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Emergy synthesis on the initial phase of a sustainable urban food garden

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Content

List of Abbreviations

EBE- emergy benefit after exchange
EBR- emergy benefit ratio
EEP-ecological economic product
EFR- emergy footprint ratio
EIR- emergy investment ratio
ELR- emergy loading ratio
EmDollar- emergy dollar
ERR- emergy restoration ratio
EYR- emergy yield ratio
GDP- gross domestic product
LCA-life cycle assessment
SD- sustainable development
Sej- solar emergy
SeJ/g- solar emergy joule/gram
SeJ/J- solar emergy joule/joule
SEK- Swedish krona
SI- emergy sustainability index
UNDP- United Nations Development Program

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Abstract

In recent years various benefits of small scale, sustainable agriculture have been revealed. However such systems have rarely been assessed on a system level.

In this study emergy synthesis of a sustainable urban, food-producing plot was performed in order to assess the benefits and possible obstacles of such systems. Emergy evaluation was chosen due to its ability to show important interactions and evaluate different types of inputs in a common form (solar energy equivalents). Preliminary results of system indices (EIR: 1.4; EYR: 1.4; ELR: 2.66; EFR: 3.66; and ESI: 0.5) have shown relative low production efficiency in contrast to the amount of resources invested. In case of our model, labor represented the highest emergy contribution, an overwhelming 96 % of all input emergies.

And even though labor was done voluntarily, considering its supporting energy flows it is a non-renewable input resource. And while feedback (controlling) resources such as labor, or imported materials can accelerate system growth, extensive and long-term use of these resources is neither sustainable nor economical.

With respect to our output, first year results suggest that overwhelming portion of inputs resources were used to establish essential material and energy pathways and to build up environmental storages. Which suggests that self-organization requires considerable amount of resources and time.

System output in terms of yield generated has shown low result, with relatively high transformty values for co-products.

But while system yield has shown to be low, resource efficiency when all output are considered is high. Which implies an advantage in favor of sustainable urban food-producing systems because in contrast to conventional systems important resource inputs have shown to be stored and recycled. Such attributes mean greater sustainability, resilience and adaptation during an era of resource scarcity.

1. Introduction

Currently the destructive notion of agro industrial systems is becoming ever more apparent. Deficiencies of such systems include resource intensity (water, fertilizer, pesticides), loss of soil and biodiversity and ever increasing system inefficiency (Mollison, 1988; 2001). In addition to the environmental repercussions, several social disturbances such as the increase in social inequality, unemployment, appearance of new degenerative diseases due to the use of various synthetic additives and the lack of nutrition can be accounted to large scale or industrial agriculture (Ponting, 1995). With the accelerating prevalence of environmental losses, a growing global population and declining fossil fuel reserves the future of intensive agricultural practices is questioned (Pimentel et al., 1995; Rockström et al., 2009). Although *sustainability*[1] future food production is a necessary constraint, restricting or limiting the use of input resources has negative implications on production and consequently on food security. It is therefore important to maintain essential material and energy flows without diminishing our ecological systems. In order to overcome challenges associated with resource scarcity and global economic contraction, resource consuming urban settlements and resource intensive agricultural lands must be transformed into diverse, small scale, self-sufficient systems (Fukuoka, 1978; Mollison, 1988; 2001; Hart, 1996, Odum, 2000). At times of limited resource availability the application of these systems could possibly increase food security, secure diversity and reduce long-term resource dependency. These goals can be achieved by incorporating sustainable food production practices into urban systems. Which in reality means, adjustment of production and resource use to their optimal efficiency and increasing environmental storages through storing and recycling. (Mollison, 1988; Stern et al., 1992; United Nations Development Program, 1996).

[1]Sustainability: Balancing local and global efforts to meet basic human needs without destroying or degrading the natural environment: Kates, R., Parris, T. & Leiserowitz, A. Harvard (2005). "What is Sustainable Development? Goals, Indicators, Values, and practice" *Environment* **47(3)**: 8–21.

Keeping these goals in mind, an experimental city plot based on the principles of sustainable design has been established. The aim of the project was to assess key system variables such as resource intensity of construction, productivity and sustainability. Such variables were then used to describe the operation our sustainable systems; indicate the path and accumulation of resource inputs; point out advantages; and quantify as well as compare key system variables. Moreover, the outcomes were also used to explain production efficiency (other authors suggested low production efficiency). As a method, emergy evaluation was chosen due to its ability to describe important interactions and to express different types of input resources in a common form (solar energy equivalents).

Thus, with respect to the goals defined, the following questions were formulated: (1) What is the actual resource intensity of the installation? (2) What is the extent of annual ecological storage increase (e.g. nitrogen, biomass and water, phosphate)? (3) And what is the relative system efficiency based on the transformities and indices calculated for the first year?

1.1 Literature review

Benefits and potential deficiencies of ecological farming systems were evaluated in several studies using energy based approach. Haden (2003) and Bergquist (2010), for instance, compared sustainability and productivity of different production and management practices and evaluated a farm as a whole. In his study Haden concluded that management practices relying on local renewable resources are more sustainable than others based on external high quality (valuable) inputs such as imported goods and human services.

The study done by Bergquist revealed that urban agriculture offers several opportunities for improving sustainability; such as more efficient use of local resources, recycling of wastes and reducing the use of imported, non-renewable resources (with important system indices showing relatively high productivity combined with low environmental stress in tropical climatic conditions).

Others such as Bastianoni et al. (2000) and La Rosa et al. (2008) have found that, in cases when more local and renewable inputs are used, i.e. higher sustainability, the productivity of organic systems fall short to conventional systems. These studies however failed to incorporate extra storages, important life sustaining and ecological services that are provided free of charge (air and water purification, soil enrichment, material for housing, energy, erosion resistance, and stable climatic conditions through transpiration). Disorder abatements accounted for various toxic chemicals and pollution emitted were neither assessed.

Constellini et al., (2006) and Lefroy and Rydberg (2003) have shown that although the magnitude of yields in case of organic systems is relatively low, when compared to conventional ones, transformities (energy qualities) of co-products were only slightly reduced (by 10%), which in terms imply greater overall efficiency (Hong-Fang Lu et al., 2006) For more detailed definition please see the glossary under *transformity*.

Lefroy and Rydberg (2003) in their comparison, (conventional lupine/wheat rotation, and the combination of both) also showed that once agro-forestry systems are matured they are less resource intensive and more productive in terms of their energy return. Another result of the same study indicated that the two largest energy flows in case of the conventional lupine/wheat system was purchased phosphate and wind erosion. Such results imply that despite larger yields these systems are heavily reliant on nonrenewable, high quality (concentrated) resources and are subject to robust environmental impairments.

Another paper that was comparing two rearing systems claimed that poultry feedlots based on conventionally produced crops were about four times as productive. However their total resource use representing the use of chemical fertilizers and pesticides however showed sixty percent increase (Castellini et al., 2006). In the light of their environmental burdens and repercussions to human health advanced productivity imparted by such conventional systems must be re-assessed.

An interesting and new approach used by Pizigallo et al. (2008) merged *Life Cycle Assessment* (see glossary) with emergy evaluation, and by doing so created an even more comprehensive methodology where energy accounting incorporates important abatement costs.

In 2001, Beck and his co-workers published a study, in which an emergy evaluation was performed on four newly installed experimental city plots, imitating four different systems (a conventional ornamental landscape, an intensive organic garden, an edible landscape, and a forest garden). Preliminary evaluation on installation was conducted and data concerning yields and other co-products where assessed based on a five year projection. However, five-year projection raises questions regarding objectivity. Based on the results, the authors found that productivity of all systems were low, due to high resource intensity of construction and small productive areas (plots with an area of 16 m^2). More importantly, the study concluded that even though local food producing systems were implemented, resource-consuming nature of cities would not change. As the study concludes, comprehensive change requires the transformation of supporting larger systems and their energy and material pathways. In spite of these drawbacks, small sustainable systems are still progressive when incremental costs such as transportation, storing and distribution are considered.

Hong-Fang Lu (2006) and his colleagues introduced important system variables such as overall increase in environmental storages and ecological economic products EEP (env. storage increase + yield) to find out whether human made sub-systems can successfully substitute or repair damaged natural systems. Other new emergy indices, such as the emergy restoration ratio ERR (env. storage increase / purchased resources), and the emergy exchange ratio EBE (env. storage increase / purchased + local, or locally reused resources), were used to determine ecological and economic benefits of restoration. More importantly calculations concerning environmental storages were performed. Such calculations became the basis for estimating the coarse extent of environmental storages in this study.

2. Materials and methods

2.1 Location

The subject of this study was constructed in the city of Uppsala on a 12 m^2 internal garden area surrounded by the buildings of Uppsala Center of Sustainable Development. There were a few expectations with respect to the design. The plot had to be constructed in a sustainable manner, in order to incorporate the essential characteristic of sustainable design (a design that mimics the interactions of ecological systems. Or by definition; a design that facilitates the aspiration for *meeting basic human needs without destroying or degrading the natural environment*). In reality, it meant that construction should have been based on low purchased input use; the garden should have sustained or improved biodiversity and facilitated urban resilience. Urban location was a similarly important criterion for minimizing transportation costs and to increase urban self-sufficiency. Furthermore emergy evaluation required a precise inventory of materials and services used, hence a relatively bare and small site had to be selected.

Established CSD urban garden system (photo: Christopher Wegweiser-2013.08.20.)

2.2 Systems Ecology

Systems ecology is an interdisciplinary field of ecology that focuses on the interaction of the elements within any open-system (any system that is subject to entropy or energy dissipation and interacts with its surrounding is an open system). It is a holistic approach to the study of ecology and can also be seen as the application of general system theory on the field of ecology.

- *Systems ecology can be defined as the approach to the study of ecology of organisms using the techniques and philosophy of systems analysis: that is, the methods and tools developed, largely in engineering, for studying, characteriszing and making predictions about complex entities, that is, systems..*
- *In any study of an ecological system, an essential early procedure is to draw a diagram of the system of interest ... diagrams indicate the system's* ***boundaries*** *by a solid line. Within these boundaries, series of components are isolated which have been chosen to represent that portion of the world in which the systems analyst is interested ... If there are no connections across the systems' boundaries with the surrounding* ***systems environments****, the systems are described as* closed*. Ecological work, however, deals almost exclusively with* open *systems*[2]

Central feature of systems ecology is the use of energetics principles which also constiute the ecosystem principles. Such priciples are applicable to all sytems at any scale and enable scientists to describe different functioning phenomena and interactions across different systems scales. For such description emergy system language is used, a tool introduced by Howard T. Odum. Odum is also noted for the development of the forth, fifth and sixth energetic principes of thermodynamics/energetics. The principles are as follows:

- **Zeroth principle of energetics**
  If two systems A and B are in thermal equilibrium, and B and C are also in thermal equilibrium, then A and C are also in thermal equilibrium.
- **First principle of energetics**
  The increase in the internal energy is equal to the amount of energy added to the system by heating, minus the amount of energy lost in the form of work done on the surroundings (eg. heat loss).
- **Second principle of energetics**
  The total entropy of any isolated system tends to increase over time.
- **Third principle of energetics**
  In case of a for the case of a perfect crystalline substance, as the temeprature approaches absolute zero of the system, all processes cease and the entropy of the system approaches a minimum value or zero.

[2] Kitching, R. L. (1983) Systems Ecology *University of Queensland Press*

- **Fourth principle of energetics**
  In the field of ecological energetics H.T. Odum regarded maximum power, the fourth principle of energetics. Which states that duing self-organization, system design prevail that maximizes power intake, energy conversion and reinforce production at optimal efficiency.
- **Fifth principle of energetics**
  The energy quality increases hierarchically. Based on the observations on ecological food chains, Odum proposed that energy transformations form a hierarchical series, similar to tropic levels that are measured by Transformity (energy density) increase (Odum 2000, p. 246). "Flows of energy develop hierarchical webs in which inflowing energies interact and are transformed by work processes into energy forms of higher quality that feedback amplifier actions, helping to maximise the power of the system" — (Odum 1994, p. 251)
- **Sixth principle of energetics**
  Energy/mass ratio determines the zone and pulse frequency of a resource flow in the energy hierarchy. (Odum 2000, p. 246). M.T. Brown and V. Buranakarn write, "Generally, energy per mass is a good indicator of recycle-ability, where materials with high energy per mass are more recyclable" (2003, p. 1).

2.3 Emergy Synthesis

For our evaluation emergy synthesis was used. Emergy synthesis is a method used in systems ecology that focuses on the interactions, pathways of any given system and consists of two parts, emergy diagramming and emergy evaluation. During diagramming boundaries and interactions of the system or process in question are defined, while during emergy accounting or evaluation, aggregated and/or separate flows are evaluated on a common basis (Solar emergy equivalents). (Odum, 1996)

Emergy analysis is composed of two parts: diagramming and emergy accounting. Diagramming is a useful tool in determining and understanding how systems are organized and affected by their larger surroundings. It is also an inventory of important resource flows, system pathways and components. By simulating such flows and pathways we can predict how systems would behave under different conditions. Emergy accounting on the other hand is used to quantify the value of various components and compare various processes of the same or different systems. Emergy analysis thus has two main functions. First, it is used to identify important human made and natural system components and pathways as well as to predict the effects of present or future conditions.

Basic steps of emergy synthesis can be summarized as the following:

- Preparing an system diagram
- Aggregating system flows by category
- Preparing the emergy table

Preparing a system diagram

1. Identifying the boundary of system view. Separating internal components and processes from outside influences.

2. List of important internal and external sources (effect is 5% or more of the total system function).

3. List of system components within the system boundary defined.

4. List of processes (flows, interactions).

5. Drawing system diagram using appropriate symbols. Arranging sources and components according to transformity, from left to right. Then symbols are connected with pathways, including money transactions.

*If time of reference is one year, storages with shorter turnover time should not be included

Aggregation

Initial detailed diagram can be simplified by aggregation. During aggregation, important components and resources flows are kept and merged into fewer symbols and pathways arranged according to their categories (local renewable, local non-renewable, purchased or imported materials and purchased services) (Odum, 1996). Important separated flows are then incorporated and evaluated in the emergy table.

Seven Column Format Emergy Table

Note*	Item	Unit (J,g or $)	Data (units/yr)	Unit Emergy Value (SeJ/unit)	Solar Emergy (E10 SeJ/yr)	Em$ Value (2005 $/yr) †
1.	(One line here for each source, process or storage of interest.)					

* Footnotes for each line.

† Solar Emergy in Column 6 devided by Emergy/money ratio of Sweden for 2005

2.4 Materials

Work on the plot began in March of 2010. Various material inputs (concrete bricks, glass plate, soil, aluminum foil, plastic bins, seeds, horse manure...etc) were purchased or collected and transferred to the university to construct the garden's four subsystems. Namely, the plant nursery, a table with plastic bins where plant seedlings were raised; a hot bed that prolonged seasonal production by utilizing the heat of horse manure; a raised bed, that occupied a few vertical m2, improved production and efficiently used available space; and a compost bin, that recycled disposed organic materials. Temporal timeframe of the project was defined as one season. All input and output data was collected during this period. W**eight** (in SI unit of **gram**) of all used resource inputs was measured while **input energy** along with **transformity** and **emergy per unit weight** (**UEV**) values (**Sej/J** or **Sej/g**) were collected from historical databases and previous studies. Other inputs such as services were measured in money paid for such services (**SEK**) and recent emergy/money (**Sej/SEK**) ratio was used for their emergy conversion. **Fig.** 1 indicates project phases.

Fig.1 Showing project sequences

2.5 Storage Increase

Storage increase calculations of the garden followed the functions presented in the Hong-Fang Lu (2006) report (annual increase - ▲Q is calculated as renewable inputs + recycled inputs – non-renewable resources + feedback resources).

2.6 Soil Degradation

Average soil degradation was calculated based on the average erosion rate in Europe and North America, which was described to be between 500 and 1000 g/m_2. (Pimentel et al., 1995; Beck et al., 2001; Lefroy And Rydberg, 2003) For soil erosion rate a relative low reference value of 500 grams was used because intensive soil management practices e.g. tillage or synthetic fertilizers were precluded. However it is assumed that once the system matures relative soil erosion rate will approach zero.

2.7 System and its environment

Fig. 2 describes the position of the garden in the regional system (Uppsala city). Within our larger system boundary, we find several subsystems. These are the local ecosystems, the garden with its net producer subsystems and the local economy. All of these systems are interconnected through various feedbacks and resource flows. Main local renewable flows are the sun, wind and rain that support both our producers and the local ecological systems, the ecology in return provide resources such as the topsoil, nitrogen and organic material, phosphorus and water. Some of these resources are then used to support the garden's production, while the remaining are used and stored by the ecological systems. The garden, in addition is connected to the local economy. There is a mutual exchange between the two. While the economy receives some agricultural products (during self organization material contribution is minimal or none. However the information provided by the system is valuable) the garden benefits from the money flow and materials provided by the economy. The wastes produced by the garden and the economy are returned to the ecosystems and/or reused by the garden.

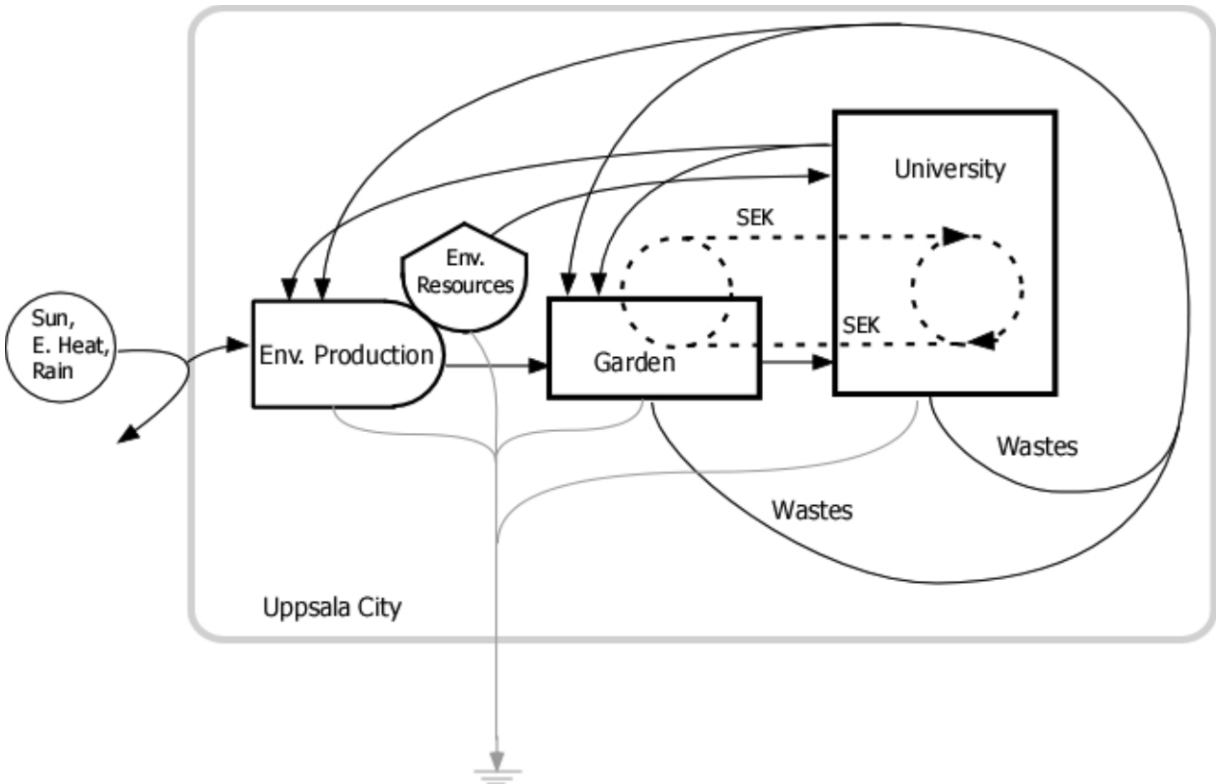


Fig. 2 - Position of urban garden in its larger environment. Ecological, transitional systems and the economy are linked with energy and material flows. The economy serves as the major feedback flow while ecological systems are responsible for production. Wastes as secondary output returns to ecological system where it is decomposed and reused for production.

3. Results and discussion

Following the guidelines of emergy synthesis given by Odum (1996) boundaries of the whole garden and its subsystems were defined (**Fig. 2**). Within the timeframe of one year aggregated and detailed solar emergy flows were calculated. **Table 1** shows aggregated input and output emergy flows for the whole system by category.

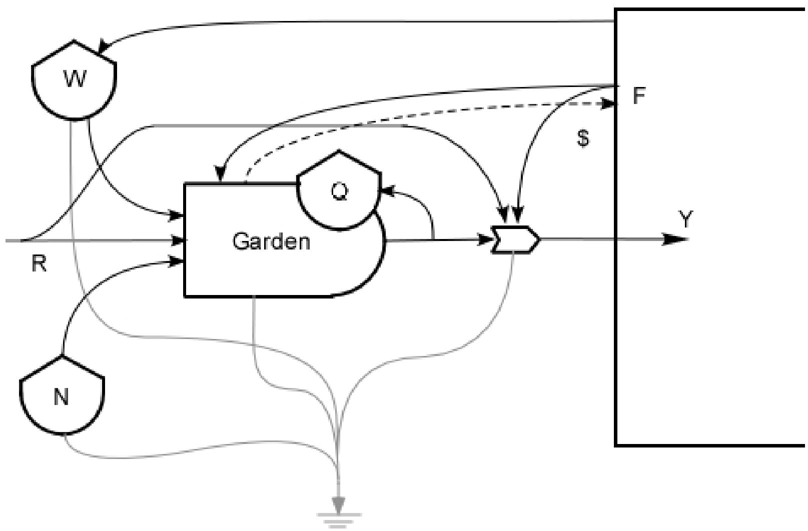
Table 1. Emergy input and output of the garden and its sub systems (Sej / yr / m^2)

Item	Emergy
Renewable input from sun, rain, wind, and deep earth heat (R)	16,27 E+15
Nonrenewable inputs from soil erosion (N)	0,7 E+11
Purchased feedback resources (F)	4,33 E+15
Free Imported resources (W)	0,11 E+15
Yield (Y)	6,0665 E+15
Storage Increase (▲Q)	6,0664 E+15

Fig. 3 shows environmental flows and storages, and the economic feedbacks that are the linked in the system. Economic feedback resources (F) supporting the garden consisted two categories, economic feedback inputs or materials and feedback services associated with these materials (i.e. transportation, extraction, manufacturing...etc.). In other words both the emergy embedded in the product itself and the emergy supporting its manufacturing must be calculated. Emergy of additional services is available through the money paid for such services.

Emergy of local renewable inputs of sun, wind, rain and deep earth heat was calculated (R). Deep earth heat as the result of radioactive disintegration and kinetic friction was treated as a separate source while the emergy of sun and wind as a co-product of the same planetary source were omitted to avoid double counting. Nonrenewable local input was soil erosion (N). Organic material (household waste), straw, compost soil from municipality, horse manure and woodchips were recycled or reused freely imported resources (W). Change in natural ecological storages (this case increase) was noted with (▲Q) and was calculated as the sum of local renewable, imported free and purchased inputs complemented with imported management feedbacks. However, to avoid double counting soil depletion had to be subtracted from the annual increase (increase in biomass affects soil by removing some of its minerals and nutrients thus facilitating depreciation in soil quality).

Several emergy indices defined by Odum (1996), the emergy yield ratio (EYR), Environmental Debt Ratio (EDR), the emergy loading ratio (ELR), the emergy footprint ratio (EFR) and sustainability index were used to indicate, the ecological economic efficiency, efficiency of environmental improvement, the amount of renewable inputs used, the ecological impact from human influence, and the system's potential for sustainable development. Other indices described by Hong-Fang Lu and colleagues (2006) such as the ecological economic product (EEP) and the emergy benefit ratio (EBR) were used to evaluate the total emergy produced by the system and its ratio over feedback inflows.



EYR = Y / F
EDR = Delta Q / F
EEP = Delta Q + Y
EBR = (EEP) / F
% Renewable = R / (R + N + F) = R / U
% Recycled = W / (W + R + N + F)
ELR = (F + N) / R
EFR = U/R
ED = U / total surface area
SI = EYR / ELR

Delta Q (Annual Storage Increase) = R + W - N + F

Fig. 3 - Network of aggregated input and output emergy flows and system indices with calculating functions.

Material and energy flows entering the garden system were converted into separate emergy units in **Table 2** (See notes for calculations). Sun, wind, deep earth heat and rain were the first input flows entering the system.

Emergy of deep earth heat was evaluated and included into this category despite of the fact that most studies are not necessarily concerned with this variable. I have included the emergy deriving this source because it is the result of two essential internal processes and thus could be considered as a separate source. Deep earth heat is the sum of the heat deriving from radioactive decomposition and the heat generated by the internal rotational fraction of earth's core.

Average annual soil degradation or topsoil loss was a local but nonrenewable (slowly renewable) resource flow. For Sweden soil depletion was defined as 500 $g^{/}m^2$ Lefroy and Rydberg, 2003). Also this value was used in this study (as noted earlier, production of biomass requires some depreciation of soil) although much of soil erosion could be discarded due to the soil amelioration attribute of the system.

Straw, household waste, paper, compost soil and horse manure were classified as recycled or reused imported feedbacks and were applied to improve soil properties. 50 kg of straw was used for mulching, while 70 kg household waste was composted and distributed between all subsystems.

1,2 kg of paper was cut and mixed into the soil. It is important to note that transformity of recycled materials slightly differ due to the difference in the process of their production (reduced resource intensity). For calculating the emergy of recycled paper and other materials I have relied on the study of Buranakarn (1998) who has done extensive calculations with respect to transformities and emergy contributions of recycled materials. Compost soil was imported from the municipality. In total 125 kg. For compost, new transformity values calculated by Bergquist (2010) were used. Unfortunately, there are only a number of papers dealing with organic farming practices. Therefore available data on sustainable systems and processes were limited.

Other freely acquired inputs were horse manure and woodchips with the weight of 350 kg and 100 kg in that order. While woodchips was used to cover walking paths, horse manure was applied due to its soil amelioration quality and exothermic property. With the extra heat generated by manure, seasonal production was extended (with approximately one month).

Table 2. Emergy accounting table (emergy inflows of 1 m2 garden by category)

Note	Item	Raw Unit	Unit Emergy Transformity (SeJ/unit)	Solar Emergy (E12 SeJ/yr)	EmSEK Value (2005 SEK/yr)	% from U (%)
ENVIRONMENTAL INPUTS						
RENEWABLE						
1	Sun	3,075E+09 J	1	0,0033	0,0021	5,06287E-05
2	Wind	2,9E+06 J	1,50E+03	0	0,0025	7,19E-05
3	Deep earth heat	1,32E+06 J	1,02E+04	0,013	0,0089	2,21E-04
4	Rain	1,75E+06 J	3,02E+04	0,083	0,035	8,73E-04
NONRENEWABLE						
5	Soil used	5,65E+05 J	1,24E+05	0,84	0,047	1,16E-03
Note	Item Raw Unit	Unit	(SeJ/unit)	(E12 SeJ/yr)	(2005 SEK/yr)	(%)
	Sum of free environmental inputs (2 omitted)			0,16	0,09	2,25E-03
IMPORTED RESOURCES						
RECYCLED						
6	Straw	6,83E+07 J	4,30E+03	0,33	0,17	4,85E-03
7	Organic material (household waste)	3,2E+02 J	1,24E+05	3,75	2,65	6,56E-02
8	Paper	2,09E+06 J	2,39E+05	0,5	0,33	8,23E-03
9	Compost soil from municipality	2,34E+08 J	3,63E+05	85,5	56,98	1,40889375
10	Horse manure	2,92E+04 g	1,27E+08	3,67	2,47	6,11E-02
11	Woodchips	0,83E+04 g	1,48E+09	12,33	8,2	0,202846154
	Sum of recycled inputs			106,25	70,83	1,751496328
PURCHASED						
12	Fuel	1,57E+07 J	8,05E+04	1,25	0,84	2,07E-02
13	Soil	1,33E+08 J	7,38E+04	9,75	6,5	0,160862598
14	Seeds	7,6E+04 J	3,64E+05	0,0275	0,018	4,56E-04
15	Municipal Water	1,33E+05 J	5,45E+05	0,083	0,048	1,20E-03
16	Concrete Blocks	3,5E+04 g	2,59E+09	90,58	60,37	1,492615385
17	Glass (Flat glass)	1,29E+03 g	2,69E+09	3,5	2,32	5,72E-02
18	Plastic	1,67E+02 g	5,29E+09	0,92	0,59	1,45E-02
19	Car	0,57E+01 g	6,70E+09	0	0,026	6,30E-04
20	Equipment	6,67E+01 g	7,90E+09	0,5	0,35	8,68E-03
21	Aluminum foil	0,83E+01 g	2,13E+10	0,17	0,12	2,93E-03
22	Labor (Free)	1,02E+07 J	5,71E+08	5811,58	3874,38	9,58E+01
23	Extra services paid	2,78E+01 $	1,50E+12	41,75	27,84	0,688368956
	Sum of imported inputs			106,75	71,18	1,759880349
SERVICES						
	Sum of services inputs			5853,33	3902,22	96,48336896
	Total Emergy			**6066,5**	**4044,33**	

Fuel for transportation was purchased and thus belonged to the group of purchased imported feedbacks. As it was earlier noted emergy of purchased resources consists of two parts: The emergy embedded in the product itself and the emergy spent on its additional services such as transportation, extraction, manufacturing, wages paid for individuals and so on. Money paid for such services was used to calculate such supplements. Emergy of money paid for services thus was calculated collectively under the name services. Quantity of fuel used during the year was determined based on average fuel consumption of the vehicle and actual mileage driven.

Additional soil that was purchased (70 kg) was mixed with the compost and spread between the beds and plant nursery.

With respect to plant species pumpkin (*Cucurbita pepo*), beans (*Phaseolus vulgaris*), cucumber (*Cucumis sativus)* and tomato (*Solanum lycopersicum)* were purchased and planted from seeds. Difference in weight and energy content of seeds was minimal and thus did not represent significant importance. Total weight of seeds was measured (45 grams) and their aggregated energy value was calculated based on their average reference value. Transformity was taken from (Martin et al., 2006). Municipal/tap water was also consumed. Although normally rainwater was collected, additional watering became necessary. Unlike rain water tap water is a feedback resource because it's cleaning and distribution requires fossil energy. The extra energy spent on such services was incorporated in the extra money paid for such supplementary services. Hence tap water holds an increased transformity value.

Labor is a resource with one of the highest energy qualities. Human work thus significantly increases the emergy value of systems or processes. Normally human labor is compensated monetarily. However during the installation of the garden all required labor was done for free of charge. Paid labor would have increased the amount of emergy invested as paid services. Which in fact increases, the ratio of feedback resources to other resources other then purchased and imported. It meant that additional expenses with respect to wages and other supplementary services were disregarded. Another important factor determined was the percentage or ratio of renewable and nonrenewable inputs that manual labor is based upon. For instance (higher) education and professional labor in Sweden is sustained by 72 percent imported and 28 percent renewable reserves. (Skuladottir, 2005). Consequently, 72 percent of the labor spent on installation is viewed as a non-renewable import while 28 percent is considered as a local renewable flow.

Transformity of some imported feedback flows were specified in emergy per unit weight quotient. Annual emergy value calculations of these resources were somewhat simplified because their measured weight could be simply multiplied with their appropriate specific emergy (emergy per unit weight).

Concrete blocks, flat glass was constituent of the hot bed; plastic was used to prepare containers. Their weights were 420 kg, 15,5 kg and 2 kg in such order. Although the full lifetime of a car is about 15-20 years only its depreciation was defined (based on its mass and actual time driven) for this time period. (Lefroy and Rydberg, 2003; Brown and Bardi, Folio#3, 2001).

Emergy contribution of tools such as shovels, rake and so on was assessed in a similar manner.

Aluminum foil, as the last material input was purchased and used for harvesting the sun's thermal energy. Used aluminum cans are often recycled and used as sun collectors. Finally, emergy of supplementary services was calculated using all the money spent for materials purchased. Emergy money ratio is normally indicated in SeJ/$. Because in Sweden SEK is used the actual money paid for services was exchanged into SEK based on the actual SEK/USD ratio (Forex, 2010). Emergy per money ratio for Sweden is calculated by dividing the total emergy used of the particular country with its GDP in USD. Emergy value of extra services is the function of total money spent per emergy per unit value for Sweden (Skuladottir, 2005).

3.1 Transformity (TR)

Transformities for co-products were calculated based on the guidelines provided by Odium, (1995, 1996). Transformity is an important value reflecting the system's overall efficiency and the quality of its products (Hong-Fang Lu, et al., 2006). Annual yield of the garden was 1 pumpkin and 13 tomatoes with a mass of 2,76 kg and 90 grams for each tomato (total wet weight was measured). Which is a relatively low yield that resulted a considerable increase in the transformities of co-products. (See **Table 3**). Caloric values for energy values of pumpkin and tomatoes were taken from www.caloricount.about.com (2010). Such high transformity values imply that overall production efficiency of the first year was low. However, by comparing the system's annual yield and environmental storage increase (▲Q), we can see that most inflowing energies were rather invested to construct the system's environmental reserves and to establish its energy or material pathways. Compared to the study of Bergquist (2010), TR for tomato was 3.34 times higher while TR for pumpkin was greater 82 times. When compared, TR of fruit co products of other systems showed similar results. For instance on an 1.8 ha organic farm specific emergy for orange was defined as 0.6 x 10^9 while specific emergy of our tomatoes and pumpkin were 6.22 x 10^{11} Sej/g and 2.64 x 10^{11} Sej/g. Other studies produced lower TR values. 5.36 x 10^6 Sej/J TR for greenhouse tomatoes was calculated by Lagerberg and Brown (1999) and 5.97 10^5 Sej/J for regularly grown tomatoes in the study of Brandt-Williams (2001). Beck and his collages (2001) arrived to a 3.28 x 10^5 Sej/J TR value for vegetables in case of an urban food garden.

Table 3. - Transformities for system's co-products

Item	Energy (J)	Transformity (SeJ/J)	Specific emergy (Sej/g)
Tomato	870272	8,36 E+08	6,22 E+11
Pumpkin	2987939	2,44 E+08	2,64 E+11

Fig. 4 shows the emergy system diagram. Important resource flows and storages are indicated. Sources and system components are placed from left to right according to their UEV value (Unit Emergy Value, measured in SeJ/g) or transformities (SeJ/J). From the left important renewable energy flows are entering the system. These are solar energy of the sun, energy of the wind, chemical energy of rain on land, and energy deriving in the form of heat from the earth cycle. Other environmental sources are also provided by the surrounding ecosystem, such as the energy embedded in the soil. Other resources placed on the top are representing purchased and none purchased imported resources used for installation and production. Recycled materials illustrated with a tank symbol are various wastes of the economy that are collected, stored and used within the garden. Money received

from the economy is similarly stored and used to reimburse services. Each sub-system is a producer. For instance plant nursery is responsible for plant development; others are generating benefits such as nitrogen, organic matter from plant residue. Yield as another output signifies important subsidies e.g. fruits and vegetables at the end of the season.

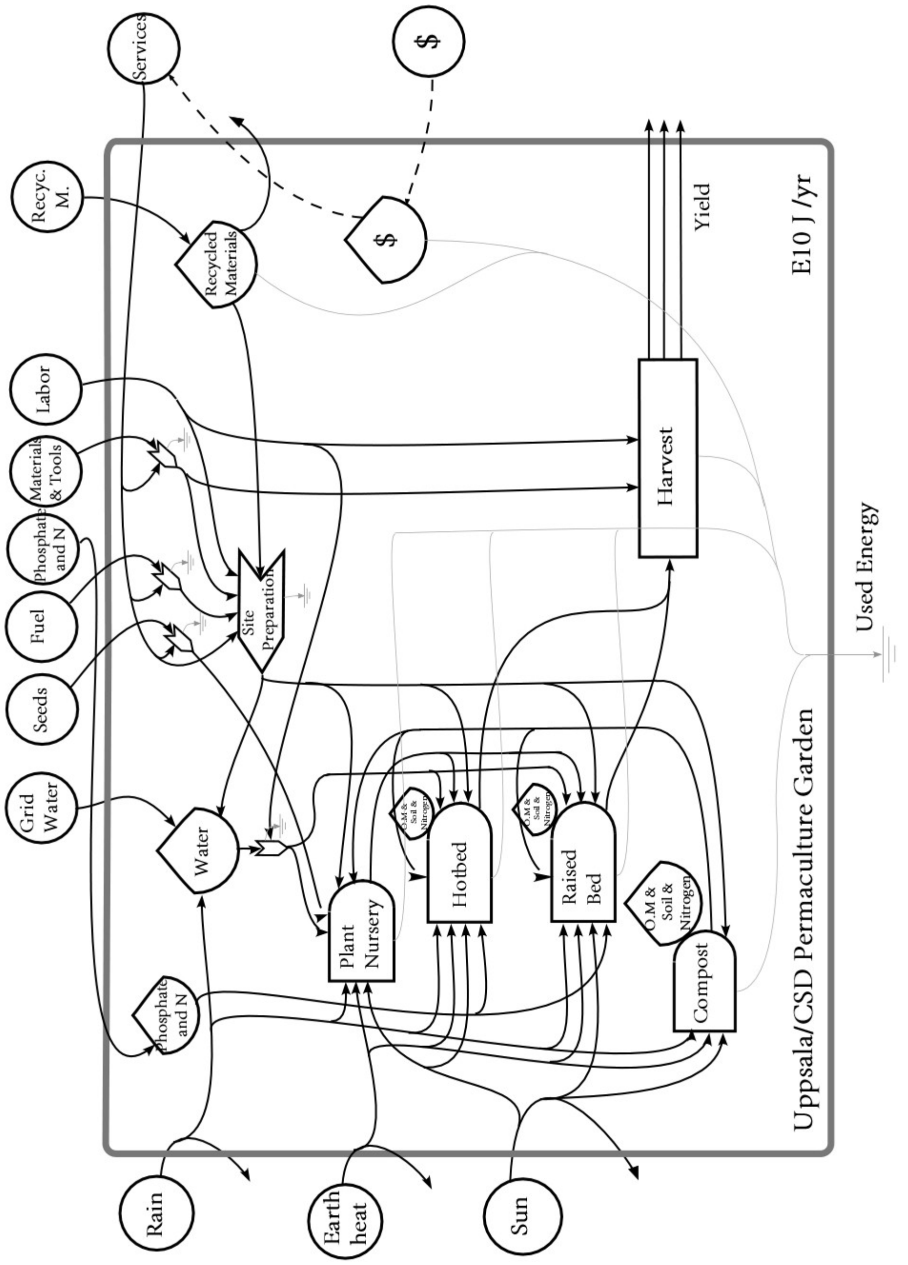


Fig. 4 - Emergy flows of the urban garden on a sub system level.

3.2 Emergy investment ratio (EIR)

Emergy investment ratio indicates the ratio of purchased resources to free environmental resources (including nonrenewable resources). High investment ratio suggests predominant use of purchased resources. In such cases, production is far from being economical (Brown and Ulgiati, 1997, 1998). On the other hand, if quotient is below 1 (which is the optimal), then the amount of feedback resources utilized by the system is low. Consequently, the system is not operating on its maximum productivity. Low EIR also suggests a low production cost since most resources are acquired locally for free. Their products therefore are often cheaper than of the competitors. Too low investment ratio implies an increased pressure on the local environment. *Maximum power principle* suggests that to be competitive, systems often adjust to the ratio common for a particular region (Odum, 1996; Brown & Herendeen, 1996).

The EIR of the garden was 2.50. (See **Table 4.**) This value indicates that during installation, the use of feedback resources exceeded the optimal 1:1 ratio. Although a relatively modest amount of imported resources was used, the balance was shifted in the favor of feedback resources due to the overwhelming application of manual labor which is primarily sustained by fossil based energy. EIR of 2.50 shows that emergy investment of feedback resources is almost three times as much compared to local renewable sources. High initial EIR on the other hand is justifiably at some cases (depends on our objective) because by increasing the rate of feedback flows, our system can be set on a growing pattern. The rate of renewable flows is eventually increased through self-organization to compensate high feedback flows and thus achieve a better EIR. Initial resource dependency, however, could have been optimized if the application of reused or recycled inputs would have been increased. It is so because by ‘transferring’ more emergy to local resources EIR approaches the favorable 1:1 ratio.

3.3 Emergy yield ratio (EYR)

Emergy yield ratio is the indicator of the yield in contrast to inputs other than local resources. It measures the efficiency of the system using purchased inputs (Ortega et al., 2005). High number means better efficiency.

EYR of the garden was 1.4. The same for Bergquist (2010), for the indigenous and organic plots of Martin et al. (2006), and for La Rosa et al. were 8.63; 12.17; 1.5-1.6 respectively. As former description indicates, this value for the garden is low due to high early investment costs and low production values. As other studies suggest, EYR increases while the system matures because the rate of efficiency starts to approximate to its optimal value (Beck et al., 2001; Haden, 2003; Hong-Fang Lu et al., 2006).

3.4 Emergy loading ratio (ELR)

ELR is the ratio of feedback and nonrenewable inputs to renewable resources. It indicates the amount of stress on the environment. Low ELR means a low impact while the opposite suggests political and legal actions to adjust production to the carrying capacity of supporting system (Brown, Ulgiati, 1997). In case of the garden ELR was moderate 2.66, a nearly identical value to its EIR. Higher ELR can be explained by high investment cost and extensive use of services such as labor that are representing significant portion of the total emergy.

Table 4. - Indices for the emergy evaluation of the urban garden system

Index	Function		
Emergy Investment Ratio	F/R	2,50	
Emergy Yield Ratio	Y/F	1,4	
Environmental Development Ratio	▲Q/F+W	1,4	
% Renewable	R/total emergy	27 %	
% Recycled	W/total emergy	1,8 %	
Environmental Loading Ratio	(F+N)/R	2,66	
Environmental Footprint Ratio	U/R	3,66	
Emergy Density	U/total surface	496,69	E+12 Sej/m2
Emergy Sustainability Index	EYR/ELR	0,5	
Emergy Benefit Ratio	EEP/F	2,8	

3.5 % Renewable

The percentage of renewable measures the system's overall sustainability. Higher use of renewable resources means a better sustainability rate and consequently a lower pressure on the natural environment (Ulgiati et al., 1994; Brown, Ulgiati, 2004).

The ratio of renewable inputs used in the first year was 27 percent. For Bergquist (2010), the rate of renewable and recycled inputs used was 80 and 40 percent. Significantly higher rate could have been achieved if larger portion of feedback resources could have been acquired as recycled or reused input. Or the amount of labor that was invested would have been based primarily on renewable supporting flows. Most of these investments, however, were restricted for the preparation year. In the following seasons, other resources such as soil or seeds will be generated by the system free of charge, while other investment, such as construction materials will not be used. Therefore the ratio of renewable to feedback resources will increase.

3.6 % recycled or reused

The percentage of recycled is the indicator of the amount of recycled materials used. Similarly to the previous indicator, higher percentage of recycled inputs improves efficiency and sustainability (Bergquist, 2010).

The percentage of recycled materials was 1,8. Although a considerable fraction of the inputs was recycled, most of these inputs have low transformity values and were applied in reduced amount. As a result their accompanying emergy was small in contrast to other products.

3.7 Environmental development ratio (EDR)

EDR was defined as the ratio of change in environmental capital to the sum of management inputs. It evaluates the relative efficiency of environmental development with products and co-products, such as biomass increase staying within the system. (Hong-Fang Lu et al., 2006).

Development ratio of the garden was 1.4. It is a relatively high number indicating that a considerable part of the increase in natural capital comes from human services, which is used to develop and maintain the system at the beginning.

3.8 Environmental footprint ratio (EFR)

Environmental footprint ratio is the ratio of total emergy to the emergy of renewable inputs. It indicates the size of support area capable of generating the same output using only renewable inflows (Haden, 2003). EFR of the garden was calculated as 3.66, which implies that the area used for production would have to be increased significantly, if system products would only based on renewable resources. Again, this result is partially misleading because based on previous studies it is expected that total emergy of the second year would differ from the emergy of the construction year (Martin et al, 2006; La Rosa et al., 2008). A reduction to about a ratio to 3 or 2 to 1 would be a good outcome for the forthcoming year.

3.9 Emergy density (ED)

Emergy density suggests the relative intensity of the system. It is the amount of emergy per unit area measured by dividing the total emergy with total surface area (Brown and Ulgiati, 2004). Emergy density of the system was little above 496 x 10^{12} Solar emergy Joules per m^2.

3.10 Emergy sustainability index (ESI)

The Emergy sustainability index is the ratio of EYR to ELR. It measures the highest EYR at the lowest environmental cost. In other words it indicates the highest possible EYR at the lowest environmental load. Higher number indicates higher productivity at a lower environmental load (Ulgiati, Brown 1997; Haden 2003).

Value of 0.6 was calculated for the garden in the first year, which suggests a relatively low productivity at a relatively large environmental cost. Similar to the other ratios, ESI most likely would improve in the forthcoming seasons because system outputs (environmental storages and yield) will most likely increase while the use of feedback resources will decline.

3.11 Emergy benefit ratio (EBR)

EBR is defined as the ratio of ecological economic products to the sum of imported inputs. It measures the ratio of emergy applied through human activity to the sum of all ecological and economical products. EBR of the garden was 2.80, which means that all output produced by the system is three times as much as the amount of imported inputs. (Hong-Fang Lu et al., 2006). It is relatively large human intervention compared to other systems. For instance 29-34 in case of a *mangium* forest subsystem (Hong-Fang Lu et al., 2006)

ELR of the garden was 2.66 while Bergquist (2010), Pizigallo et al. (2008) and Martin et al. (2006) calculated values of 0.24; 10.59; and 0.10 for the same. Finally, ESI of the different studies had similar result. ESI values were 35.43 (Bergquist, 2010), 0.03-0.08 (La Rosa at al., 2008), 0.01 (Haden, 2003), 0.0002 (Beck et al., 2001) and 0.5 (this study). In case of EYR higher values mean better production efficiency, however it is the opposite when evaluating ELR (ratio of feedback and renewable).

When result of the three systems evaluated by Martin and his colleagues (2006) (corn, black berry, indigenous) were compared, important system indices of EYR (1, 1.45, 12.17), ELR (18.83, 2.23, 0.10), ESI (0.06, 0.65, 115.98) suggested that once our system imitating an indigenous system with its complexity develops to its fullest potential it would produce the higher EYR and the lower ELR than of its industrial counterparts.

4. Conclusions

Introducing methods to improve material and energy use and thus to increase production efficiency brings both ecological and economic benefits.

Transformation of current food producing systems and energy consuming cities is inevitable. New alternatives based on ecological principles not only safeguard essential ecological systems from collapsing, but at times of resource scarcity could improve living conditions, maintain production and ultimately could facilitate an evolution in our social domain that is absolutely essential today. Without substantial change in the structure of our society, the quest for a sustainable future will most likely fail. Proliferation of self-sustaining gardens and other cooperative systems can facilitate such transition.

For evaluating the net benefits, annual storage increase and relative sustainability of our urban food-producinggarden system emergy synthesis was used. Such method is not only useful in determining values but can identify sustainable interactions between the natural environment and social economy. The project aimed to quantify the input output values (input requirements), the annual storage increase, and both the sustainability and relative efficiency of the system. Calculated indices of this, study have clearly shown that establishing such sustainable and self-managing systems is quite resource intensive because preparation, selection and reproduction of essential system components and energy flows (i.e.: self-organization) requires significant amount of energy and time. Consequently, optimal efficiency for maximum power has a theoretical lower limit that open systems can only attain after a long period of self-organization (Odum, 1996). And while the use of recycled and reused resources is vital in order to optimize resource use and reduce environmental stress, the application of feedback energies could reduce installation times.

However, it must be emphasized that such large investments are often restrained to preliminary phase. As the system improves environmental storages build up gradually and as a consequence the amount of emergy invested declines, and overall productivity increases. Calculated transformity values of this study compared with the transformity values of other matured gardens confirm this assumption. However, it should be affirmed with further evaluations.

Calculations with respect to annual environmental storage increase (▲Q) and yield of this research has shown that in the early stage of self-organization yield is relatively low because most material and energy are used for establishing essential pathways. Most energy thus is used to build up essential environmental storages and to construct necessary material pathways.

In terms of invested energy, human labor far outweighed other inputs, even though labor was done voluntarily on a free of charge basis. It also means that although educated labor seems free, it is a high quality input that is mostly supported by feedback energy flows. (Selection, duplication and transfer of information at our educational institutions are primarily based on fossil energy).

Other important indicators such as system indices (EIR: 1.4; EYR: 1.4; ELR: 2.66; EFR: 3.66; and ESI: 0.5) that during self organization production performance remains low and that the selection of input materials highly affects system growth and values indicating production and sustainability rates. And while such indicators are low during the phase of self-organization they most likely improve in the following seasons as environmental storages build up.

Finally although a comprehensive assessment was aimed for individual evaluation of separate storage values are missing. Such calculations along with the evaluation of system variable for the forthcoming seasons are open for future research.

Thus, as a personal recommendation I would have continue to measure the calculated variables for the forthcoming seasons to see how they change over time. From such data, general conclusions on the operation and organization of the system can be drawn. In addition, I would also calculate the emergy contribution of the separate resource flows. And then compare the overall result with similar systems that are located in different parts of the world.

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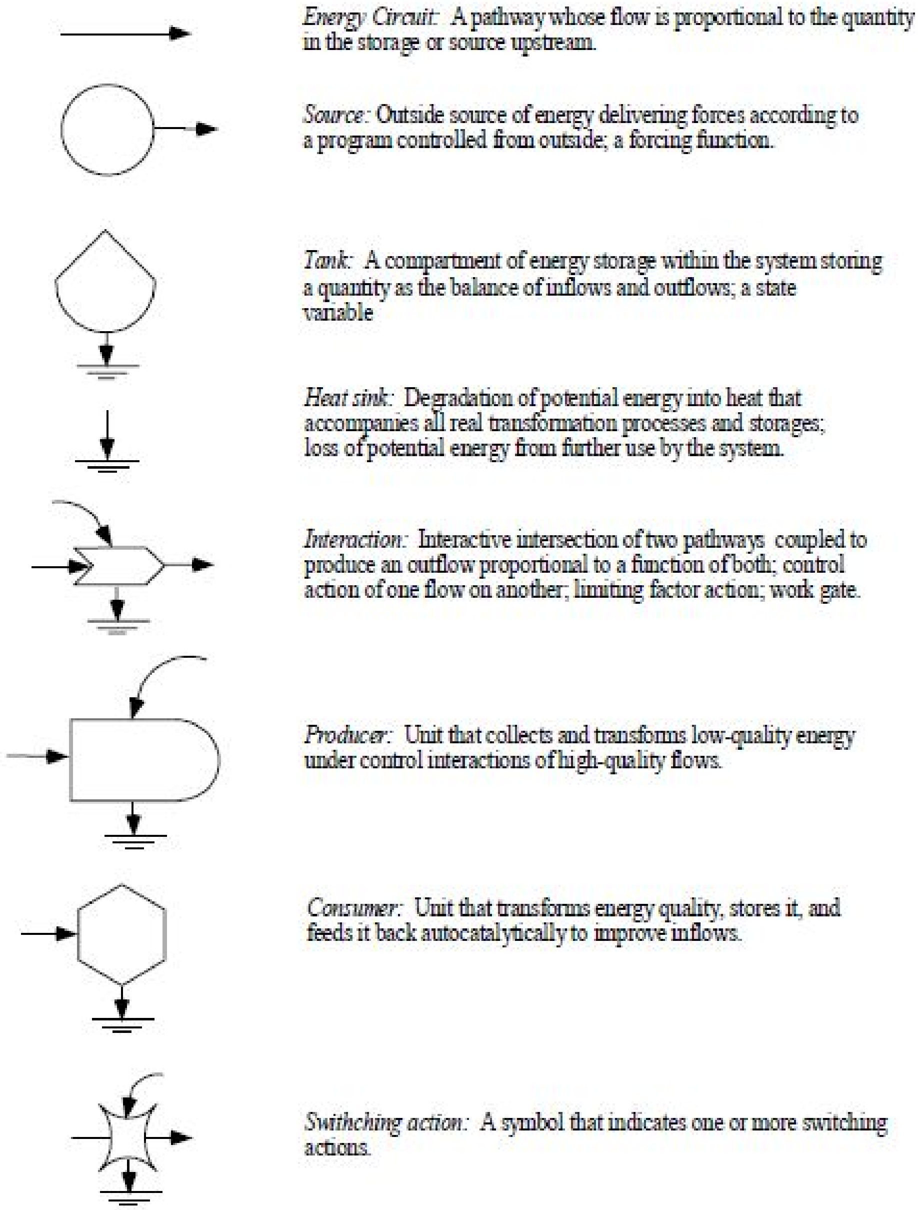
Appendix A

Energy system symbols and definitions (adopted from Bardi, 2002)



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: Degradation 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 proportional to a function of both; control action of one flow on another; limiting factor action; work gate.

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

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

Swithching action: A symbol that indicates one or more switching actions.

Appendix B (Notes)

Item Number	Item Description
1	Average solar insulation at Uppsala 3.61 x 10^9 J/m^2 per year (NASA eosweb, 2011). Energy received over land (Ometto, 2004) = 12 m^2 (land area) x 3.61 x 10^9 J/m^2 per year x (1-0,15) (1-albedo) = 3.69 x 10^{10} J per year. Transformity = 1 by definition (Odum, 1996)
2	Eddy diffusion coefficient 25 m^2/s (Brown and Bardi, Folio #3, 2001). Vertical gradient of wind 3 m/s (Brown and Bardi, Folio#3, 2001). Wind energy absorbed (Brown and Bardi, Folio#3, 2001) = 3 m/s / 1000m (height of atm. boundary) x 1.23 kg/m^3 (air density) x 25 m^2/s x 12 m^2 (area) x 3.15 x 10^7 sec per year = 3.49 x 10^7 J per year. Transfomity from Odum (1996).
3	Heat flow of crustal radioactivity 1.98 x 10^{20} J (Odum, 1996); Heat flow from mantle 1.32 x 10^6 J/m^2 (Odum, 1996). Deep earth heat used = 12 m^2 (area) x (1.98 x 10^{20} J)(heat flow of crustal radioactivity) + 1.32 1,32 x 10^6 J/m^2)(heat flow from mantle) / 5.10 x 10^{14} m^2 (earth's surface area) = 1.58 x 10^7 J per year. Transformity from Odum (1996).
4	Annual average precipitation Stockholm-Uppsala 554 mm per year (EuroWEATHER, 2011); Evapotranspiration of annual crops = 0.58 % of precipitation (Lefroy and Rydberg 2003) = 321 mm. Chemical potential energy of rain on land (from rainfall + collected) (Odum, 1996) = [12 m^2 (area) x 0.32 m (evapotranspiration) x 1 x 10^6 g/m^3 (density of water) x 4,94 J/g (Gibbs free energy of water)] + [4 m^3 per year x 1 x 10^6 g/m^3 x 4,94 J/g] = 2.10 x 10^7 J per year. Transformity from Odum (1996).
5	Average rate of erosion 500 g/m^2 (Odum, 1996); Organic fraction 0.05 organic matter (Odum, 1996). Average topsoil loss (Odum, 1996) = 12 m^2 (area) x 500 g/m^2 x 0.05 x 5.4 kcal/g (Gibbs free energy of soil) x 4186 J/kcal = 6.78 x 10^6 J per year. Transformity from (Odum, Brown, Brandt-Williams, Folio#1, 2001)
6	Energy per unit weight of straw 3.92 x 10^3 kcal/kg (Castellini, 2006) 1977).Annual energy of straw = 50 kg (weight) x 3.92 x 10^3 kcal/g x 4186 J/kcal = 8.20 x 10^8 J per year. Transformity from (Castellini et al., 2006).
7	Energy per unit weight of organic matter is 5.4 x 10^3 kcal/kg (Odum, 1996). Annual energy of organic matter from household waste = 17 kg (weight) x 5.4 x 10^3 kcal/kg x 4186 J/kcal = 3.84 x 10^8 J per year. Transformity from Odum (1996).
8	Energy per unit weight of paper 5 x 10^3 kcal/kg (Buranakarn, 1998). Annual energy of paper = 1.2 kg (weight) x 5 x 10^3 kcal/kg x 4186 J/kcal = 2.51 x 10^7 J per year. Transformity from Buranakarn (1998).
9	Annual energy of compost soil = 125 kg (weight) x 5.4 x 10^3 kcal/kg x 4186 J/kcal = 2.83 x 10^9 J per year. Transformity from Bergquist (2010).
10	Emergy per unit weight of horse manure = 3.50 x 10^5 grams (weight) x 1.27 x 10^8 SeJ/g (Bastianoni et al., 2001).

11 Emergy per unit weight of woodchips = 1.0 x 10^5 grams x 1.48 x 10^9 SeJ/g (Buranakarn, 1998).

12 Energy per unit weight of gasoline 3.18 x 10^7 J/kg (USDE, 2011). Average fuel consumption of a VW Transporter ’94 = 10.395 L per 100 km (www.carbuddy.com.au) Volume = 77 km (total mileage) x 0.135 L = 8.00415 L; Annual energy of fuel (Odum, 1996) = 8.00 x 10^{-3} m^3 per year (volume) x 7.37 x 10^2 kg/m^3 (density of fuel) x 3.18 x 10^7 J/kg = 1.88 x 10^8 J per year. Transformity from Odum (1996).

13 Caloric energy of soil 5.4 x 10^3 kcal (Odum, 1996). Annual energy of soil (purchased) = 70.2 kg (weight) x 5.4 x 10^3 kcal x 4186 J/kcal = 1.59 x 10^9 J per year. Transformity from (Odum, Brown, Brandt-Williams, Folio#1, 2001)

14 Energy content of seed 2 x 10^4 J/g (Beck et al., 2001). Annual energy of seed = 45.6 g (weight) x 2 x 10^4 J/g = 9.12 x 10^5 J per year. Transformity from (Martin et al., 2006)

15 Annual energy of municipal water = 3.22 x 10^{-1} m^3 per year x 1 x 10^3 kg/m^3 (density of water) x 4990 J/kg (Gibbs free energy of water) = 1.6 x 10^6 J per year. Transformity from (Buenfil, 2001).

16 Weight of concrete blocks used = 4.20 x 10^5 grams. Emergy per unit weight of concrete 2.59 x 10^9 SeJ/g (Buranakarn, 1998).

17 Weight of flat glass used = 1.55 x 10^4 grams. Emergy per unit weight of glass 2.69 x 10^9 SeJ/g (Buranakarn, 1998).

18 Weight of plastic used = 2.00 x 10^3 grams. Emergy per unit weight of plastic 5.29 x SeJ/g (Buranakarn, 1998).

19 Weight of VW Transporter ’94 1.6 tons (www.volswagentrasportbilar.se). Assumed useful lifetime 20 years. Annual mass used (Lefroy and Rydberg, 2003) = 6 hours (operating hours/yr) / 20 years x 1.6 tons x 1 x 10^6 g/tons = 6.85 x 10^1 gram per year. Emergy per unit weight of mixed metals 6.7 x 10^9 SeJ/g (Brown and Bardi, Folio#3, 2001)

20 Assumed useful lifetime of machinery 10 years. Annual mass used (Lefroy and Rydber, 2003) = 8 x 10^3 gram (weight) / 10 years = 8 x 10^2 gram per year. Emergy per unit weight of steel 7.9 x 10^9 SeJ/g (Buranakarn, 1998).

21 Weight of aluminum used = 1.00 x 10^2 grams. Emergy per unit weight of aluminum 2.13 x 10^{10} SeJ/g (Buranakarn, 1998).

22 Labor is based on 72 % imported and 28 % local renewable resources and includes energy spent on education (Skuladottir, 2005). Average per capita energy consumption 2500 kcal (Odum, 1996). Annual energy of labor = 2.8 x 10^2 hours / 24 x 2500 kcal x 4186 J/kcal = 1.22 x 10^8 J per year. Transformity from Odum (1996).

23 Exchange rate of Dollar to Swedish Krona 1.52 x 10^{-1} (Skuladottir, 2005). Total money spent in $ = 2.2 x 10^3 SEK x 1.52 x 10^{-1} = 3.34 x 10^2 USD per year. Emergy per unit 1.5 x 10^{12} SeJ/$ (Skuladottir, 2005)

Glossary

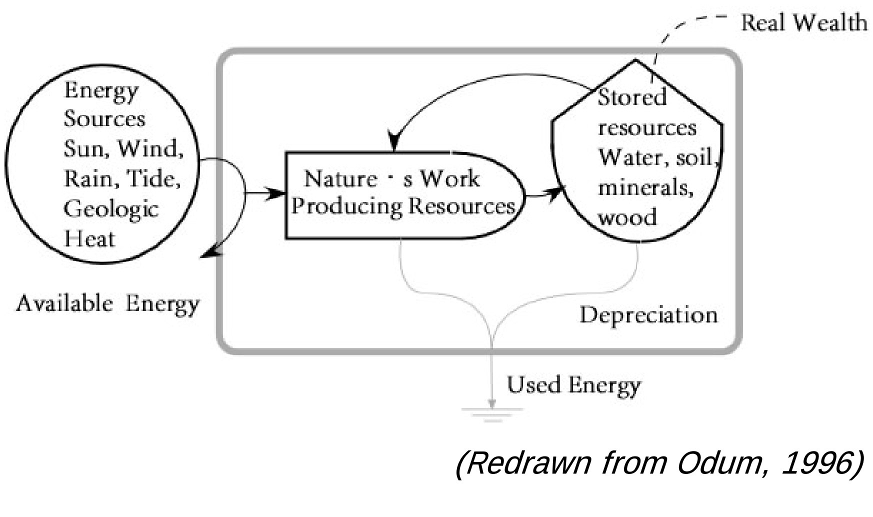
Available energy - by definition is the energy that is available to perform work (production). In open system thermodynamics it is also often quoted as exergy. Exergy is the remnant of energy transformation or production. Emergy however, is different from exergy, which in terms measures all the energy used during each phases of production (Odum,1996).

Power/Empower - defined by the rate of flow of useful energy. Empower thus is the rate of flow of useful energy expressed on a common basis (Solar energy equivalent) (Odum, 2007).

Ecological Economic Product (EEP) – EEP is the emergy of environmental storages plus the emergy of the system's yield. (Hong-Fang Lu et al., 2006)

Emergy Benefit Exchange (EBE)- Measures the ration of emergy left over the emergy return through market exchange. If the index is less than one more emergy leaves the system than is returned. (Hong-fang Lu et al., 2006)

Emergy – emergy or energy memory is the total amount of energy stored in a product or service. As long as there is inflowing energy the emergy of a product or service increases. (See figure below) Once the energy flow stops, the emergy of the product declines because the first law of thermodynamics implies a continuous dissipation or energy loss. If a product completely dissipates all its emergy is lost. Emergy by Odum is also defined as real wealth (Odum, 1996; Scienceman, 1987). Emergy is expressed in Solar Emergy, Joule abbreviated as SeJ.

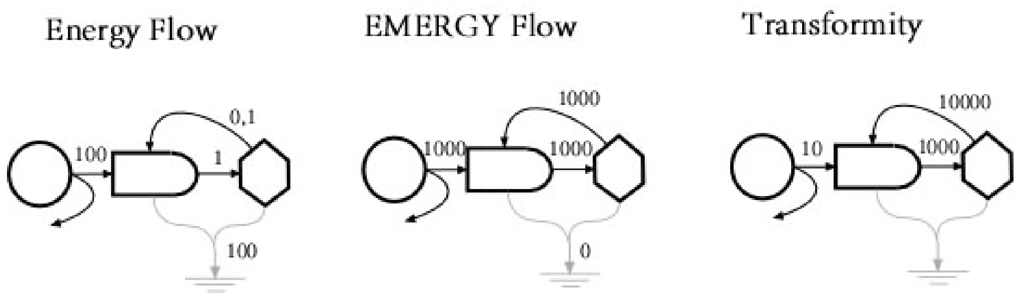


(Redrawn from Odum, 1996)

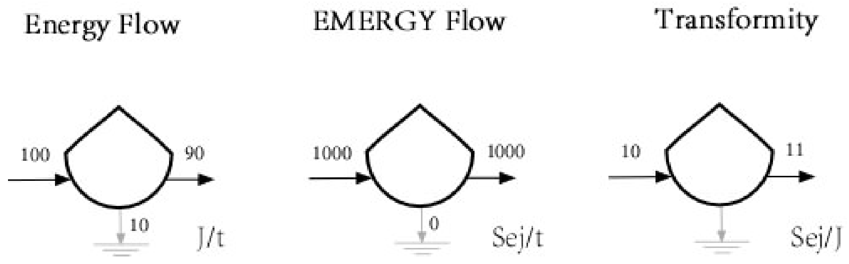
Transformity – transformity indicates the rate of energy density or energy quality of a product or service. During energy conversion, some of the available energy is lost as heat through a sink or energy drain. The remaining energy is reduced but it is more concentrated. Its ability to accomplish work declines, but its capacity to control processes increases. Thus its quality increases. Transformity is calculated by dividing total emergy with the available energy. Transformity is either expressed in Solar Emergy Joule/Joule or Solar Emergy Joule/gram. (Odum, 1996). High transformity suggests a low system's efficiency (Hong-Fueng Lu at al., 2006).

Item	SeJ/J
Sunlight	1
Wind kinetic energy	623
Unconsolidated organic matter	4,420
Geo-potential energy of rain	8,888
Chemical energy of rain	15,423
Consolidated fuels	18,000-58,000
Human services	80,000-5,000,000,000
Information	10,000-10,000,000,000,000

(Redrawn from Odum, 1996)



Correlation between energy, emergy and transformity. Available energy declines while it is being stored and concentrated. Energy memory or emergy (all energy used up) however increases until it is fed back as controlling or amplifying feedback flow. Energy quality or transformity increases during each transformation phases (Redrawn from Odum, 1996).



Influence of storage on available energy, emergy and transformity. Transformity increases during storing because storing requires additional energy use and thus subject to energy loss (Redrawn from Odum, 1996).

LCA – Life Cycle Assessment is a technique to assess environmental impacts associated with all life stages of a product or service. (US EPA, 2010)

Heterotrophic – an energy consuming component or system.

Open system – open system is a system that continuously interacts with its surrounding. Interaction most commonly takes form in energy, information or material exchange (Atkins, 2010).

Resilience – system's capability to respond to disturbances. (Holling, 1992)

Maximum power principle – Proposed as the fourth principle of open systems thermodynamics. The maximum power principle can be stated: "During self-organization, system designs develop and prevail that maximize power intake, energy transformation, and those uses that reinforce production and efficiency. (Odum, 1996) In other words during self-organization maximum power intake is always emphasized over maximum efficiency.

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