/yr
3. Annual harvest: [solar transformity of harvested spruce/pine at roadside (9500 sej/J; Table 12b) is used to estimate total solar emergy basis for annual forest harvest in Sweden]: (57×10^{6} m^{3}f/yr currently harvested)(425 kg/m^{3}f)(20.52×10^{6} J/kg) = 497×10^{15} J/yr; then: (497×10^{15} J/yr)(9500 sej/J) = 4.7×10^{21} sej/yr; (4.7×10^{21} sej/yr)/(1.45×10^{12} sej/$) = 3.25 billion macro-economic em$/yr
4. Forest products used in heating: 7 million m^{3}f/yr forest wood used as domestic heating fuel in 1988 (Table 11, page 56), then: (7×10^{6} m^{3}f/yr)/(57×10^{6} m^{3}f/yr harvested) = 12.3% of total harvest; (0.123)(3.25×10^{9} em$/yr) = 0.40 billion macro-economic em$/yr
5. Manufactured wood products:
    a. Forest input to forest industry sector: (1 − 0.123) = 87.7%; (0.877)(57×10^{6} m^{3}f/yr) = 50×10^{6} m^{3}f/yr; (0.877)(3.25×10^{9} em$/yr) = 2.85 billion macro-economic em$/yr

Footnotes to Table 16, continued.

- b. Purchased societal inputs (F) = Y (from footnote 5c below) – I (from footnote 5a above) = 22.8 – 2.9 = 19.9 billion macro-economic em\$/yr.
- c. Total solar emergy of manufactured forest industry products (Y) is estimated as the sum of domestic-use (note 6 below) and export products (note 7 below) = (5.7 + 17.1)x10^{9} em\$ = 22.8x10^{9} em\$/yr

6. Products of forest industry used within Sweden (domestic-use):
   - a. Fuel wood: solar transformity for fuel wood calculated from the emergy required for wood chips delivered to users (Y$_3$ + F$_5$; Table 14, page 71) divided by the energy of the wood chips delivered: [(136.9 + 10.4)x10^{12} sej/ha] / [(0,95)(1,117) m^{3}f/ha)(425 kg/m^{3}f)(20.52x10^{6} J/kg) J]= 15920 sej/J; then [(7.0x10^{6} m^{3}f fuel wood/yr, Table 11, page 56)(425 kg/m^{3}f)(20.52x10^{6} J/kg)(15920 sej/J)] / (1.45x10^{12} sej/USD) = 0.67x10^{9} em\$/yr
   - b. Sawn wood: [(4.5x10^{6} m^{3}f/yr, Table 11, page 56)(425 kg/m^{3}f)(20.52x10^{6} J/kg)(29886 sej/J; Figure 24, footnote a 1)] / (1.45x10^{12} sej/USD) = 0.81x10^{9} em\$/yr
   - c. Pulp and paper products: [(5.4x10^{6} m^{3}f/yr, Table 11)(425 kg/m^{3}f)(20.52x10^{6} J/kg)(129700 sej/J; weighted average)] / (1.45x10 sej/\$) = 4.25x10^{9} em\$/yr

   Total solar emergy basis for forest products used domestically = fuelwood + sawlogs + paper = (0.67x10^{9} + 0.81x10^{9} + 4.25x10^{9}) em\$/yr = 5.7 billion macro-economic em\$/yr
7. Products of forest export industry (items 54–58 from national analysis, Table 3, page 44) = roundwood + sawn wood + chem. pulp + mech. pulp + paper products = (2.05 + 19.44 + 49.16 + 20.11 + 157.59)x10^{20} sej = 248.3x10^{20} sej; (248.3x10^{20} sej) / (1.45x10^{12} sej/\$) = 17.1x10^{9} em\$/yr

Trade benefits from foreign sales of forest products

Of the 57 million cubic meters of forest material harvested in 1988, about 48% was processed and sold abroad (refer to Table 11). Total market revenues derived from export sales of these products was about 8 billion U.S. dollars (52x10^{9} SEK; Table 17), representing about five percent of the GNP in 1988. This study indicates about 75% of the solar emergy supporting Sweden's forest industry was sold as forest products in export markets. This translates into roughly 17 billion dollars in macro-economic value (250x10^{20} sej, Table 17), representing about 10% of the GNP in 1988 or twice the contribution accounted for by market revenues.

Market revenues received from the sale of forest products to purchasing nations is used by Sweden to purchase necessary fuels, goods and services that are not currently available within its borders. A solar emergy exchange ratio between those products sold and those received or purchased with incoming revenues was used to investigate foreign trade alternatives. Transactions with exchange ratios greater than one deliver a net contribution to the receiving country; those with exchange ratios less than one act to draw down a country's overall resource base, potentially diverting resources from other ecologic-economic sectors. Exchange ratios for 1) exported wood products (sawlogs, sawn wood and plyboard) and for 2) pulp and paper were evaluated in order to identify net benefits or losses based on purchases of (a) general goods and services and of (b) imported fuels with the revenue from sales (Figure 24).

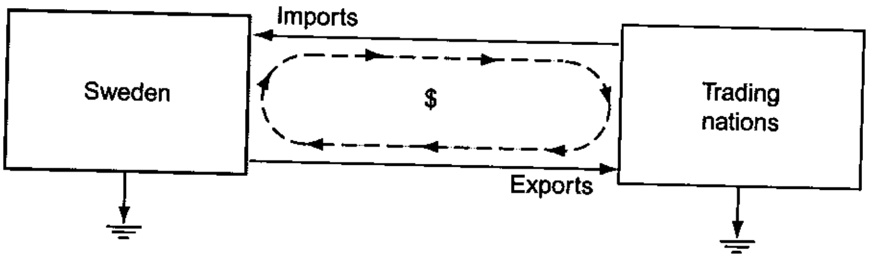
Table 17. *Quantity, market revenues and solar emergy of Sweden's forest export products, 1988.*

Export item	Quantity[1)] (million m³f or tons)	Revenues (billion, 1988)[1)] SEK	USD	Solar emergy[2)] (10^{20} sej)
Wood products				
Sawlogs, roundwood	0.73 m³f	0.32	0.05	2.05
Sawn wood	6.88 m³f	9.01	1.39	19.44
Plyboard[3)]	0.64 m³f	0.82	0.13	1.56
	8.25 m³f	10.15	1.56	23.05
Pulp and paper products				
Mechanical pulp	0.45 tons	1.20	0.19	20.11
Chemical pulp	2.73 tons	10.66	1.64	49.16
Paper products	6.38 tons	29.97	4.61	157.59
	9.56 tons	41.83	6.44	226.86
Total		51.98	8.00	249.91

[1)] Source: Sweden general trade statistics, 1989.

[2)] Items 54–58, Table 3, page 44; derivations given as footnotes.

[3)] Volume of exported plyboard estimated as (0.272×10^6 tons)(10^6 g/t)/(0.425×10^6 g/m³f) = 0.64 million m³f.



	solar emergy benefit ratio
wood products exported for goods and services	1.2
wood products exported for fuels	15.4
pulp and paper products exported for goods and services	0.6
pulp and paper products exported for fuels	6.4
all forest products exported for goods and services	0.6
all forest products exported for fuels	7.3

Figure 24. Perspectives on net solar emergy derived from international sales of forest products to a European market. The solar emergy delivered represents the forest product sold; the solar emergy received represents the potential contribution from the sale if the income received is used to purchase general goods and services from outside of Sweden. The net solar emergy benefit ratio is the solar emergy received divided by the solar emergy delivered. Calculations are based on 1988 export volumes and revenues summarized in Table 17.

Footnotes to Figure 24:

Calculation steps: Multiply microeconomic revenues, in USD, received for sale of wood product by solar emergy/\$ relation of trade partners (2.0E+12 sej/\$) to obtain the puchasing power of the product revenues in solar emergy terms by buying goods and services from outside. Then divide that value by the actual solar emergy input to produce the forest product to get the solar emergy benefit (or loss) due to that transaction.

a) *Net solar emergy benefit if revenues from export forest products were used to purchase goods and services from outside.*

1. Wood products (sawlogs, sawn wood and plyboard): Since forest industry products were not evaluated in this study, an estimate was made of the solar emergy in forest products by summing the solar emergy required to produce the wood resource and the emergy of the human services involved, estimated as the solar emergy supporting export sales. This is considered a low estimate, since only environment and services were included and not other inputs of machinery-use and fuel consumption.

Solar emjoules in exported wood products: nature's input per m^3f = (351.7×10^{12} sej/8.989 m^3f/ha/yr; Table 12, page 59) = 39.1×10^{12} sej/m^3f; (39.1×10^{12} sej/m^3f)(export vol.; 8.25×10^6 m^3f) = 3.23×10^{20} sej; human services = (1.56×10^9 \$/yr)(1.45×10^{12} sej/\$;) = 22.66×10^{20} sej/yr; nature's input + human services = (3.23 + 22.66)$\times 10^{20}$ sej = 25.9×10^{20} sej/yr

Exchange on European market = [(revenues)(trade partners's solar emergy/\$)]/(solar emergy of products sold) = (1.56×10^9 \$)(2.0E+12 sej/\$)/(25.9×10^{20} sej) = 1.21

The solar emergy/\$ relation for wood products is estimated as 25.9×10^{20} sej/1.56×10^9 \$ = 1.66×10^{12} sej/\$

A solar transformity for wood products (used in items 54 and 55, Table 3) is estimated as (25.9×10^{20} sej)/[8.25×10^6 m3f) (425 kg/m3f)(20.52×10^6 J/kg)] = 35996 sej/J

2. Pulp and paper products (solar emergy from subsystem analyses of pulp and paper industry, see Figures 21–23): exchange ratio on European market estimated as: [(6.44×10^9 \$/yr)(2.0×10^{12} sej/\$)]/(227×10^{20} sej/yr; sum of items 56+57+58, Table 3.) = 0.57

The solar emergy/\$ relation for paper products = 227×10^{20} sej/6.44×10^9 \$ = 3.53×10^{12} sej/\$

3. Avg. solar emergy benefit est. for all forest products = [8.00×10^9 \$/yr)(2.0×10^{12} sej/\$)]/(249.9×10^{20} sej/yr) = 0.64

b) *Net solar emergy benefit if revenues from export forest products were used to purchase fuels at present cost.*

An estimate of solar emergy delivered for each SEK spent on refined petroleum products (solar emergy/\$ relation for purchased fuels) based on 1988 fuel prices:

Solar emergy of fuel imports/cost of fuels = crude oil + refined petroleum = [(641×10^{15} J crude; item 26, Table 3)(53000 sej/J) + (356×10^{15} J petrol; item 27, Table 3)(66000 sej/J)] = 574×10^{20} sej; solar emergy/\$ relation for fuel estimated as (574×10^{20} sej)/(2.53×10^9 \$) = 22.7×10^{12} sej/\$; solar emergy benefit ratio for purchased fuels estimated as (22.7×10^{12} sej/\$)/(2.0E+12 sej/\$) = 11.4

1. Wood products: [(1.56×10^9 \$/yr)(22.7×10^{12} sej/\$)]/(23.1×10^{20} sej/yr) = 15.4
2. Pulp and paper products: [(6.44×10^9 \$/yr)(22.7×10^{12} sej/\$)]/(227×10^{20} sej/yr) = 6.4
3. Avg. solar emergy benefit estimated for all forest products: [(8.00×10^9 \$/yr)(22.7×10^{12} sej/\$)]/(249.9×10^{20} sej/yr) = 7.3

If Sweden purchased imported fuels with its earned revenues from forest export sales it would receive a potential net benefit ten times greater than it would by purchasing general goods and services from abroad (an exchange ratio of 7.3 for fuels compared with 0.6 for goods and services). Exported wood products in general appear to deliver a greater net contribution than sales of pulp and paper (15.4

compared with 6.4 if imported fuels were purchased and 1.2 compared with 0.6 if goods and services were purchased). These two general observations are explained by 1) more solar emergy received per dollar spent (solar emergy/$ cost ratio) for fossil fuels than received for general goods and services at 1988 market prices, and 2) a greater amount of solar emergy supporting paper industry products per dollar earned (solar emergy/$ revenue ratio) than forest industry products.

Fossil fuels are currently a better buy because they deliver a greater net contribution to the economy than goods and services. As previously discussed, this is because a greater portion of solar emergy in fossil fuels is a result of geologic and environmental work than that proportion supporting goods. These other commodities are upgraded through value-added economic transformations resulting ultimately with a smaller fraction of free "services" from the environment (their net yield ratios are lower). Similarly, pulp and paper products have higher solar transformities than forest industry products, with more of the needed resources supplied as transformed market goods, services and upgraded fuels (their net yield ratios are lower). With projected declining fossil carbon reserves in the future, alternate energy sources such as wood fuels will become more competitive as extraction and refinement costs increase for fossil fuels with decreasing qualities and supplies.

For this analysis, sej/$ indices were calculated for wood products, pulp and paper, fossil fuels, and general goods and services by dividing the solar emergy in the commodity by either its market revenues (for Sweden's forestry products) or its market cost (for imported fuels, goods and services) at 1988 prices (see footnotes to Figure 24). Purchased fuels were estimated to deliver 22.7×10^{12} sej/$ based on import quantities and market payments in 1988. Compared with an estimated sej/$ for goods and services in the European Community of 1.5×10^{12} sej/$, fuel purchases appear to contribute as much as 15 times the solar emergy than general goods and services from abroad.

An estimated sej/$ index for wood products of 1.7×10^{12} sej/$ compared with 3.5×10^{12} sej/$ for pulp and paper products suggests that a buyer would receive about twice as much solar emergy per unit cost if pulp and paper were purchased than if wood products were purchased. From Sweden's perspective, more solar emergy is delivered per unit sale of pulp and paper products with a correspondingly lower amount of revenues with which to purchase outside resources. This is reflected in an exchange ratio of less than one for pulp and paper sales and a positive net exchange ratio for less processed forest products. Pulp and paper in Sweden are high quality finished products as seen by their large solar transformities. This study indicates that pulp and paper sales are currently profitable due to inputs of hydropowered electricity and forest resources supported by environmental transformations of unmonied energy sources. Although greater net benefits are delivered from export sales of forest industry products over pulp and paper, Sweden may still benefit from pulp and paper sales if this service benefits the greater European Community and enables Sweden to purchase necessary goods, services or fuels that would otherwise not be available.

Summary and recommendations

In this section, we review the forestry sector analyses undertaken in this study. Comparisons are drawn between forest alternatives based on calculations of solar transformities, net yield and investment ratios. Net yield of forest products are related to forest turnover rates and harvest cycles. Current and potential roles of forests are discussed based on emergy contributions to national welfare.

Perspectives on forest production and industries in Sweden

Solar transformities calculated from this study (Table 18) reveal a range of solar emergy requirements per unit output for forest products through value-added processes of economic transformations. This hierarchy of product transformations ranges from about 5 000 sej/J for growing stocks of wood in the field to over 200 000 for pulp and paper products – as much as a 40 fold increase in resource-use. A solar transformity for a product or process reveals its position in an energy hierarchy such as Sweden's ecological-economic system (refer to Figure 4). The larger the transformity, the greater the quantity of resources required to develop the product. The higher the transformity, the larger the control action of the product. Therefore if Sweden invests large quantities of energy and human resources into its forest sector, the output delivered should be commensurate with the emergy of the sources consumed in production. Solar transformities give some measure of hierarchical position and thus proper use.

Products reinforce other parts of systems by interacting as transformation agents, amplifying lower level processes and transforming lower quality sources into useful products of value to the system. A general principle may be that more wealth is generated, increasing system performance, by production processes that join smaller quantities of high transformity goods and services with larger quantities of lower level components. This is conceptualized in Figure 4 as positive feedback reinforcing loops or control arms. It may also be true that high transformity products are mismatched when put in direct use with resources whose transformities are smaller by orders of magnitude. An example in Sweden may be the direct consumption of electricity for general heating. Design of district heating plants to utilize partially transformed wood products addresses this misuse of energy.

Solar transformities only indicate total system requirements of production but do not address origin of the sources. Tracking the resource requirements for production steps and calculating net yields and ratios of investment are useful for comparisons and identifying areas of possible improvement in transformation chains. In Table 19 resource requirements (sej/m^{3}f) for each process step in the development and combustion of wood powder are summarized. Production of wood powder (step F_6) is the most emergy intensive, requiring 38% of all purchased materials and 30% of all system requirements including environmental sources. Wood powder combustion in modified heating plants consumes 44x10^{12} sej/m^{3}f or 19% of all purchased inputs. Environmental sources, the free components supporting production, totalled

Table 18. *Summary of solar transformities of forest products calculated from this study and others for perspective.*

Forest product	Solar transformity (sej/J)	Reference to page number
Standing stemwood biomass, in forest:		
short rotation willow, controlled experiments	4790	Table 13, p. 66
spruce/pine, silviculturally grown	4870	Table 12, p. 58
spruce/pine, natural regeneration	5700	Figure 14, p. 58
short rotation willow, practical agriculture	7190	Page 68
spruce/pine, "old growth"	9490	Figure 14, p. 59
Harvested wood, delivered to road-side:		
short rotation willow, controlled experiments	6600	Table 13, p. 66
silvculturally managed spruce/pine	9500	Table 12, p. 58
short rotation willow, practical agriculture	9880	Page 68
Chipped wood:		
spruce/pine logging residues	14790	Table 14, p. 71
Charcoal [1]	18100	
Wood powder:		
from spruce/pine chips	27440	Table 14, p. 72
Sawn wood, plyboard [2]	36000	Figure 24, p. 93
High temperature heat:		
from spruce/pine wood chips	33660	Table 15, p. 76
from spruce/pine wood powder	40020	Table 14, p. 72
Chemical pulp	85500	Figure 21, p. 83
Mechanically usable heat:		
from wood chips	86310	Table 15, p. 76
from wood powder	98830	Table 14, p. 72
Paper products	112850	Figure 23, p. 88
Electricity generated from wood [3]	200000	
Mechanical pulp	206310	Figure 22, p. 86

[1] from analysis of 18th Century charcoal production in Sweden (Sundberg *et al.* 1991).

[2] estimated using environmental contribution plus human services (calculated in proportion to sales), refer to Figure 24–1a for details.

[3] from analysis of wood generator plant in Jari, Brazil (Odum *et al.* 1986; updated in Odum 1996).

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Table 19. *Summary of resource requirements for each process step in the development and combustion of wood powder in Sweden, under current management practices: (a) purchased solar emergy per wood yield (sej/m³f), (b) percent of total purchased solar emergy used in each production step, and (c) percent of total solar emergy required for each production step.*

Process step (F_i)		Quantity of F [1] (10^{12} sej/m³f)	% F-total (F_i/F_{tot})	% total yield (F_i/Y)
I	environment	–	–	20
F_1	silviculture	5.0	2	2
F_2	harvest	28.9	12	10
F_3	field transport	19.9	9	7
F_4	chipping	24.5	11	8
F_5	transport to plant	10.4	5	4
F_6	powder production	88.7	38	30
F_7	transport to heating facility	10.4	4	4
F_8	combustion	44.4	19	15
			100% F	100% Y

Total solar emergy purchased (F_{total}): 232×10^{12} sej/m³f

Total solar emergy contribution
($Y_{total} = I_{total} + F_{total}$): 291×10^{12} sej/m³f

[1] Calculations based on solar emergy required for wood volume delivered from each production step for average annual production, beginning with 9 m³f net forest production to 6.7 m³f harvested, finally to 1 m³f wood powder combustion (refer to Tables 12 and 14).

20% of all required inputs; almost 80% of the sources used in the development of wood powder fuels is drawn from the greater economy. These figures help to illuminate areas of high production costs.

In Table 20, net yields and investment ratios are compared between product transformations of spruce/pine and willow. Net yield ratios approach 1.0 for district heat produced from both forest wood and short rotation willow, indicating that these alternate sources cannot at this time replace existing fossil fuels which yield between 3 and 6 times more emergy due to past contributions of environmental and geologic work. The investment ratio indicates which of these alternatives are more competitive as heating fuels. Harvested willow, because of intensive management, requires investments five times that of spruce/pine. This results in an investment ratio of purchased to environmental resources of almost 20 to 1 for heat derived from willow cuttings compared with a 4 to 1 ratio for silvicultured and processed spruce/pine. These measurements are revealed in a net solar emergy yield from forest wood of 52×10^{12} sej/m³f compared with 12×10^{12} sej/m³f for wood delivered from energy forestry.

Table 20. *Summary of solar transformities, net yield ratio, investment ratio, and net solar emergy for wood products calculated from this study, with estimates for wood chips, powder and combustion heat produced from short-rotation willow*[1].

Wood product	Solar transformity sej/J	Net yield ratio[2] Y_i/F_i	Investment ratio[3] F_i/I_i
Standing stemwood biomass:			
spruce/pine forest stand	4 870	12.6	0.1
short rotation willow	4 790	1.5	2.1
Harvested wood:			
spruce/pine	9 500	3.2	0.5
short rotation willow	6 720	1.3	3.0
Chipped wood:			
spruce/pine chips	14 790	1.7	1.3
willow chips	11 740	1.2	6.4
Wood powder:			
spruce/pine powder	27 440	1.4	2.8
willow powder	24 050	1.1	14.2
Combustion heat:			
from spruce/pine chips	33 660	1.3	2.9
from willow chips	23 420	1.1	13.8
from spruce/pine powder	40 020	1.3	3.6
from willow powder	31 290	1.0	18.8

Net solar emergy[4] $[(Y_i - F_i)/m^3f]$:

spruce/pine wood:	52.5×10^{12} sej/m^{3}f
short rotation willow:	12.0×10^{12} sej/m^{3}f

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[1] Solar transformities for spruce/pine products from Tables 12,14, and 15. Willow transformities are from Table 13 for standing crop Y_1 and harvested wood Y_2. Chipped willow Y_3, willow powder Y_4 and combustion heat Y_5 were estimated using input requirements for 1 m^{3}f of spruce/pine for each production step (F_3-F_8) from Table 19. The solar emergy values were then divided by the available energy in 1 m^{3}f of willow $[(0.394\ t/m^3f)(1.95\times10^{10}\ J/t) = 7.68\times10^9\ J/m^3f]$.

Net yield and investment ratios for willow chips, powder and combustion were calculated similarly, using input requirements for spruce/pine chip and powder production and combusiton.

[2] Total contribution (Y_i) divided by purchased,upgraded sources (F_i) for each management system and production step.

[3] Purchased sources (F_i) divided by free, environmental contributions (I).

[4] Free environmental contribution per solid cubic meter wood produced:
for spruce/pine: $(351.1\times10^{12}$ sej/ha/yr$)/(6.704$ m^{3}f/ha/yr harvested)
for willow: $(351.7\times10^{12}$ sej/ha/yr$)/(29.2$ m^{3}f/ha/yr harvested)

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Forest rotation and net contribution

There is a relationship between net yield and forest turnover time or plantation cycle as evident from the analyses undertaken in this study. Figure 25 shows the resources required for production and harvest of one solid cubic meter of fuelwood under three management systems in Southern Sweden. These three systems are all based on analyses documented in this report (natural forest regeneration, silviculturally managed spruce/pine stands, and short rotation energy forests). Forest rotations under natural self-thinning growth (Figure 25a) has the highest net return and the lowest investments since no stand management is required during the growth cycle. Solar transformities for standing crop and harvested wood are lowest for intensively managed willow, yet the net yields are low because most of what is required are subsidies from the economy which increases investments. From these summaries and comparisons, it is evident that knowledge of both solar transformities and indices of net yield and investment are necessary to draw inferences on public utility and contributions to public welfare.

Another way of understanding the role of management on forest cycling time is to compare theoretical delivery rates of forest products under different management systems (Table 21). In this example the required delivery time, measured in equivalent years, to produce 425 m^3f of wood was estimated for each system based on average annual production. Because these mean rates of net production are not representative of all forest development years (early years after clearing have slower production; later years approach zero net production) the estimates of delivery time are faster than real time conditions. The comparisons between management systems are useful parameters relating cycling time and management subsidies. There is an intuitive and inverse relationship between management intensity and delivery rate; the greater the input of societal-based resources affecting production, the lower

Table 21. *Overview perspectives on delivery rates and management requirements for production and delivery of fuelwood under three managed agro-ecosystems in Southern Sweden.*

Agro-ecosystem	Delivery rate [1] (equivalent years)	% Societal-based contribution [2]	% Environmental-based contribution [3]
Natural forest regeneration [4]	80 years	28 %	72 %
Silviculturally managed forest stand [5]	48 years	38 %	62 %
Short-rotation energy forest [6]	15 years	75 %	25 %

[1] The estimated number of years necessary to produce standing crop biomass of 425 m^3f/ha (average, steady state forest volume in Southern Sweden).

[2] $(F_1+F_2)/Y_2$ for respective agro-forest system

[3] I/Y_2 for respective agro-forest system

[4] refer to Figure 14 (page 58); equivalent years = (425 m^3f/ha)/(5.3 m^3f/ha/yr).

[5] refer to Table 12 (page 58); equivalent years = (425 m^3f/ha)/(9 m^3f/ha/yr).

[6] refer to Table 13 (page 66); equivalent years = (425 m^3f/ha)/(28 m^3f/ha/yr).

the cycling time (the faster the delivery rate). In this example, short rotation forest applications deliver equivalent volumes of wood in one-third of the time of spruce/pine stands, requiring almost two times as much input from outside.

From these examples, general principles of forest management are drawn. Sustainable, long-run natural forest systems which rely on renewable energies form

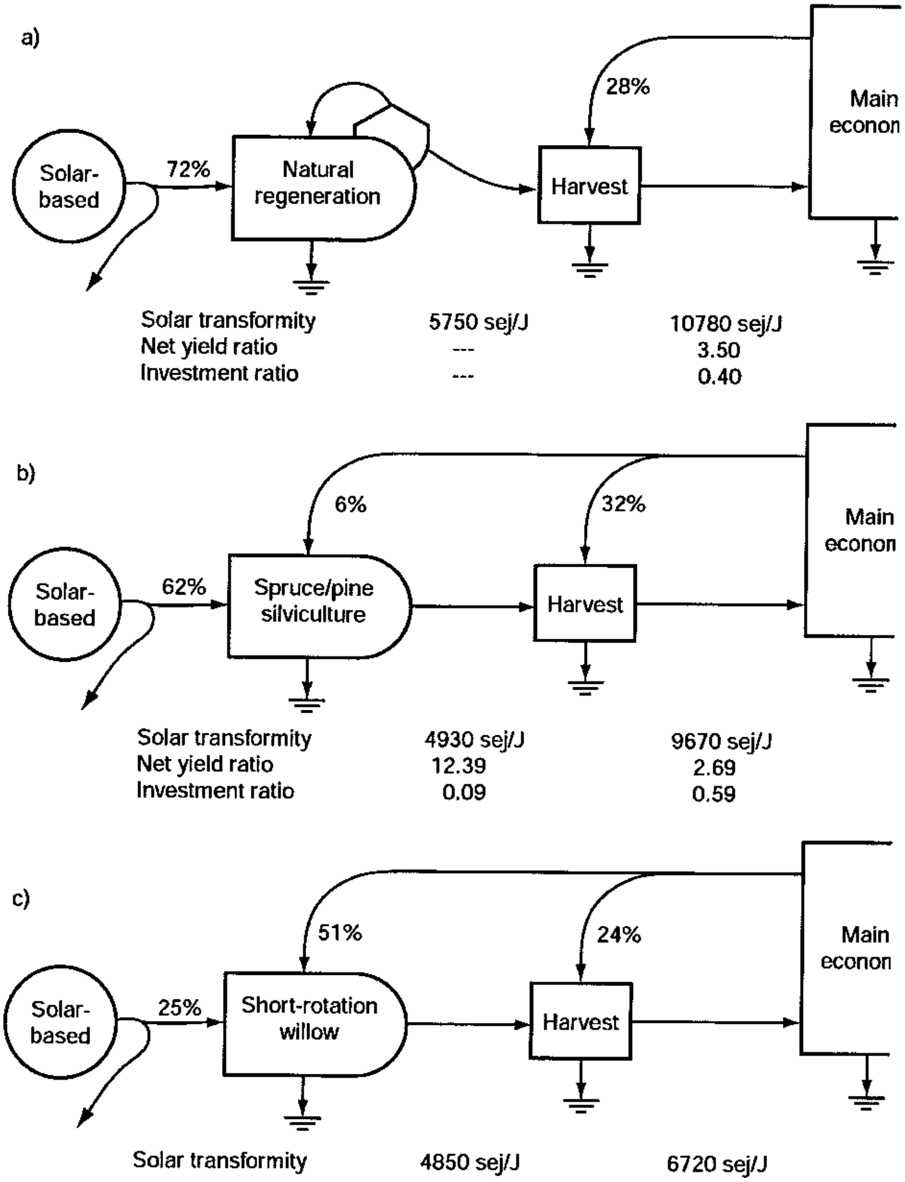

Figure 25. Solar emergy requirements for production of one solid cubic meter (m^3f) of fuelwood under three forest management systems in Southern Sweden: (a) natural forest regeneration; (b) silviculturally managed spruce/pine forest stands; and (c) short rotation energy forestry. Inputs are given as percentages of total production requirements; see Figure 14 (page 58) and Tables 12 (page 58) and 13 (page 66) for actual data.

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the environment often exhibit greater gross production than managed plantations, yet generally have smaller net yields. This is in part because more of their production is re-invested to design and maintain diverse structure and cooperative pathways. In plantations, feedbacks in the form of fossil fuels, irrigation, pest management, planting and thinning direct more of the gross production into extractable biomass producing greater yields per unit time. Although managed forest systems may increase delivery rates (*i.e.* shorten rotations or turnover times), because of large investment requirements, these systems often deliver little "net" contribution to the larger ecological-economic system of which they are a part. Thus, there is a general relationship between turnover time and net solar emergy yield.

Current and potential roles of forests in Sweden

By calculating forest production and current industry use on an equivalent basis of solar emergy, overview perspectives on the role of forests in Sweden are considered (Table 22). Based on evapo-transpired rainfall on forested lands in Sweden, forests annually contribute more than 4 billion dollars in macro-economic value to the nations welfare, about 3.2% of the total emergy used annually (item 1). This contribution is based only on forest net growth, not yet considering the multiple roles of forest products and services beyond production. Harvested wood under current management schedules contributes another 2.4 billion emergy-based dollars and could be increased to over 3 billion dollars under whole tree utilization programs (item 2).

Based on current estimates of heating needs (200 TWh/yr), 83 million cubic meters of fuel wood would be required if domestic heating plants were converted for fuelwood combustion. This translates into 68×10^{20} sej/yr from forests or 2.7% of the nation's annual emergy-use. Total standing stock of forests in Sweden, estimated at 2.7 billion m^3sk, have a value of 112 billion macro economic $ (item 3) – almost 75% of the gross economic product in 1988 and over 86% of the annual emergy-use in the country. If agricultural lands were converted to forest production and additional 5.2 billion dollars would be generated.

The role of forests includes the attracted investments in related industries that are developed as a function of forest production and utilization. By multiplying current and projected forest emergy uses by the regional investment ratio of 4.65 (refer to Table 5), gross estimates of actual forest contributions are obtained (items 7 and 8, Table 22). Harvested forest products, by attracting on a national average 4.65 units of emergy for every one unit produced, generate as much 8.5% of the annual emergy-use. Total forest production on 23.6 million hectares generate 19.4 billion dollars – about 15% of the national emergy budget, making forests and their attracted investments worth 10% of Sweden's gross economic product in 1988. These perspectives illustrate the important contributions of forests to Sweden's welfare and the increased roles of forest industries in its ecological-economic system.

Table 22. *Overview perspectives for forests in Sweden; their current and potential roles based on forest solar emergy contributions to the national economy.*

Footnote	Item	Solar emergy (10^{20} sej/yr)	Percent of national solar emergy budget[1]	Macro-economic value[2] (billion USD)
1	Solar emergy contribution of forested lands	83	3.2	4.2
2	Contribution of harvested wood			
	a. Current schedule	47	1.8	2.4
	b. Natural regeneration	106	4.1	5.3
	c. Sustainable, whole tree utilization	63	2.5	3.2
3	Heating potential			
	a. Sustainable (before processing)	22	–	–
	b. “Mined”	2237	86.7	111.9
4	Wood required to meet national annual heating needs (200 TWh)	68	2.7	3.4
5	a. National solar emergy base (U)	2580	–	129.0
	b. Renewable solar emergy base (R)	456	17.7	22.8
6	Solar emergy contribution if agricultural lands were put into forest production	104	4.0	5.2
7	Contribution of harvested forest wood plus its attracted investments[3]			
	a. Current harvest schedule	220	8.5	11.0
	b. Sustainable, managed harvest	295	11.4	14.7
8	Contribution from annual forest production plus attracted investments			
	a. 23.6 million hectares of forested land	387	15.0	19.4
	b. forested lands plus agricultural lands	485	18.8	24.2

[1] Solar emergy divided by national solar emergy base (item 5a), given as percentage.

[2] Solar emergy divided by the relation of solar emergy/GNP for U.S.A., 1988 $(2.0\times10^{12}\ \text{sej}/\$)$.

[3] Attracted investments are those purchased inputs which may amplify a typical production sector. It is derived using the average investment ratio calculated for the region (4.4:1 for Sweden; Table 5, item 8).

Footnotes to Table 22:

1. Solar emergy contribution of forested lands.
   a. Calculated using transpired rainfall over forested lands: (0.8 m rain/yr)(49% evapotranspired)(23.6×10^6 ha forested land)(10000 m^2/ha)(1000 kg/m^3)(4940 J/kg) = 4.57×10^{17} J/yr; (4.57×10^{17} J/yr)(18200 sej/J) = 83.2×10^{20} sej/yr
   b. Calculated using avg. annual growth per hectare (8.989 m^3f/ha/yr) and the solar transformity for forest growth (4873 sej/J, Figure 16): (8.989 m^3f/ha/yr)(23.6×10^6 ha)(0.425×10^6 g/m^3f)(2.052×10^4 J/g) = 1.85×10^{18} J/yr; (1.85×10^{18} J/yr)(4873 sej/J) = 90.2×10^{20} sej/yr
   Solar emergy calculated using work of transpiration (a) is used here since the estimate of annual growth of 8.989 m^3f/ha/yr used in calculation (b) is for southern Sweden and considered high for the country.

Footnotes to Table 22, continued.

2. Wood harvest.
    a. Current cutting levels: 47×10^{20} sej/yr (see item 3, Table 16)
    b. Sustainable harvest based on natural regeneration [using solar transformity for harvested, unsilvicultured wood = (nature's input 352×10^{12} sej/ha/yr + harvest requirements 173×10^{12} sej/ha/yr) / 7.84×10^{10} J/ha/yr = 6 700 sej/J]: (838 m^3f/ha of mature forest) / (109 yrs regeneration time) = 7.69 m^3f/ha/yr; (7.69 m^3f/ha/yr)(0.425×10^6 g/m^3)(2.052×10^4 J/g)(6 700 sej/J) = 449×10^{12} sej/ha/yr; (449×10^{12} sej/ha/yr)(23.6×10^6 ha forested land) = 106×10^{20} sej/yr
    c. Sustainable harvest based on silvicultural management: (8.989 m^3f/ha/yr)/(6.704 m^3/ha/yr current cutting level) = 134% of present cutting level, then: (1.34)(47.2×10^{20} sej/yr) = 63.3×10^{20} sej/yr
3. Heating potential (based on solar emergy value of wood before processing):
    a. sustainable: (352×10^{12} sej/ha)/(9 m^3f/ha)(57×10^6 m^3f harvested, 1988) = 22.3×10^{20} sej
    b. 100% clear cut ("forest mining"): (2.7×10^9 m^3f standing forest biomass)(8.72×10^9 J/m^3f)(9 500 sej/J) = $2\,237 \times 10^{20}$ sej
4. National heating needs (200 TWh/yr); (200×10^9 kWh/yr)(3.6×10^6 J/kWh) = 7.2×10^{17} J fuel wood required annually; (7.2×10^{17} J/yr)(9 500 sej/J; Table 14) = 68.4×10^{20} sej/yr (before processing)
5. a. National solar emergy base for Sweden (see summary of national analysis; Table 5): $U = R + N_1 + F + G + P_2I$ = $2\,580 \times 10^{20}$ sej/yr
    b. Renewable solar emergy base (Table 4): R = 456×10^{20} sej/yr
6. Solar emergy contribution of forests if agricultural lands were converted to forest: agricultural lands in Sweden, 6.0×10^6 ha + forested lands, 23.6×10^6 ha = 29.6×10^6 ha; (351.7×10^{12} sej/ha/yr forest contribution)(29.6×10^6 ha) = 104×10^{20} sej/yr
7. Contribution of harvested forest wood to national emergy basis including contribution due to attracted investments (using regional investment ratio for Sweden of 4.65; item 8, Table 5)
    a. Current: 47.2×10^{20} sej/yr wood harvested (item 3, Table 16); (47.2×10^{20} sej/yr)(4.65) = 220×10^{20} sej/yr
    b. Sustainable: 63.3×10^{20} sej/yr [item 2(c), above]; (63.3×10^{20} sej/yr)(4.65) = 295×10^{20} sej/yr
8. Contribution of annual forest production plus attracted investments:
    a. item 1 above: (83×10^{20} sej/yr)(4.65) = 387×10^{20} sej/yr
    b. item 6 above: (104×10^{20} sej/yr)(4.65) = 485×10^{20} sej/yr

References

Alsefelt, P. 1989. *Energi från skogsindustrin.* STU-info 730-1989. Styrelsen för Teknisk Utveckling. Stockholm.

Cook, E. F. 1976. *Man, energy, society.* Freeman, San Francisco. 478 pp.

Costanza, R. 1980. Embodied energy and economic valuation. *Science 210: 1219-1224.*

Danielsson, B.-O., Eriksson, H., Eriksson, M., Lundström, A., Lönner, G., Lönnstedt, L., Nilsson, P. O., Nyström, K., Rosén, K., Söderberg, U. and Törnqvist, A. 1990. *Inventeringsstudie biobränslepotential i södra Sverige. English summary: Inventory of the biofuel potential in southern Sweden.* Vattenfall, Projekt Bioenergi, Report 1990/40, Stockholm. 148 pp.

Diamond, C. 1987. *Energy basis for the regional organization of the Mississippi River Basin.* M.S. Thesis, University of Florida, Gainesville. 136 pp.

Doherty, S. J. and Brown, M. T. (eds.). 1991. *Emergy synthesis perspectives, sustainable development, and public policy options for Papua New Guinea.* Final Report to The Cousteau Society. Center for Wetlands, University of Florida, Gainesville. CFW #93-06.

Eriksson, B. and Odin, H. 1990. Climate. In: Nilsson, N-E (ed.) *The forests: National Atlas of Sweden.* The National Board of Forestry, SNA. ISBN 91-87760-06-1. pp. 34-37.

Hall, C. A. S., Cleveland, C.J. and Kaufmann, R. 1986. *Energy and resource quality: the ecology of the economic process.* John Wiley & Sons, Inc., New York. 577 pp.

Hammer, M. 1991. Sweden's herring fisheries: A comparison between coastal, offshore and industrial fisheries. In: Nilsson, P. O. and Doherty, S. J. (eds.). *Emergy analysis: A biophysical bridging between the economies of humanity and nature.* Working paper, Department of Bioenergy, Swedish Univ. of Agric. Sci., Uppsala.

Hannon, B., Casler, S. D. and Blazeck, T. S. 1985. *Energy intensities for the U.S. economy - 1977.* Campaign, IL. 166 pp.

Huang, S.-L. and Odum, H. T. 1991. Ecology and economy: Emergy synthesis and public policy in Taiwan. *Journal of Environmental Management 32: 313-333.*

Jansson, A-M and Zuchetto, J. 1978. *Energy, economic and ecological relationships for Gotland, Sweden – a regional systems study.* Ecological Bull. no. 28, Natural Science Research Council, Stockholm, Sweden. 154 pp.

Kempe, G. and von Segebaden, G. 1990. What do forests look like? In: Nilsson, N.-E. (ed.) *The forests: National Atlas of Sweden.* The National Board of Forestry, SNA, Italy. ISBN 91-87760-06-1. pp. 56-69.

Kinsman 1965. *Wind, waves, their generation and propagation on the ocean surface.* Prentice-Hall, Englewood Cliffs, N.J. 676 pp.

Lapp, C.W. 1991. *Emergy analysis of the nuclear power system in the United States.* Masters project, University of Florida, Gainesville. 64 pp.

Lotka, A.J. 1925. *Elements of physical biology.* Williams and Wilkins, Baltimore. 460 pp.

Marks, J. 1990. *Wood powder: an upgraded wood fuel.* The Swedish Univ. of Agricultural Sciences, Research Notes no. 182 (ISBN 91-576-4214-1). Garpenberg, Sweden. 28 pp.

McClanahan, T. and Brown, M. T. 1990. *Emergy evaluation of Thailand.* Report to The Cousteau Society. Center for Wetlands publ., Univ. of Florida, Gainesville.

Miller, G. A. 1966. The flux of tidal energy out of the deeep oceans. *J. Geophys. Res. 71:2485-2489.*

Monin, A.S. 1972. *Weather forecasting as a problem in Physics.* MIT Press, Cambridge, Mass.

Munk, W. H. and MacDonald, G. F. 1960. *The rotation of the earth: A geophysical discussion.* Cambridge Univ. Press, London, UK. 323 pp.

Nilsson, N.-E. (ed.). 1990. *The forests: National Atlas of Sweden.* The National Board of Forestry, SNA, Italy. ISBN 91-87760-06-1. 144 pp.

Odum, H. T. 1971. *Environment, power and society.* John Wiley & Sons, Inc., NY.

Odum, H. T. 1983. *Systems ecology: An introduction.* John Wiley & Sons, Inc., NY. 644 pp.

Odum, H. T. 1988. Self-organization, transformity, and information. Science. 242: 1132-1139.

Odum, H. T. 1996. Environmental accounting. Emergy and environmental decision making. John Wiley & Sons, Inc., NY.

Odum, H. T. and Arding, J. E. 1991. *Emergy analysis of shrimp mariculture in Ecuador.* Working Paper. Coastal Resources Center, University of Rhode Island, Narragansett, R.I. 114 pp.

Odum, H. T., Brown, M. T. and Christianson, R.A. 1986. *Energy systems overview of the Amazon Basin.* Report to The Cousteau Society. Center for Wetlands publ. #86-1, Univ. of Florida, Gainesville. 190 pp.

Odum, H. T. and Odum, E. C. 1983. *Energy analysis overview of nations.* International Institute for Applied Systems Analysis WP-83-82, Laxenburg, Austria. 366 pp.

Odum, H. T., Odum, E. C. and Blissett, M. 1987. *Ecology and economy: emergy analysis and public policy in Texas.* Lyndon B. Johnson School of Public Affairs Policy Research Project Report #78. Office of Natural Resources and Texas Dept. of Agriculture. 178 pp.

Rybchikov, A. 1975. *The Changing Face of the Earth.* Progress Publishers, Moscow. 203 pp. (in English)

Sclater, J. F., Taupart, G. and Galson, I. D. 1980. The heat flow through the oceanic and continental crust and the heat loss of the earth. *Review of Geophysics and Space Physics. 18: 269-311.*

Sennerby-Forsse, L. 1986. *Handbook of energy forestry.* Dept. of Ecology and Environmental Research, Swedish Univ. of Agr. Sci. ISBN 91-576-2677-4. Uppsala, Sweden. 29 pp.

Skogsstyrelsen. 1987. *Swedish forest: facts about Swedish forestry and wood industries.* Bernadotte, B. and Gustafsson, U. (eds.). National Board of Forestry, Jönköping, Sweden. 111 pp.

Slesser 1978. *Energy in the economy.* St. Martin's Press, New York. 164 pp.

Sundberg, U. 1991. *An energy analysis of the production at the Great Copper Mountain of Falun during the mid 17th century.* J. Forest Eng. 3(1) (supplement).

Sundberg, U., Odum, H. T. and Doherty, S. J. 1991. *18th century charcoal production.* Swedish Univ. of Agr. Sci., Research Notes no. 212. Garpenberg, Sweden. 10 pp.

Sweden General Trade Statistics. 1989.

Swedish Power Association. 1981. *Hydro-power in Sweden.* Vattenfall, Stockholm. 143 pp.

Todd, E. K. 1970. *The Water Encyclopedia.* 2nd ed. Lewis Publ. Chelsea, Michigan.

Wulff, F, Rahm, L. and Laarsson, P. (eds.). 2001. *A Systems Analysis of the Baltic Sea.* Springer-verlag. NY. 455 pp.

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[1] Professor Emeritus Ulf Sundberg was a very valuable advisor to the bioenergy group for many years. He sadly passed away on 6 October 1997.

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Figure A.
Major urban areas. Sweden is the fifth largest country in Europe and the fiftieth in the world in terms of suface area, but it has only 9 million inhabitants (8.5 million in 1988). Two thirds of the people live in the southern third of the elongated country (1,574 km from north to south).

Figure B.
District heating facilities.

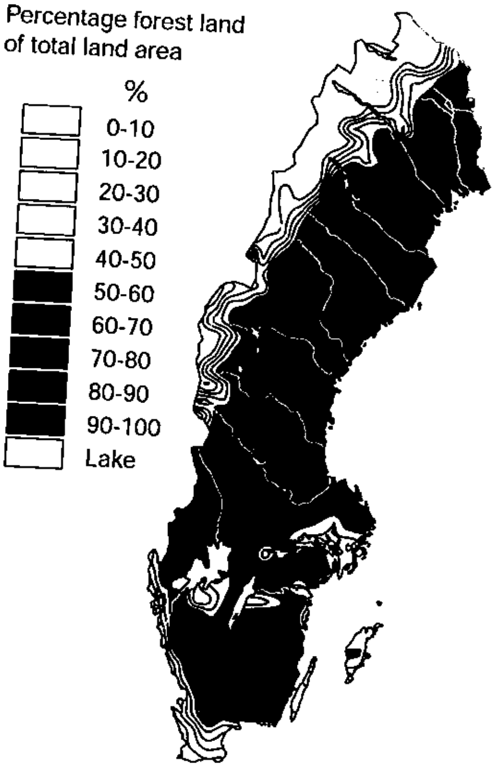

Figure C.
Forest areas, about 28 million ha of which 23 million ha are considered productive and object for economic use.

Figure D.
Growing forest stock. One quarter of the stock stands in the southern fifth of the country. Due to climatic preconditions the forest production capacity per hectare in this part is twice as high as in the rest of the country.

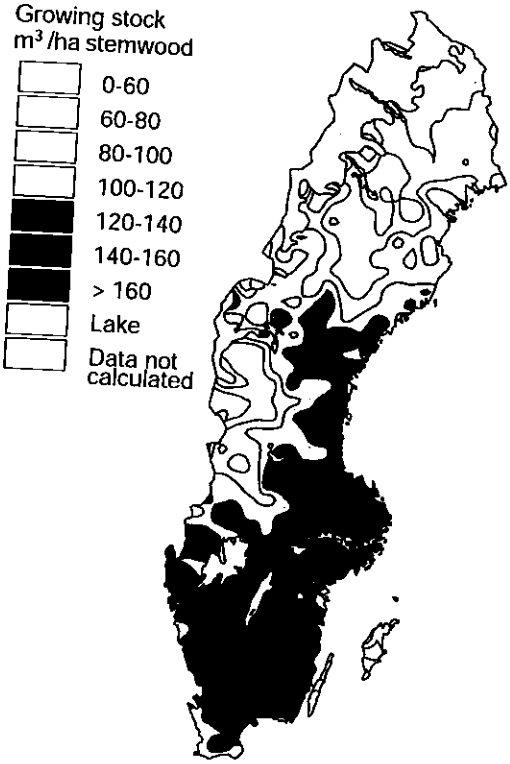

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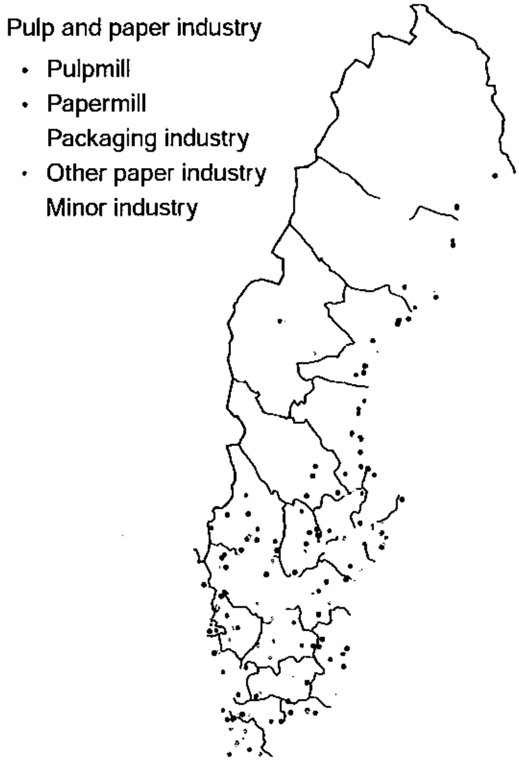
Figure E.
Location of saw milling industry.

Figure F.
Location of pulp and paper mills.



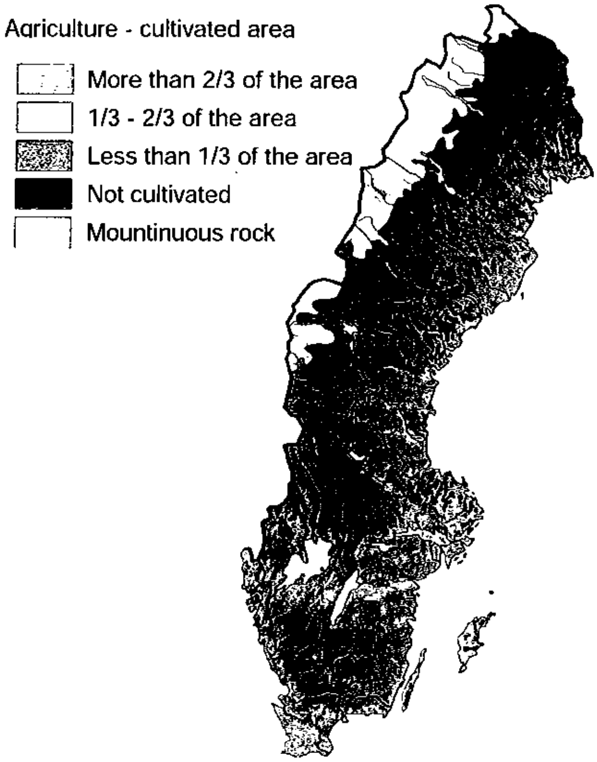


Figure G
Agricultural lands, about 3 million ha, mainly located in the southern part of the country.

Figure H.
Mining centers.

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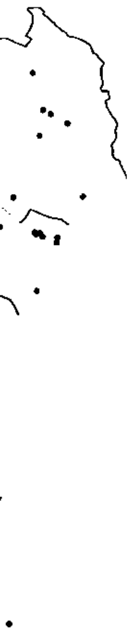

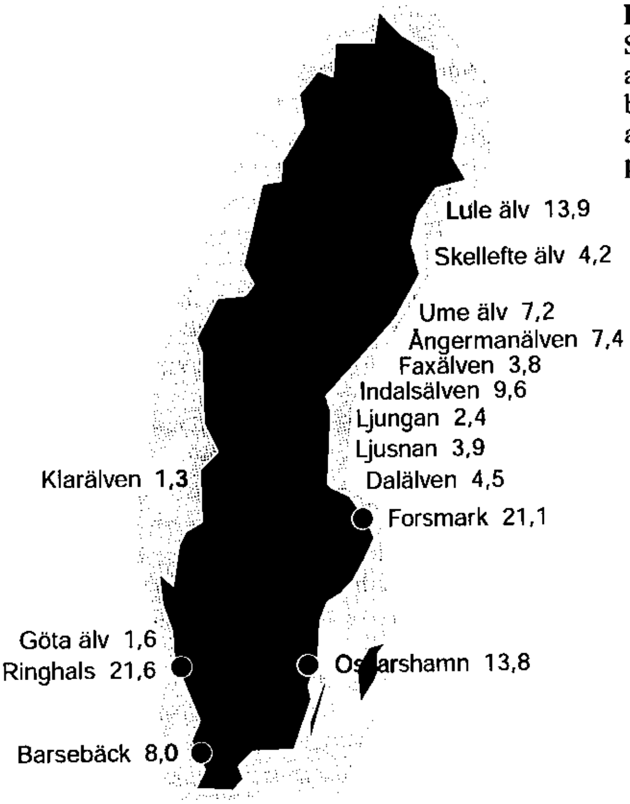

Figure I.
Sweden's hydroelectric rivers and nuclear power plants in the beginning of the 1990s. Numbers are showing average electricity production in TWh/year.

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25. Solar emergy requirements for production of one solid cubic meter (m^{3}f) of fuelwood under three forest management systems in Southern Sweden: (a) natural forest regeneration; (b) silviculturally managed spruce/pine forest, (c) short-rotation willow cultivation.

Appendix A. Maps showing an overview of Swden's (A) main urban centers; (B) district heating plants; (C–D) main forest areas; (E–F) forest industries; (G) agricultural lands; (H) mining centers; and (I) hydroelectric rivers and nuclear power plants.

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