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Journal of Cleaner Production 7 (1999) 421–434

Journal of Cleaner Production

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# Improving agricultural sustainability: the case of Swedish greenhouse tomatoes

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Received 11 May 1999; received in revised form 24 June 1999; accepted 25 June 1999

**Abstract**

Of major concern to agriculturists and society are issues of sustainability and land and resource requirements for food and fiber. Sustainability of Swedish domestic agriculture is explored using the production of tomatoes in greenhouses as a case study. Issues of sustainability are related to net yields, environmental loading, greenhouse gases, employment and land use. A model for evaluation of sustainability is developed and illustrated using the concepts and theories of EMERGY analysis. The intensive tomato production system investigated was shown to be highly dependent on non-renewable resources and human service fed back from society. Substituting wood powder from logging residues for the oil used for heating reduced the environmental load and improved the sustainability of the system significantly. © 1999 Elsevier Science Ltd. All rights reserved.

*Keywords:* EMERGY; Energy; Environmental load; Resource use; Sustainability; Wood powder

## 1. Introduction

Sustainability is an elusive concept. The broadest definition and the one most often quoted is from the Brundtland report [1] as follows: “Sustainable development is a new form of development which integrates the production process with resource conservation and environmental enhancement. It should meet the needs of the present without compromising our ability to meet those of the future.”. This paper suggests that the sustainability of agriculture is related to the net yield (higher the better), i.e. the net output of the system under consideration, and its load on the environment (lower the better). It also relates agricultural production to energy and resources as well as to requirements for environmental and human services.

Quantitatively evaluating these flows based on production cycles within the same analysis for comparative purposes requires that they be in common units. It is not possible to compare hours of human service to gallons of fuel for instance unless they are given values within the same reference system. Money has been used in the past, but price has significant problems where no markets exist, not to mention that it is a strongly egocentric concept of value.

During recent years different kinds of energy analysis have been employed to address resource use in processes. Exergy analysis [2] is suitable for optimizing transfer of mechanical work in technical processes. Input–output analysis [3] assigns energy values of fossil fuels and electricity to sectors of society in accordance with its monetary flows. Cleveland [4] presents another method using monetary costs to address use of fossil fuels and electricity in American agriculture. The most common energy analysis used is the technique of energy analysis according to the process method. With this method the direct and indirect use of fossil fuels by all inputs to processes are summed. Several researchers have used process analysis to analyse agricultural crops. Stanhill [5] compared direct and indirect fuel inputs of six tomato production systems. Similar analyses were performed by Pimentel and Pimentel [6] who calculated the fuel energy inputs to a number of crops. Jolliet [7] estimated the energy inputs and pollution of tomato production in Switzerland. The energy requirements of a large number of agricultural and horticultural crops were

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PII: S0959-6526(99)00230-9

investigated by Fluck et al. [8]. Reist and Gysi [9] estimated the energy inputs and pollution from soilless tomato cropping in the greenhouse and field production in several European countries whereas Nienhius and de Vreede [10] performed life cycle assessments of Dutch tomato production.

Most investigations employing the process analysis approach do not account for energy flows other than those of fossil fuels. Although life cycle assessment estimates the depletion of material storages and pollution from mining and other human activities, few investigations assess the wider environmental support to the system under investigation. In addition, the problem of how to handle energy inputs from human labor, i.e. services from the human economy, remains unsolved within the process analysis.

EMERGY [11–13] is a scientifically based measurement of the accumulated energy inputs required to produce a product or service, calculated on a common basis of solar energy. Its unit is solar emergy joule (sej). By expressing the energies previously required to generate a product or service in a common unit, EMERGY analysis offers possibilities to compare systems in a straightforward way. The method embraces environmental inputs as well as inputs from the human economy. It also assigns EMERGY values to human labor, i.e. services. Weighting of the inputs to a process is based on the amount of resources that it took to make them, for instance a coal joule is given an EMERGY value of 43 000 sej/J whereas the EMERGY value of diesel fuel is 71 000 sej/J (including human service, calculated from Odum [13]).

The EMERGY analysis may be used in order to investigate the resource basis and policy alternatives for single processes as well as for regional or countries' economies. [13,14]

This present study presents an EMERGY analysis of a Swedish conventional tomato production system, exploring the environmental load and sustainability of the system. In an attempt to enhance the sustainability performance of the system, wood powder from logging residue (branches, needles and cones) considered renewable was substituted for fossil fuel used in heating the greenhouse facility.

## 2. Methodology

### 2.1. The tomato production system

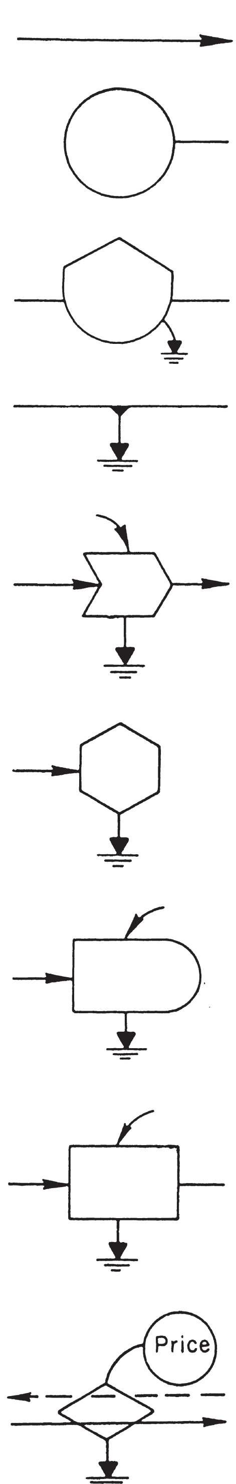
The tomato system was designed to represent a real conventional well managed production system. Since the domestic tomato producing sector of Sweden is very heterogeneous, the system was chosen to operate at harvest level above the country's average although not belonging to the best performing companies. The company was placed in the South of Sweden, which is the country's major tomato producing region, within 50 km distance from the city of Malmö in the southwestern part of the region. As Swedish tomatoes are produced in heated greenhouses and the dominant system is a soilless system with rockwool substrate, this system was chosen for the study.

The system constituted a fairly new (less than five years old) 9000 $m^2$ Venlo type greenhouse of glass, of which 8000 $m^2$ was plant area. An area of 4500 $m^2$ grounds outside the greenhouse, of which 1000 $m^2$ were covered with macadam (crushed stone) and 3500 $m^2$ was grassy ground, also belonged to the facility. Materials, energies and services within this boundary were included in the system. Consequently, the resulting analysis was an analysis of a company totally specialized in tomato production, which is usually the case among the conventional growers at this harvest level, rather than of a single subsystem of a company. To facilitate future comparisons with other growing systems and companies, transportation of the produce to retail was not considered in the evaluation.

In keeping with industry norms, the greenhouse was considered to be heated with oil and propane and artificial light from high pressure sodium lamps was used in seedling production. The propane also supplied carbon dioxide ($CO_2$) to the tomato crop. In these greenhouses water is not recycled and generally there is excess watering of 25% to ensure no buildup of salts in the rockwool slabs. In these types of production systems seeding takes place in late December and the tomatoes are harvested from mid March to late October. In November, the greenhouse is cleared and cleaned in preparation for the seeding. The harvest was set to 42 kg/$m^2$, a harvest level that is above industry averages, but not among the highest yielding companies. Materials, energies and services associated with the building and equipment of the tomato company as well as the annual inputs for operating the system were quantified. When wood powder from logging residues was substituted for oil, accompanying adjustments in material inputs and costs were also made. The transportation of material and fuel inputs were included in the analysis, estimated by the direct use of fuels and electricity by the vehicles. Data were collected from manufacturers and retail as well as from a tomato growing company and the extension service. Distances of transportation were obtained from transportation companies and measured on road maps [15]. Inputs were scaled to annual flows in accordance with their economic depreciation times. In general, the assigned depreciation times ranged from 10 to 20 years. Data from 1995 and 1996 were used.

### 2.2. EMERGY analysis

EMERGY analysis starts with a systems diagram drawn in accordance with the energy circuit language [11]. This helps to identify the systems boundary as well as the main components and interactions within and across the boundary. Fig. 1 shows energy systems symbols and definitions. All processes are accompanied by energy transformations and loss of available energy in the resulting product. The systems diagram is used to organize thinking and as a device to inventory all flows of energy, materials, and human services that are required by the process. An EMERGY evaluation table is constructed from the systems diagram, where each flow that crosses the systems boundary becomes a row in the table to be evaluated. Flows of energy, materials and




*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.

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

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

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

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

Fig. 1. Selected symbols of the energy circuit language. Modified from Odum [23]. Printed with the permission of University Press of Colorado.

services are first evaluated in energy terms, then converted to EMERGY by multiplying by a transformity (whose units are sej/J). Transformities are generally calculated in previous evaluations similar to the present study.

Fig. 2 explains the key concept of transformity. The system draws resources directly from nature as well as inputs fed through the economic system. The EMERGY increases with each transformation along the chain or web of processes that generate the product or service. The transformity is the EMERGY of the inputs divided by the energy of the product and is thus expressed in sej/J. The transformity, measured in solar EMERGY joule per joule (sej/J), is a quality index by which the EMERGY of an item can be calculated by multiplying its available energy by its its transformity. The transformity indicates how much environmental work has been invested, directly or indirectly through the economic system, in order to produce a given service or product and also reflects the amount of environmental activity needed to match the use of this product or service [14].

Money paid for the purchase of energy and materials corresponds to the inputs of human services that accompany them. EMERGY in human services is evaluated using a standard conversion for an economy that is derived from the ratio of total emergy used in the economy to the GDP (sej per unit currency). This transformation of the currency reflects the average resource basis required in support of currency circulation. Thus services from the human economy are assigned EMERGY values through the price paid in the economy.

Once EMERGY evaluation tables are complete several emergy ratios can be calculated and compared to other processes and products for perspective. Fig. 3 is a simplified diagram of a generic process (economic use) that uses some free renewable and nonrenewable sources from the environment, purchased non-renewable energies from the economy, and some human services (labor). All flows are in EMERGY terms (sej). Dashed lines represent money flows and always flow opposite the direction of EMERGY flows.

Using Fig. 3 as a guide, the following ratios and indices may be calculated: The EMERGY yield ratio (EYR) is calculated by dividing the EMERGY yield by the purchased EMERGY inputs from the economy. The EMERGY yield is the result of summing all the inputs. The EYR indicates how dependent a process is on non-local inputs. In the case of fuels, EYR gives information on

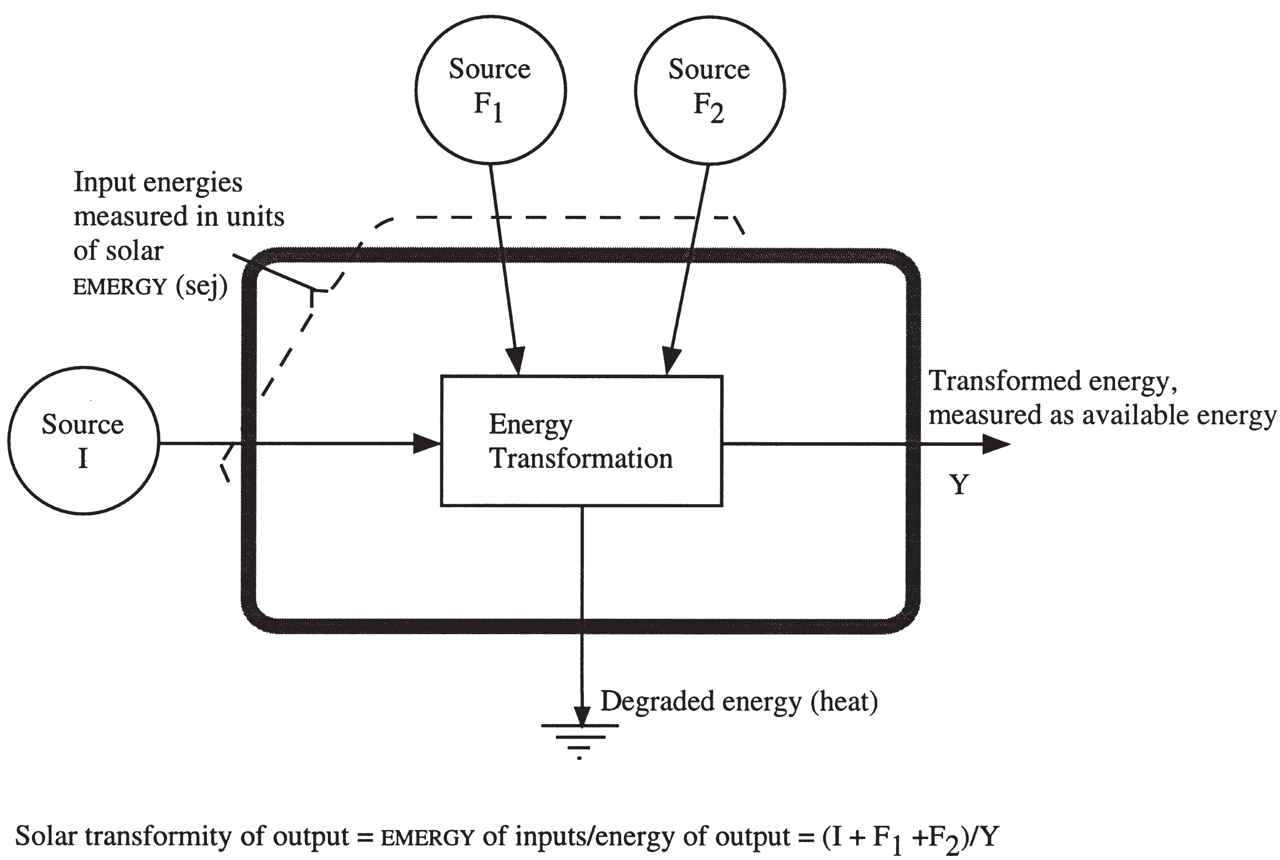
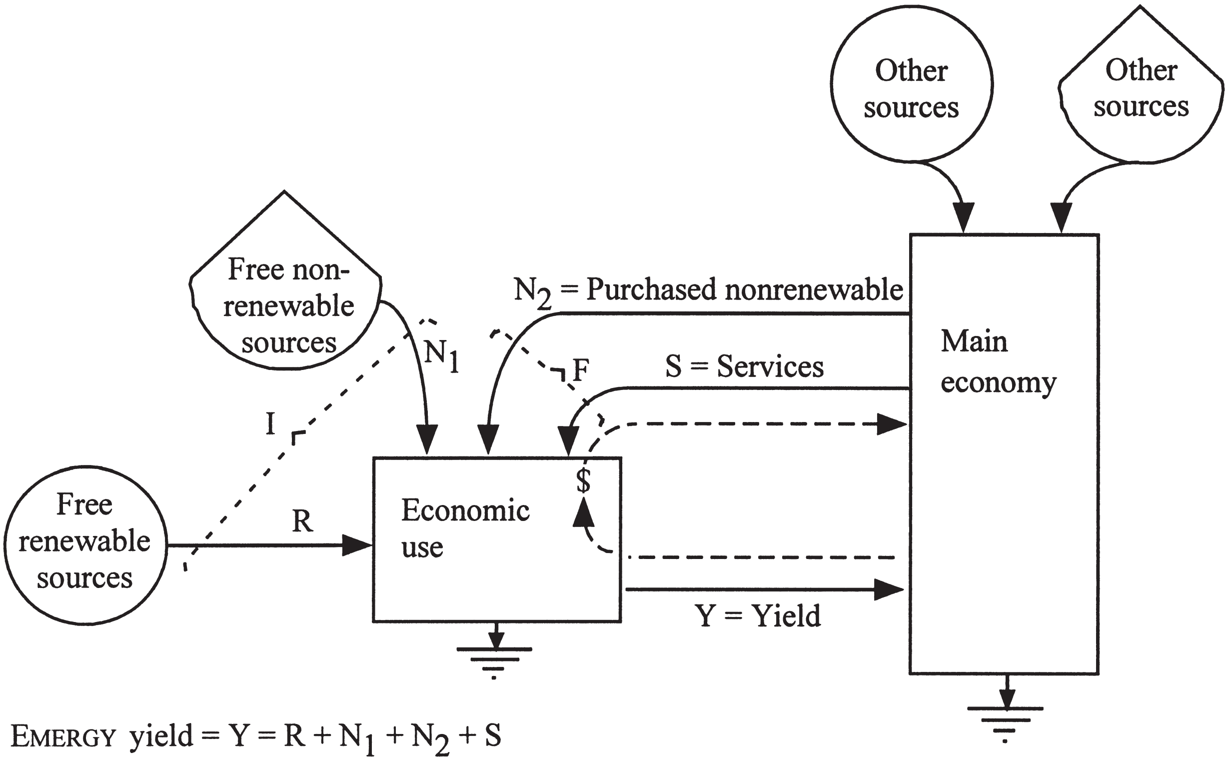



Fig. 2. Energy flows involved in an energy transformation process and calculation of the transformity of the resulting product.




EMERGY yield = $Y = R + N_1 + N_2 + S$

EMERGY yield ratio of products (EYR) = $Y/(N_2 + S)$

EMERGY investment ratio (EIR) = Purchased/free = $(N_2 + S)/(R + N_1)$

Nonrenewable to renewable ratio (NRR) = $(N_1 + N_2)/R$

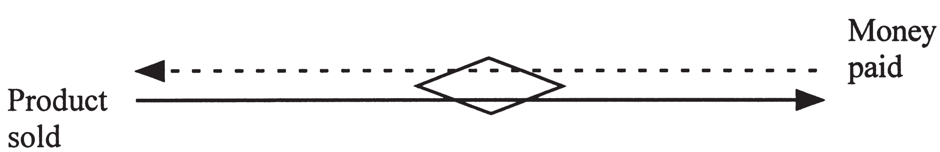
Services/free inputs = $S/(N_1 + R)$

Services/resources = $S/(R + N_1 + N_2)$

Empower density = Y/(area of system)

Environmental loading ratio (ELR) = $(N_1 + N_2 + S)/R$

EMERGY sustainability index = EYR/ELR = $Y*R/((N_2 + S)(N_1 + N_2 + S))$




EMERGY exchange ratio = EMERGY of product/EMERGY of money paid

Fig. 3. EMERGY indices for evaluation of a local system.

whether the process is competitive in supplying a primary energy source for the economy.

The EMERGY investment ratio (EIR) is calculated by dividing the purcased inputs by the EMERGY received free from the environment. The EIR indicates whether the system is an efficient user of the inputs from the economy, compared with alternative processes. If the process draws less inputs from the economy and more free from the environment than competing processes, the EIR is less. The price of products from this process will the be lower than for products from competing processes. In like manner, if a process draws more inputs from the economy per unit of input from the environment, the process may be less competitive and product prices may be higher.

The Environmental Loading Ratio (ELR) is calculated as the sum of the EMERGY of non-renewable goods and services supplied by the economy and the local free non-renewable sources, divided by the free renewable EMERGY drawn from the environment, i.e. developed resource flows divided by renewable flows. The ELR indicates the stress or load exerted by the process upon the local ecosystem. The EMERGY sustainability index (ESI) is defined as the ratio between the EYR and ELR and is thus an aggregate measure of yield and environmental loading, both of which are key components of sustainability [14]. The empower density is calculated by dividing the total EMERGY use by the area of the system. It is thus a measurement of the intensity or spatial concentration of EMERGY. The EMERGY exchange ratio is the ratio of EMERGY of the product to EMERGY of the money paid in a transaction. The economy receiving the larger amount of EMERGY is stimulated the most.

### *2.3. System boundaries*

Fig. 4 shows the system boundaries for the two conditions evaluated in this study. In the top diagram the system boundary is drawn more or less at the property boundary. In the bottom diagram the system boundary is expanded to include the forest and wood powder production to adress the renewable resources accompanying the wood powder. Based on evaluations by Doherty [16], 37% of the wood powder EMERGY flow was regarded as free renewable.

## 3. Results

Fig. 5 shows a systems diagram of Swedish tomato production showing the main flows supporting the system. Direct environmental inputs to the left as well as materials and services fed through the economic system of society interact to run the system. The accumulated energy (EMERGY) is increasing while the energy contents of the product is decreasing to the right of the diagram. The solar energy is thus converging through the system, reading the diagram from left to right. Leaving the system are tomatoes ready for the market and waste. The numbers on inputs correspond to numbered rows in the EMERGY table (Table 1).

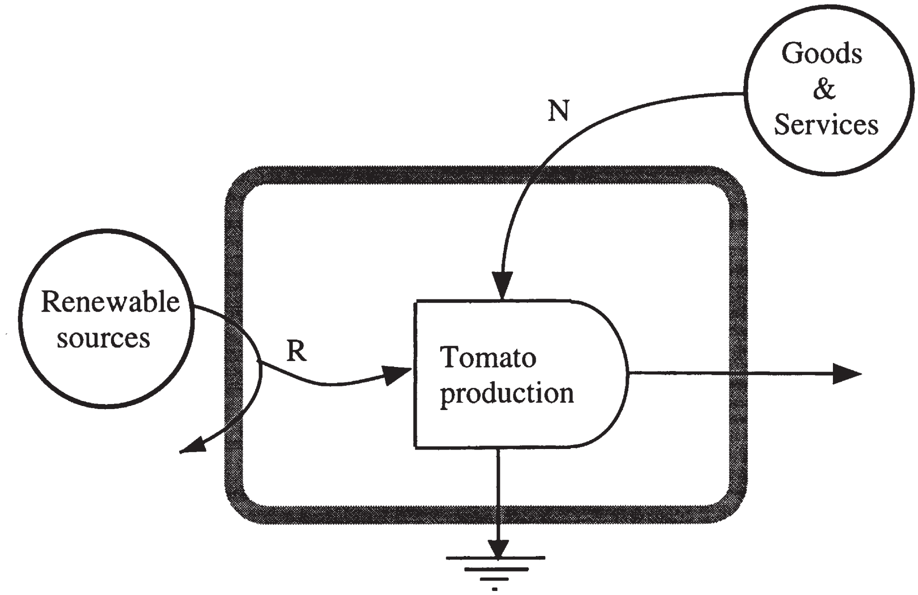
Tables 1 and 2 give the results from the EMERGY analysis. The EMERGY inputs from sun, wind and rain (items 1, 2 and 3 of Table 1) are byproducts of the same global flow. To avoid double counting, as explained by Odum [13], only the largest of these components was counted in the analysis. The direct environmental input (i.e. the rain component) was extremely small compared with the purchased inputs to the system, which constituted nearly 100% of the total EMERGY inflow.

Fuels and electricity and associated services constituted the major input to the system, about 67%, including the fuels for transportation of about 1%. Direct fuels and electricity contributed 57% and the associated services contributed 9% of the EMERGY running the system. About 39% of the total EMERGY flow was accounted for by the oil for heating the greenhouse facility, including services. The propane contributed fifteen percent of the total EMERGY.

The EMERGY of the services, amounting in total to about 37%, constituted a significant part of the resource flow. Nearly 13% originated from direct labor inputs (item 33).

Of the 2% of total EMERGY attributed to materials associated with the construction of the greenhouse facility, steel (item 7) contributed the major part. Fertilizers (items 16–24) contributed 2% to the total EMERGY supporting tomato production. EMERGY indices and ratios of the Swedish oil heated system as well as a comparison with a system where the oil was substituted by wood powder from logging residues from an 80 year rotation spruce/pine forest of Southern Sweden [16] are given in Table 2. Table 2 also presents indices of Florida tomatoes produced in the field [17] for further comparison. In this present study the water (item 32 of Table 1) extracted by far exceeds the recharge of water generated on the systems area and the water is regarded as a non-renewable resource which is depleted faster than it is renewed. If, however, the pressure on the water resources is low enough on the regional scale the use of water may be considered renewable on this larger scale.

As expected, the substitution of fuels resulted in a reduced environmental load and a dramatic increase in the sustainability of the production. The ELR decreased about 700-fold, from close to 10 000 to 14, and the ESI increased 800-fold, from 0.0001 to 0.08. The sustainability index was, in fact, shown to be higher than that for the Florida field tomatoes. The substitution also resulted in a 24% decrease of the empower density. The EMERGY investment ratio decreased from above 400 to less than 14. The non-renewable to renewable ratio



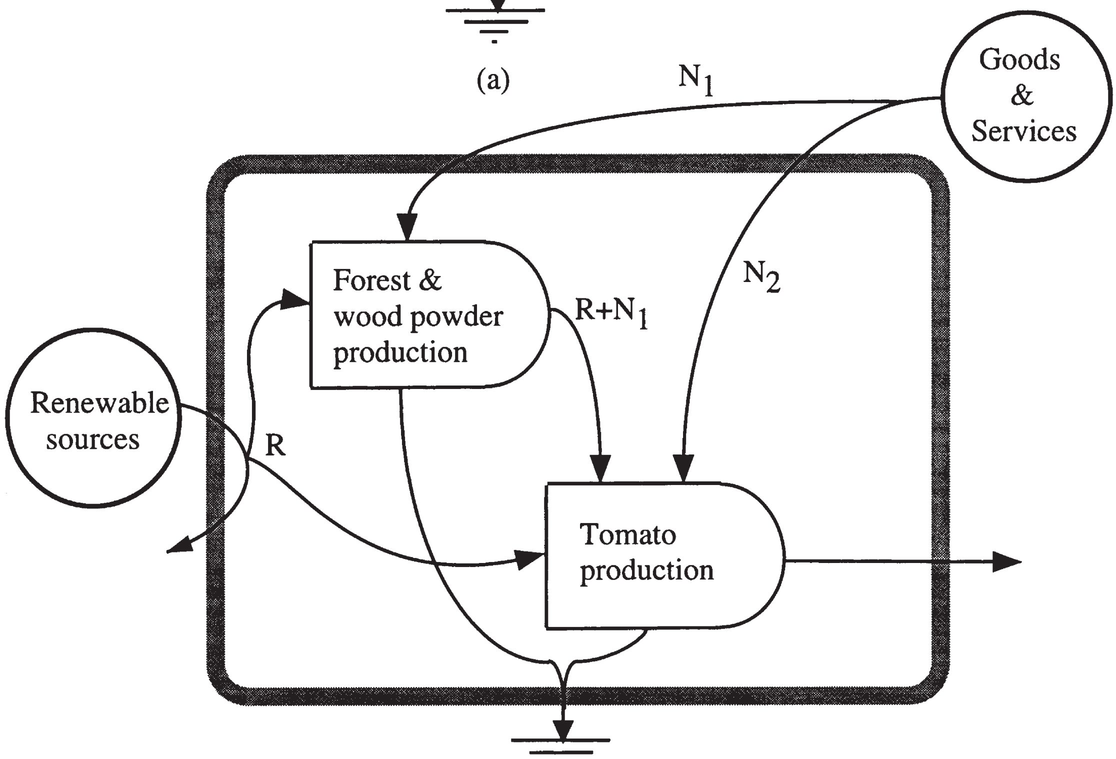




Fig. 4. Simplified diagram showing the difference in boundary between the system using oil and the system using wood powder for heating. (a) oil. (b) Wood powder.

changed significantly, decreasing from 6230 to six. The ratio of services to free inputs also decreased substantially and the ratio of services to resources was doubled.

Comparisons with field grown tomatoes in Florida, showed that the greenhouse tomatoes are very energy intensive having an empower density between 70 and 90 times that of the field tomatoes. Yields are very high in the greenhouse system where total annual yield was about 420 000 kg/ha as compared with the annual yields of about 36 900 kg/ha for the Florida field tomatoes. Yet, even with these very high yields, the transformity for the greenhouse tomatoes was about 19 times that of the field tomatoes. Since transformity measures the extent of convergence of materials and energy in a production pro-

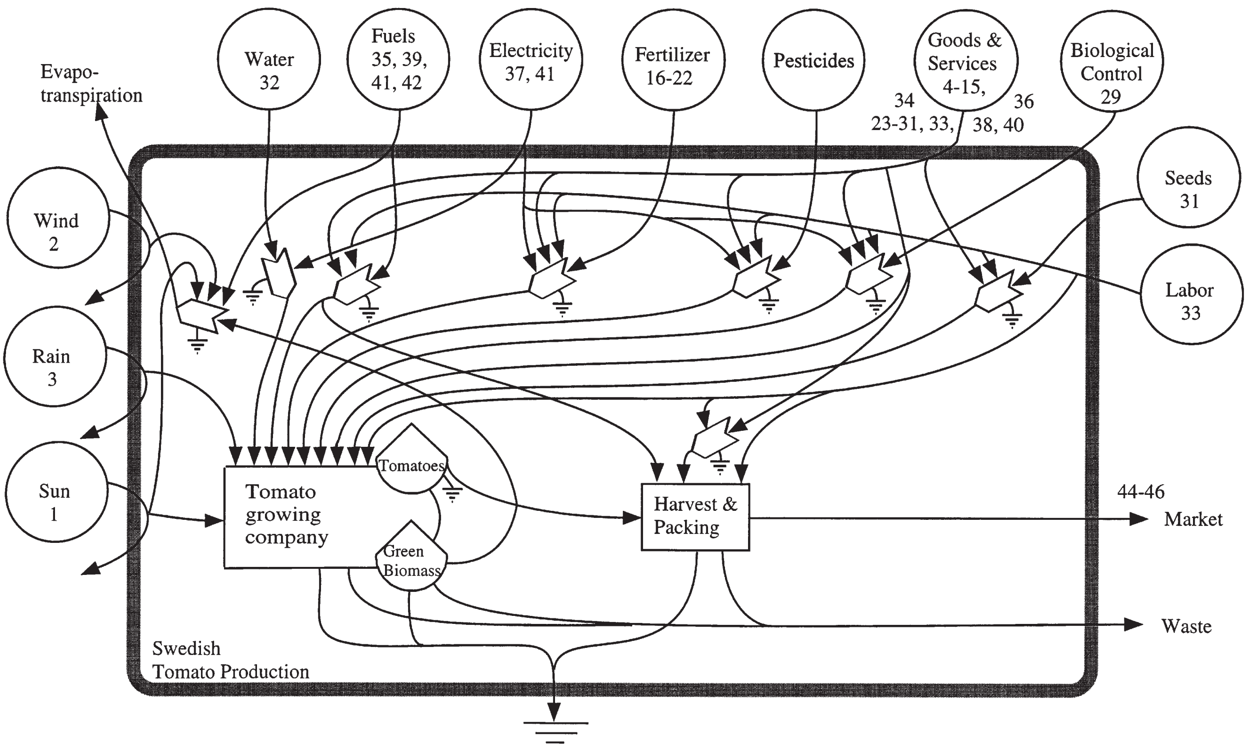



Fig. 5. Overview of the tomato production system under study. Numbers on flows refer to items in the EMERGY analysis table (Table 1).

cess, comparisons of transformities of similar products yield information about overall efficiency. When wood powder is used in place of oil, the efficiency of greenhouse tomato production increases by about 24%. Indices of $CO_2$ production and employment suggest that wood powder use increases the requirement of human services (6% increase in the total service requirement) and decreases overall $CO_2$ production.

## 4. Discussion

As expected, tomato production in greenhouses is an intensive operation, requiring large inputs and producing large output on a relatively small area of land. Consequently, the empower density was about 90 times that of field grown tomatoes in Florida. The intensity was also detected by the high EIR, indicating that this system is highly dependent on EMERGY inputs fed back from the economy. One must remember, though, that this present EMERGY analysis concerns a whole company, including offices, outside economic areas, all buildings and all the machinery and tools, services like extension service, taxes, loans etc. Previous studies concerning agricultural crops [18–20] are concerned with the inputs applied to the field and leave out many of the inputs attributed to the whole company. This present study therefore most likely accounts for more materials and services associated with the production system.

### 4.1. EMERGY indices

The overall resources required to produce tomatoes, reflected by the transformities, was less within the system using wood powder instead of oil. The transformity (in sej/kg fresh weight) of the tomatoes grown in oil heated greenhouses was about 13 times the transformity of Florida field tomatoes. The lower transformity of the tomatoes produced with wood powder heating was caused by the decrease in overall emergy use, i.e. the lower EMERGY yield. The extremely high ELR of the oil heated system not only originates from the large amount of feedback from the economy but also from the large percentage of non-renewable feedback. As was pointed out by Brown and Ulgiati [14], a system requiring large inputs from the economy may be considered sustainable, provided that a large portion of these inputs can be regarded as renewable flows.

### 4.2. Human labor

The impact of human labor is often underestimated by process analysis, which merely accounts for the services associated with the direct inputs of labor measured in

Table 1
Emergy evaluation of Swedish tomato production under glass 1996. 8000 $m^2$ plant area, 1000 $m^2$ non-plant area and 4500 $m^2$ outside area. Annual flows

| Item no.[a] | Item, unit | Data (units/year) | Transformity (sej/unit) | Solar EMERGY (sej/yr) | % of total EMERGY | Reference for transformity |
|---|---|---|---|---|---|---|
| *Local renewable inputs* | | | | | 0.01 | |
| 1 | Sun, J | 2.88E+13 | 1.00E+00 | 2.88E+13 | 0.00 | [13] |
| 2 | Wind, J | 5.34E+10 | 1.50E+03 | 8.01E+13 | 0.00 | [13] |
| 3 | Rain, chemical potential, J | 1.10E+10 | 1.82E+04 | 2.00E+14 | 0.01 | [13] |
| *Non-renewable inputs* | | | | | 32.82 | |
| 4 | Macadam, kg | 2.99E+04 | 9.75E+05 | 2.92E+10 | 0.00 | [13] |
| 5 | Concrete blocks, kg | 1.61E+03 | 3.54E+11 | 5.70E+14 | 0.03 | [24] |
| 6 | Concrete ready mix, kg | 2.23E+04 | 4.40E+11 | 9.81E+15 | 0.50 | [24] |
| 7 | Steel, kg | 6.36E+03 | 2.16E+12 | 1.37E+16 | 0.69 | [24] |
| 8 | Cast iron, kg | 4.45E+02 | 1.74E+12 | 7.74E+14 | 0.04 | [24] |
| 9 | Aluminum, kg | 5.40E+02 | 1.77E+13 | 9.56E+15 | 0.48 | Appendix B |
| 10 | Glass, kg | 7.15E+03 | 8.40E+11 | 6.01E+15 | 0.30 | [26] |
| 11 | Service in building, SEK[b] | 3.24E+05 | 2.14E+11 | 6.95E+16 | 3.51 | [25] |
| 12 | Plastics, kg | 8.52E+02 | 3.80E+11 | 3.24E+14 | 0.02 | [26] |
| 13 | Remaining metals, kg | 2.14E+01 | 1.00E+12 | 2.14E+13 | 0.00 | [13] |
| 14 | Cardboard, kg | 1.42E+04 | 1.41E12 | 2.01E+16 | 1.01 | [16] |
| 15 | Rockwool, kg | 4.30E+03 | 1.86E+12 | 8.00E+15 | 0.40 | [27] |
| 16 | Nitrogen, kg | 1.53E+03 | 4.60E+12 | 7.04E+15 | 0.36 | [13] |
| 17 | Phosphorus, kg | 5.62E+02 | 1.78E+13 | 1.00E+16 | 0.51 | [13] |
| 18 | Potassium, kg | 1.97E+03 | 1.74E+12 | 3.43E+15 | 0.17 | [13] |
| 19 | Calcium, kg | 7.56E+02 | 1.00E+12 | 7.56E+14 | 0.04 | [13] |
| 20 | Sulphur, kg | 2.17E+02 | 1.00E+12 | 2.17E+14 | 0.01 | [13] |
| 21 | Magnesium, kg | 1.64E+02 | 1.00E+12 | 1.64E+14 | 0.01 | [13] |
| 22 | Micronutrients, kg | 2.06E+01 | 1.00E+12 | 2.06E+13 | 0.00 | [13] |
| 23 | Service in macronutrients, SEK | 4.92E+04 | 2.14E+11 | 1.05E+16 | 0.53 | [25] |
| 24 | Service in micronutrients, SEK | 5.69E+03 | 2.14E+11 | 1.22E+15 | 0.06 | [25] |
| 25 | Slaked lime, kg | 7.40E+01 | 5.41E+11 | 4.00E+13 | 0.00 | [13] Appendix B |
| 26 | Soft soap, J | 2.40E+09 | 7.20E+05 | 1.73E+15 | 0.09 | [11] |
| 27 | Farbanet, kg active subst. | 1.47E+01 | 1.48E+13 | 2.18E+14 | 0.01 | [26] |
| 28 | Wetting agent, kg active subst. | 3.10E−01 | 1.48E+13 | 4.59E+12 | 0.00 | [26] |
| 29 | Biological control, SEK | 6.83E+03 | 2.14E+11 | 1.46E+15 | 0.07 | [25] |
| 30 | Pollinators, SEK | 4.26E+04 | 2.14E+11 | 9.13E+15 | 0.46 | [25] |
| 31 | Seed, SEK | 3.33E+04 | 2.14E+11 | 7.14E+15 | 0.36 | [25] |
| 32 | Water, J | 3.56E+10 | 1.10E+05 | 3.92E+15 | 0.20 | [19] |
| 33 | Direct human services in labor, SEK | 1.17E+06 | 2.14E+11 | 2.51E+17 | 12.68 | [25] |
| 34 | Remaining human services, SEK | 9.47E+05 | 2.14E+11 | 2.03E+17 | 10.26 | [25] |
| *Fuels and electricity* | | | | | 65.87 | |
| 35 | Oil, J | 1.36E+13 | 5.61E+04 | 7.63E+17 | 38.57 | [13] |
| 36 | Indirect services in oil, SEK | 5.77E+05 | 2.14E+11 | 1.24E+17 | 6.25 | [25] |
| 37 | Electricity, J | 5.56E+11 | 1.28E+05 | 7.12E+16 | 3.60 | [13] |
| 38 | Indirect services in electricity, SEK | 9.27E+04 | 2.14E+11 | 1.99E+16 | 1.00 | [25] |
| 39 | Propane, J | 2.85E+12 | 1.01E+05 | 2.87E+17 | 14.50 | [13] |
| 40 | Indirect services in propane, SEK | 1.79E+05 | 2.14E+11 | 3.84E+16 | 1.94 | [25] |
| *Transportation of main components* | | | | | 1.30 | |
| Transportation of material inputs | | | | | | |
| 41 | Oil, J | 9.78E+09 | 4.71E+04 | 4.61E+14 | 0.02 | [13] |
| | Diesel oil, J | 2.18E+10 | 5.61E+04 | 1.22E+15 | 0.06 | [13] |
| | Electricity, J | 4.53E+07 | 1.28E+05 | 5.80E+12 | 0.00 | [13] |
| Transportation of fuels | | | | | | |
| 42 | Oil, J | 3.61E+11 | 4.71E+04 | 1.70E+16 | 0.86 | [13] |
| | Diesel oil, J | 1.24E+11 | 5.61E+04 | 6.96E+15 | 0.35 | [13] |
| 43 | Sum of inputs | | | 1.98E+18 | 100.00 | |
| *Outputs* | | | | | | |
| 44 | Harvest, kg fresh weight | 3.36E+05 | 5.89E+12 | 1.98E+18 | | |
| 45 | Harvest, kg dry matter | 1.68E+04 | 1.18E+14 | 1.98E+18 | | |
| 46 | Harvest, J | 2.82E+11 | 7.01E+06 | 1.98E+18 | | |
| 47 | Sales value of harvest, SEK | 3.74E+06 | 2.14E+11 | 8.02E+17 | | |

[a] The notes to items listed are given in Appendix A.
[b] SEK=Swedish Crowns, the currency of Sweden. In 1996, the currency exchange ratio was 6.70 SEK/USD.

Table 2
Emergy indices for three different tomato production systems: oil heated greenhouse in Sweden,wood powder heated greenhouse in Sweden, and Florida field tomatoes. Indices are defined in Fig. 3

| Indices | Oil[a] | Wood powder[b] | Florida field tomatoes[c] |
|---|---|---|---|
| EMERGY yield (sej/yr) | 1.98E18 | 1.51E18 | 1.62E16 |
| EMERGY yield ratio | 1.00 | 1.07 | 1.06 |
| EMERGY investment ratio | 480 | 13.5 | 16.2 |
| Non-renewable to renewable ratio | 6230 | 6.3 | 8.7 |
| Services/free inputs | 179 | 7.5 | 7.6 |
| Services/resources | 0.59 | 1.06 | 0.8 |
| Empower density (sej/m$^2$) | 1.47E14 | 1.12E14 | 1.62E12 |
| Environmental loading ratio | 9910 | 14.1 | 16.4 |
| EMERGY sustainability index | 0.0001 | 0.08 | 0.06 |
| Transformity (sej/J) | 7.01E6 | 5.36E6 | 3.7E5 |
| Transformity (sej/kg fresh weight) | 5.89E12 | 4.50E12 | 4.38E11 |

[a] R=2.00E14 sej/yr; $N_1$=3.92E15 sej/yr; $N_2$ =1.24E18 sej/yr; S=7.35E17 sej/yr.
[b] R=1.00E17 sej/yr; $N_1$=3.92E15 sej/yr; $N_2$=6.29E17 sej/yr; S=7.79E17 sej/yr.
[c] Brandt-Williams and Odum [17].

joules. In the intensive production systems analysed by Stanhill [5] and Pimentel and Pimentel [6], only a negligible part of the total energy requirements were assigned to labor inputs. This present analysis, attributing 37% of the total EMERGY to direct (13%) and indirect (25%) services, clearly recognized the systems dependence on human labor. In fact, the difference between high tech products and low tech ones may lie in the fact that more of the services of the high tech system are embedded in their previous history. Therefore a low tech system requiring more direct services may seem more labor intensive while it may in fact not be when analysed according to the EMERGY method, and vice versa.

### 4.3. Wood powder substitution

The present tomato production systems dependence on direct inputs of fossil fuel for heating was confirmed by the EMERGY analysis and consequently the substitution of the oil by a fuel considered to be renewable proved to be an interesting experiment. In addition to reducing the non-renewable to renewable ratio dramatically, the wood powder used for substitution was a domestic regionally produced fuel. A system using more domestic labor, i.e. where more of the production takes place within the domestic or regional economy would prove interesting to policy makers concerned with unemployment and social welfare of the population.

Replacing oil with wood powder would also reduce the release of carbon dioxide ($CO_2$) into the atmosphere from heating which is another important aspect of sustainability. The oil combustion in the oil heated system would release about 1.2E6 kg of $CO_2$ annually including precombustion activities (extraction, refining etc.) whereas with wood powder these $CO_2$ emissions would be reduced to about 0.1E6 kg annually. Since combustion of wood powder does not in itself contribute a net release of $CO_2$, the $CO_2$ released with the wood powder alternative originates from fossil fuel use in precombustion activities (including forestry). Extrapolated to include all of the domestically produced tomatoes of Sweden (1.82E7 kg fresh weight), this present system would reduce $CO_2$ emissions by 60E6 kg annually. Substitution of oil for heating with wood powder would then require logging residue from an area of 84 000 ha (estimated from about 1550 ha for the present system). This may not pose any problem in the present economy of Sweden, where land is not in shortage. Also, the forest producing wood powder produces lumber in a sustainable way. In the future, however, there may be new uses competing for land and other resources.

### 4.4. Space, time and EMERGY

It has long been known that there is a strong relationship between space and time. Spatial scale, i.e. the area over which something acts, is related to temporal scale [21,22], for instance. Small things that act over small spatial areas turn over quickly (i.e. have a small temporal scale), while larger things occupy larger spatial areas and turn over at an increasingly slower pace. It is also true that small things require less energy than do large things. Consider for instance the energy requirements of microbes verses elephants. The total requirements during a lifetime for a microbe are infinitesimally small compared to the elephant. Not only is the magnitude quite different, but the flux is as well. During a typical day, the elephant will consume millions of times the energy that a microbe will and will cover millions of times the distances in order to gather the energy.

Space, time, and EMERGY are interrelated and may be substitutable, one for the other. It is possible to maintain large things in relatively small areas (an elephant in a zoo, for instance), but only with large amounts of supporting EMERGY. Increases in the speed at which a process functions are usually accompanied by increases in driving energy. Therefore a general principle that may hold for all systems is that decreases in either space or time required for a process will result in an increase in the required EMERGY to drive the process. Agriculture is no different. Yields for agricultural commodities are more or less fixed, given a certain technology assumption. To drastically decrease the area and maintain the same yield requires significant increases in energy and material inputs. The green revolution accomplished meaningful increases in yields per hectare, but at a large energy cost. Reducing energy costs of agriculture will, by necessity, require an increase in the area of land that is farmed. The greenhouse tomato system clearly illustrates these tradeoffs between time, space and energy. Producing the same amount of tomatoes as the greenhouse system in the field under Swedish conditions would require about 7 ha. Alternatively, producing the same amount of tomatoes in the field on the same area as the present intensive system (0.8 ha plant area) would prolong the time needed for production to about 9 years. Thus an increase in energy inputs may reduce the acreage needed and also the time of production.

From a quantitative perspective, sustainability is a function of yield and environmental load. Since agricultural crops have relatively low net yields (as they should because they are not sources of concentrated energy, but are the result of transformations of fuels, technology and human service) sustainability becomes more dependent on minimizing environmental load. In this paper we have used several EMERGY indices to demonstrate agricultural sustainability of alternative tomato production systems. An alternative that used wood residues for heating in place of fossil fuels was found to increase sustainability and reduce environmetal loading.

Improving sustainability can be quantitatively evaluated when flows of materials and energies that drive production processes are expressed in EMERGY. Comparisons are possible when all required inputs are expressed in the same form of energy and indices of production and efficiency that lead to quantitative determination of sustainability are possible. In this paper we have demonstrated the EMERGY methodology applied to agricultural production in Sweden and have evaluated increases in sustainability by using renewable wood by-products for heating greenhouses for the production of tomatoes.

## 5. Conclusions

There is potential for improving the performance of the analysed tomato system in the direction of increasing its sustainability. Since the fuel for heating the greenhouse was a dominating input, replacing fossil fuels with more renewable ones will be an important strategy. Substitution of oil for heating with wood powder from logging residues reduced the environmental load and enhanced the sustainability of the tomato production. The EMERGY analysis clearly visualized the dependence of the larger economic system of which the tomato system is a part. If the larger economy, i.e. society, does not act sustainably, the chances of the subsystem to do so are small.

In all, increasing sustainability of agriculture depends on increasing the use of renewable energy sources. This can be done, to a certain extent, through substitution like the wood powder derived from forest residues, or through careful resource management like insuring water resources are used no faster than they recharge, or by increasing land area (and therefore the use of environmental energies like sunlight and rain). Technological 'fixes' to agriculture, while possibly increasing yields somewhat, have high nonrenewable energy use, driving down sustainability and increasing environmental loads. Future improvements of sustainability in agriculture will lie in improving the use of renewable energies, which will either increase time or space (or both) devoted to food production.

## Acknowledgements

The fulfilment of this paper was made possible by a travel grant from the Swedish Council for Forestry and Agricultural Research, partly financing Lagerbergs trip to Gainesville. Lagerberg also wish to acknowledge that the SLU (Swedish University of Agricultural Sciences) financed a previous visit to the University of Florida, forming the basis for this collaboration. The authors are indepted to all the persons and companies who supplied data for the EMERGY analyses.

## Appendix A. Footnotes to Table 1

Item 1. The normal value 1961–1990 of the global insolation in Lund [28]=972.9 kWh/$m^2$. Consequently, the insolation on 9000 $m^2$ would be area × insolation × (1 − albedo) = 9000[$m^2$] × 972.9[kWh/$m^2$] × 3.6E6[J/kWh] × 0.60[assumed transmission of light into the greenhouse] = 1.8913E13 J/year.

The remaining 4500 $m^2$ outside areas receive 4500[$m^2$] × 972.9[kWh/$m^2$] × 3.6E6[J/kWh] × (1 − 0.37) = 9.9294E12 J/year.

Sum: 1.8913E13 + 9.9294E12 = 2.884E13 J/year.

Item 2. Water uptake by the plants amounts to 75% of the total water consumption. The transpired water from the 8000 $m^2$ plant area is then given by 75% of total water consumption − water in harvest[harvest × water contents] − water in plant tissue = 0.75 × 7200[$m^3$] × 0.9982E3[kg/$m^3$, at 20°C] − 336 000[kg] × 0.95[%] − 0.1E−3[$m^3$/plant] × 0.9982E3[kg/$m^3$] × 2.5[plants/$m^2$] × 8000[$m^2$] × 30[weeks, assumed incorporation febr. − decapitation] ≈ 5.011E6 kg of water.

This water would raise the humidity in the greenhouse to approximately 100%, if there was no ventilation. Optimum humidity in the greenhouse is 75–80%. The humidity of the outside air is 65–75% and 85–90% during the summer and winter respectively in the Malmö region. The 5.004E6 kg of water has to be moved out of the greenhouse in order to decrease the RH from 100% to an assumed seasonal average of 75%.

Air of 100% RH [1 kPa, 21°C] can hold 15.14 g of water/kg dry air whereas air of 75% RH can hold about 83[grains/pound] × 1/7[g/kg/grain/pound] ≈ 11.86 g of water per kg dry air (Ref. [29] p. 499). ⇒1 kg of 75% air can remove 15.14 − 11.86 = 3.28 g of water to remove 5.011E6 kg=5.011E9 g of water we thus need 5.011E9/3.28 ≈ 1.53E9 kg of 75% air. The kinetic energy required to move this air mass is given by KE = $mv^2$ / 2⇒5.0011E9 / 3.28 × $5.5^2$[m/s, wind speed estimated from data from the Swedish Meterological and Hydrological Institute]/2 ≈ 2.31E10 J.

Wind contribution on remaining area=kinetic energy=(air mass)×(windspeed absorbed; 40% of windspeed at 1000 m)$^2$ / 2 = 4500[$m^2$] × 1000[m, boundary layer] × 1000[kg/$m^3$, density of air] × (0.4 × 5.5[m/s]/0.6)$^2$/2 = 3.025E10 J.

Sum: 2.31E10+3.025E10=5.34E10 J.

Item 3. The normal value of precipitation in Lund 1961–1990 [28]=658 mm=0.658 m. 25% of the total rainfall was considered to be evapotranspired. Free energy of rainfall=(area) × (evapotranspired rain) × (density of water) × (Gibbs free energy) = 13500[$m^2$] × 0.658[m] × 0.25[25%] × 1000[kg/$m^3$] × 4.94E3[J/kg] = 1.097E10 J

Item 4. The mean transformity of granitic rock and metamorphic rock was used.

Item 11. Services associated with the greenhouse building, major components (incl. artificial light) and maintenance.

Item 13. Brass, cupper and unknown metals.

Item 15. Transformity excluding indirect inputs.

Item 25. The molecular weight of slaked lime, $Ca(OH)_2$, is 40.08 + 2 × 16.00 + 2 × 1.01 = 74.10 g/mole, of which 40.08 / 74.10 = 54.1% is Ca. 74 kg then contain 0.541 × 74 = 40.034 kg of Ca. The transformity of mineral ore in the earths crust is 1E9 sej/g [13]⇒ transformity of $Ca(OH)_2$ = 40.034[kg Ca] × 1E9[sej/g] × 1E3[g/kg]/74[kg $Ca(OH)_2$] = 5.41E11 sej/kg.

Item 26. The energy contents of lauric acid (the predominant fatty acid of soap) is 8.816 kcal/g [11]. Assuming that soft soap contains about 0.5 kg soap/$dm^3$, gives an energy content of 130 $dm^3$] × 0.5[kg/$dm^3$] × 8.816E3[kcal/kg] × 4186[J/kcal] = 2.40E9 J in 130 $dm^3$ soft soap.

Items 27 and 28. Assuming that the active substance contents is 50%.

Items 29–31. Since the energy contents of biological control agents, including predators and yellow sticky traps, seed and pollinators are so small, the EMERGY values of these items were estimated by their service component.

Item 32. Water used for irrigation = 7200[$m^3$] × 4.94E6[J/$m^3$] = 3.56E10 J.

Item 33. Including tax.

Item 34. Including costs for remaining materials, insurance, interest on loans and costs for amortization on remaining materials.

Item 35. Oil used for heating is more refined than the oil for transportation. Therefore the transformity of refined fuels was used.

Item 37. Mean transformity of world average [13] and Swedish hydropower [16] = (1.74E5 + 8.02E4) / 2 = 1.28E5 sej/J.

Table 3
Transformity of aluminum, based on data from Tillman et al. [32]

| Item no. | Item, unit | Data (units) | Transformity (sej/unit) | Solar EMERGY (sej/yr) |
|---|---|---|---|---|
| *Inputs* | | | | |
| 1 | Bauxite, kg | 4.81E+03 | 1.00E+12 | 4.81E+15 |
| 2 | Rock salt for NaOH manufacturing, kg | 315.00 | 1.00E+12 | 3.15E+14 |
| 3 | Limestone, kg | 87.90 | 1.00E+12 | 8.79E+13 |
| 4 | Carbon anode, kg | 430.00 | 1.03E+12 | 4.43E+14 |
| 5 | $H_2SiF_6$, kg | 15.40 | 1.70E+13 | 2.62E+14 |
| 6 | Electricity, J | 5.89E+10 | 1.74E+05 | 1.02E+16 |
| 7 | Oil, J | 3.26E+10 | 4.71E+04 | 1.54E+15 |
| 8 | Diesel, J | 1.81E+08 | 5.61E+04 | 1.02E+13 |
| 10 | Sum | | | 1.77E+16 |
| *Output* | | | | |
| 11 | Cast aluminum, kg | 1000 | 1.77E+13 | 1.77E+16 |

Item 39. Assume that the relationship with the energy contents of natural gas corresponds to the relationship between the transformities. The enthalpy of propane is 93.8 MJ/$m^3$ and 38.0 MJ/$m^3$ of natural gas [30]. The transformity of natural gas is 4.08E4 sej/J excl. services (calculated from sedimentary coal in Odum [13]). Thus, the transformity of propane is 93.8[MJ/$m^3$]/38.0[MJ/$m^3$] $\times$ 4.08E4[sej/J natural gas] = 1.007E5 sej/J propane.

Items 41 and 42. The transportation of inputs was evaluated by the inputs of fuels and electricity.

Item 43. Items 1, 2, and 3 are byproducts of the same solar emergy flow. To avoid double counting, only the largest of these components (rain) are used when summing the emergy inputs to the system.

Item 45. 95% water contents.

Item 46. 1.68E7 J/kg dry matter calculated from tables of protein, fat and carbohydrate contents of fresh tomatoes [31]. Energy contents of protein, fat and carbohydrates [30].

## Appendix B. Transformity calculations of aluminium

Table 3

Item 1. Transformity of in situ bauxite [13].

Item 2. Transformity of in situ sedimentary minerals [13].

Item 3. Transformity of in situ limestone [13].

Item 4. The transformity of sedimentary coal is 3.4E4 sej/J [13]. hard coal has a heat content of 30.23E6 J/kg [30]. The transformity of coal would then be 3.4E4[sej/J] $\times$ 30.23E6[J/kg] = 1.03E12 sej/kg, excluding services.

Item 5. $H_2SiF_6$ is a by-product of phosphorus extraction. Since the $H_2SiF_6$ accompanies the phosphorus, it is consdiered a co-product and thus carries the same transformity as the mined phosphorus, i.e. 1.70E13 sej/kg P or 1.70E13 sej/kg $H_2SiF_6$ (Odum [13], human service excluded on p. 124).

Item 6. Mean transformity of electricity including human services of plant operations in Odum [13], p. 305.

Item 7. Transformity of crude oil calculated from Odum [13], excluding human services.

Item 8. Transformity of refined petroleum, excluding services, calculated from Odum [13].

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