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Østergård, Hanne; Markussen, Mads Ville

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Energy Self-sufficiency from an Emergy Perspective Exemplified by a Model System of a Danish Farm Cooperative

Hanne Østergård and Mads Ville Markussen

ABSTRACT

Contemporary food production is highly dependent on fossil fuel for production of fertilizer and as diesel for field operations. One way to enhance agricultural resilience is to increase self-sufficiency at the farm level with necessities such as energy, food, fodder, nutrients and seed. It is even better if the farm is a net energy producer since energy used for processing, distribution and trade of farm products should be supplied also by agriculture in order to increase the resilience of food supply systems. In this project we analyze these potentials based on a model system of a multifunctional Danish organic farm cooperative with a small biogas plant shared between five farms. We model the energy, matter and emergy flows in a crop rotation scenario developed by the Danish organic farmers association including grass-clover lays, cereals, oilseed rape and legumes; also we consider the emergy flow for labor in different ways. The five farms produce bioenergy (biodiesel from oil seed rape and electricity and hot water from anaerobic fermentation of grass-clover), food and fodder (cereals and legumes) and green manure (effluent from biogas production). All green manure, about half of the biodiesel and a little electricity and heat are used on the farms; the remaining products are supplied to the society. Different emergy indices for resource use efficiency are evaluated and compared to results from other bioenergy studies. The roles of nutrient balances and green manure are discussed.

INTRODUCTION

Agriculture has been the key driver for societies for thousands of years. Recently, however, ‘cheap’ resources from the lithosphere have changed the role of agriculture in the society (Rydberg and Haden, 2006). In the coming decades, the society has to adapt to limitations in fossil oil supply (peak oil) and climate change and to shift towards a more biobased economy (Østergård et al., 2010). Correspondingly, a paradigm shift in agriculture is needed to keep our global resources from vanishing (Østergård et al., 2009). One of the components is to enhance energy self-sufficiency at the farm level, and make farms energy providers again. Beneficial for this planning process is some kind of back-casting from sustainability principles like those of The Natural Step (2009) or The International Federation of Organic Agriculture Movements (IFOAM, 2009). For decision making in this process, emergy assessment is a valuable tool as it takes into account the work done by nature as well as by society.

An association of organic farmers, consumers and business (Økologisk Landsforening) and The Danish Agricultural Advisory Service have made a vision for future organic farming (Danish Agricultural Advisory Service, 2009). This is based on the three principles for organic agriculture formulated by The Danish Research Centre for Organic Farming (DARCOF, 2000): recycling, precaution and nearness. The vision aims at designing a farming system with energy self-sufficiency at the farm level based on biogas production as well as recycling of nutrients using the effluent from the biogas production as fertilizer. A specific scenario is a 5-years rotation where grass-clover is grown every 5th year and providing the feedstock for a biogas plant. How much work from nature the system provides to the society needs to be calculated as well as how many resources are needed from the society. This will be analyzed here by means of emergy accounting.

MATERIALS AND METHODS

System, inputs and outputs

The system consists of five neighbouring stockless farms each of 100 ha producing food, fodder and energy crops. Each farm has an oilseed press and all share a biogas plant (Figure 1). Each farm has two employees and the biogas plant has one. Each farm uses a 5-year crop rotation being grass-clover, oilseed rape, winter wheat, oat and pea; as a consequence each year 20 ha is grown with each of the five crops. The purchased goods for plant production are lime, grass-clover seeds (other seeds are farm saved), lubricants and machinery. Nutrients are provided from the atmosphere and the soil, and diesel for machineries is provided within the system.

Plant production is modeled based on budget estimates from Danish Agricultural Advisory Service (2008) for fertile loamy soil that is not irrigated. Grass-clover and peas are fixing N_2 from the atmosphere. These crops as well as the oilseed rape crop succeeding the grass-clover are not fertilized; the wheat and oat are fertilized by the biogas effluent. Diesel use for plant production and spreading of biogas effluent is modeled based on Dalgaard et al., (2001) and Danish Agricultural Advisory Service (2008). Diesel use for transport of biogas feedstock and effluent is modeled based on Berglund and Börjesson (2006). Oil seed rape is used for producing vegetable oil on a farm scale oilseed press. This oil is replacing imported diesel in the farm machinery, and the byproduct, oilseed cake, is sold as a fodder together with the peas. Wheat and oat are sold as food.

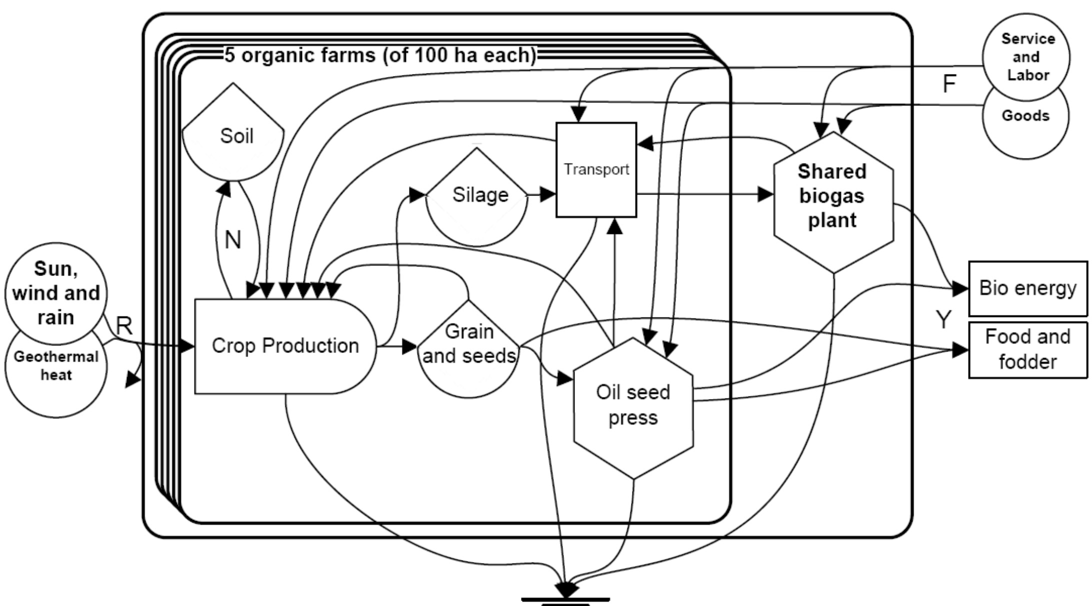

Figure 1. *System diagram of emergy flow for an organic combined food and bioenergy production system with five farms of 100 ha with oilseed press and a shared biogas plant.*

Grass-clover silage is transported to the biogas plant for producing biogas at appropriate time intervals; the average distance from each of the farms to the biogas facility is assumed to be 3 km. The microorganisms for the biogas plant are provided within the system. The biogas is combusted on site in a combined heat and power unit. The biogas production and conversion is modeled using data from ecoinvent (Jungbluth et al., 2007), Börjesson and Berglund (2006) and Berglund and Börjesson (2006) (see Appendix A note 29 and 30). The ecoinvent data for materials are for a 300 m^3 biogas plant designed to digest manure and co-substrates; these are scaled down by 1/3.

All material and energy flows are based on data from different sources in the following priority: Danish or Swedish data, ecoinvent database (Jungbluth et al., 2007), other sources. A detailed description of all energy and matter flows is found in the notes (Appendix A).

Emergy accounting

Emergy flow is representing the solar energy (solar emergy joules (sej)) embodied in all the inputs to the system. These inputs include nature's work like rain, water, soil and nutrients as well as input from the economy like machinery, buildings, human labor and services. The emergy flow is calculated for each input by multiplying the input measured in J, g or DKK (Danish currency) with the transformity converting this input into sej. Transformities are more or less context dependent; here they have been chosen from several sources according to the following priority: Danish data, most recently published related studies and their references, the emergy folios.

Table 1. Inputs and emergy flow for an organic combined food and bioenergy production system with five farms of 100 ha with oilseed press and a shared biogas plant.

Notes	Items	Unit	Amount per 500 ha/year	Transformity	Solar Emergy (sej/year)	Ref. for transformities[a]
Local renewable sources						
1	Solar radiation	J	1.87E+16	1	1.87E+16	**By definition**
2	Rain (evapotranspiration)	g	2.10E+12	1.51E+05	3.17E+17	**Folio 1**
3	Wind	J	2.26E+13	2.52E+03	5.71E+16	**Folio 1**
4	Geothermal heat	J	1.11E+13	1.20E+04	1.33E+17	**Folio 1**
5	N deposits	g	7.50E+06	7.73E+09	5.80E+16	**Odum (1996)**
Sum of local renewable inputs (2+4+5) (R)					**5.08E+17**	
Local non-renewable sources						
6	Phosphorus	g	5.99E+06	3.36E+10	2.01E+17	**Folio 3 (Doherty 1995)**
7	Potassium	g	8.97E+06	2.92E+09	2.62E+16	**Folio 4 (Odum 1996)**
Sum of local nonrenewable inputs (N)					**2.27E+17**	
Sum of local inputs (N+R)					**7.35E+17**	
Purchased inputs for plant production						
8	Lime	g	2.00E+08	1.68E+09	3.36E+17	**Folio 4 (Odum 1996)**
9	Grass-clover seeds	g	2.60E+03	1.39E+09	3.62E+12	**This study (see note 9)**
10	Lubricants	J	3.12E+08	1.11E+05	3.45E+13	**Folio 4 (Odum 1996)**
11	Farm buildings (service)	DKK	1.03E+05	2.39E+11	2.46E+16	**This study (see note 11)**

12	Agriculture steel machinery	g	9.90E+05	6.97E+09	6.90E+15	**Buranakarn (1998)**
13	Human labor (farming)	J	9.10E+09	1.20E+07	1.09E+17	**This study (note 13)**
Sum of farming phase (F_1)					**4.77E+17**	
Sum of farming phase - Without labor and services					**3.43E+17**	
Purchased inputs bioenergy phase						
14	Ground water	g	6.13E+09	1.25E+06	7.67E+15	**Coppola et al., (2009)**
15	Oil seed press	g	7.00E+04	6.97E+09	4.88E+14	**Buranakarn (1998)**
16	Biogas plant (service)	DKK	3.50E+05	2.39E+11	8.37E+16	**This study (see note 11)**
17	Gas engine	g	2.50E+04	6.97E+09	1.74E+14	**Buranakarn (1998)**
18	Concrete	g	3.14E+06	1.81E+09	5.68E+15	**Pulselli et al.,. (2008)**
19	Reinforcing steel	g	1.08E+05	6.97E+09	7.53E+14	**Buranakarn (1998)**
20	Chromium Steel	g	1.30E+04	6.97E+09	9.06E+13	**Buranakarn (1998)**
21	Polystyrene	g	5.70E+03	9.86E+09	5.62E+13	**Buranakarn (1998)**
22	Polyethylene	g	4.25E+02	9.86E+09	4.19E+12	**Buranakarn (1998)**
23	Synthetic rubber	g	3.00E+03	9.86E+09	2.96E+13	**Buranakarn (1998)**
24	Glued laminated timber	J	8.31E+08	7.39E+04	6.14E+13	**Buranakarn (1998)**
25	Human labor (biogas)	J	9.10E+08	1.20E+07	1.09E+16	**This study (see note 13)**
Sum bioenergy phase (F_2)					**1.10E+17**	
Sum of bioenergy phase without labor and services					**1.50E+16**	
Sum of feedback from economy ($F = F_1+F_2$)					**5.87E+17**	
Sum of total inputs (Y)					**1.32E+18**	
Sum of total inputs without labor and services					**1.09E+18**	
Products						
26	Grain	J	**1.42E+13**	9.32E+04		
27	Fodder	J	**5.81E+12**	2.28E+05		
28	Vegetable oil	J	**1.12E+12**	1.18E+06		
29	Electricity	J	**2.67E+12**	4.94E+05		
30	Heat	J	**3.68E+12**	3.59E+05		
Sum of products		**J**	**2.75E+13**	4.81E+04		

Emergy indices of system	With labor and services	Without labor and services
Renewability (R/Y %)	**38%**	**46%**
Environmental Loading Ratio (ELR=(N+F)/R)	**1.60**	**1.15**
Emergy Yield Ratio (EYR=Y/F)	**2.25**	**3.05**
Emergy investment ratio (EIR= F/(N+R))	**0.80**	**0.49**

a. The references to folio 2, 3 and 4 refers to respectively Odum (2000), Brown and Bardi (2001) and Brandt-Williams (2001). The references in the brackets following folio 3 and 4 indicate the primary reference used in the folios.

RESULTS AND DISCUSSION

The overall material flow for each farm is illustrated in Figure 1. The emergy flow is calculated for the five 100 ha farms (Table 1) and the emergy profile shown (Figure 2). The mix of crops implies that the system of five farms each year is producing 100 ha of each of the five crops: grass-clover, oilseed rape, winter wheat, oat and pea. The farms produce food, feed, vegetable oil, electricity and heat and the system all together has a net production of all products when subtracting farm saved seeds, diesel used by machineries and heat and electricity used by the biogas plant. In this way the goal of energy self-sufficiency has been fulfilled within the chosen system boundary. However, farm households, which also demand heat and electricity, are not included.

The system is designed to be as self-sufficient as possible. At first, the energy goals are satisfied by having the oilseed press and the biogas plant. Also, seed is provided within the system as farm-saved seed (except for grass-clover), inoculum for the biogas plant is self-regenerating and all straw is kept in the fields to counterbalance the potential soil organic matter loss by erosion (cf. Coppola et al., 2009). Further, the rotation provides a system in approximate nitrogen balance; the farmer does not need to import organic fertilizer since the combination of nitrogen fixing legumes, nitrogen deposit from the air and effluent from the biogas plant counterbalance the loss of nitrogen in the sold products (M.Tersbøl, pers. com.). However, for phosphorus and potassium it is necessary to consider the loss from the soil due to the amount of these nutrients leaving the system in the sold products; the system, so to say, mines the stock of phosphorous and potassium. At present, soils in Denmark are rich in these nutrients but this will not last. In fact, the global production of phosphorus may peak as early as 2030 (Cordell et al., 2009).

The N_2 fixation in grass-clover and peas is, like photosynthesis, powered by the local renewable sources already accounted for in the first part of the emergy analysis (Item 1-4, Table1). Therefore, there is no specific input to the emergy flow for N_2 from the atmosphere. This principle is different from the one used by Cavalett and Ortega (2009) for soybean production. In their study, fixation of N_2 from the atmosphere is specifically contributing to the emergy flow with a transformity of 6.38E+12 sej/kg. The primary reference for this value, reached after some steps of secondary references, seems to be kg ammonium fertilizer (Odum 1996, Table C.4.). This choice may be misleading as the industrial process leading to ammonium fertilizer is very different in resource use from the N_2 fixation by plants.

A certain amount of ammonia (NH_3) originating from polluting sources like synthetic fertilizer and manure is, however, in our study considered as input from the atmosphere to the system. These nitrogen components are deposited on the soil and thus directly available for the crop plants.

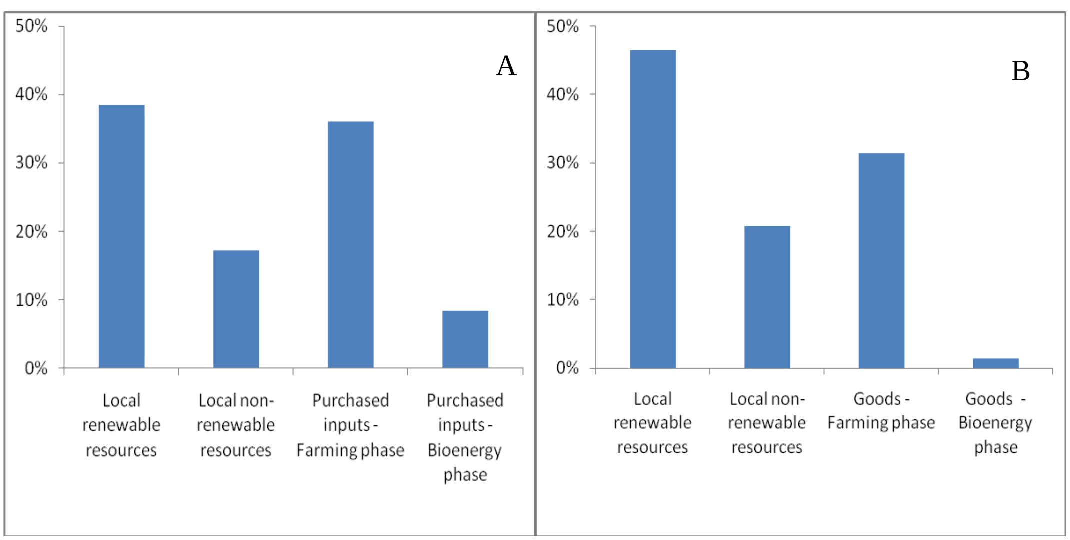

Figure 2. *Emergy profile for the system. A: With labor and services, B: Without labor and services.*

The energy embodied in this nitrogen is assumed to be similar to that of synthetic fertilizer so we have applied the transformity 7.73E+09 sej/g for ammonium fertilizer based on g N (Odum, 1996).

Among all inputs to the system, lime is the most resource demanding (Table 1). Its transformity is of the same order of magnitude as another fertility building product, potassium, but the quantity used is much higher. The lime input depends to a large extent on soil type and crop type and what has been applied here is an average number according to Danish Agricultural Advisory Service (2008). The large quantity may reflect that lime is an abundant resource in Denmark.

The amount of feedstock for the modeled biogas plant (including water to obtain 10% dry matter content suitable for anaerobic fermentation) is very small compared to most biogas plants described in literature. The present plant digests only about 1700 t feedstock per year corresponding to about 5 m^3 per day in a 100 m^3 reactor. Because we have calculated material use for the biogas plant based on a 300 m^3 plant scaled by 1/3, this may slightly underestimate the requirements for materials as smaller plants may be need more materials per m^3 of reactor volume.

For the oilseed press, the oil yield is set to 1/3 of the oil seed weight (Jørgensen and Dalgaard, 2004). This is a general accepted number for farm scale systems, but it should be noted that there are some problems with respect to producing the oil as well as using vegetable oil in diesel engines. The labor needed for this process is expected to be covered by the 2 persons working on the farm.

The purchased inputs for the bioenergy production constitutes a rather small proportion of the total emergy flow (8% with labor and services included and 1% without; Figure 2) compared to the purchased inputs needed for the crop production (36% and 31%, respectively; Figure 2) which in addition also provides food and feed (Figure 2). This difference between the industrial and agricultural phase is similar to numbers in a recent study of biodiesel production from soybean in Brazil: 7% and 32%, respectively, with labor and services (Cavalett and Ortega, 2009).

The services of relevance for the system are investment in and maintenance of farm buildings, farm machineries and the biogas plant as well as cost of farming consultancy. The emergy flows for services are calculated based on an em-DKK (sej/DKK) ratio based on the total emergy flow in Denmark in 1999 (Rydberg and Haden, 2006) as this is the most recent data. Despite that the economic situation in Denmark has changed since then, this estimate is considered to be reasonable for this study. The price of the biogas plant is assumed to be 7 million DKK divided over 20 years corresponding to an emergy flow of 8.37E+16 sej/year. This number is very uncertain as there is only little experience with building biogas plants of this scale in Denmark. Maintenance of farm buildings is included based on a monetary cost per ha per year (Haden, 2003) and the actual value is 2.46E+16 sej/y. Data for investments in and maintenance of farm buildings have only been found for average Danish farm (Haden, 2003) and these numbers may not be representative for stockless farms which might have the lowest costs. Cost for maintenance of the biogas plant and farm machinery as well as cost for agricultural advisors is not included but they are expected to be smaller than the contribution from maintenance of farm buildings so, in conclusion, we would expect that including monetary cost for other expenses would not change the overall evaluation significantly.

Labor contributes with about 9% of the total emergy flow which is similar to the contribution from the services calculated above constituting 8% (Table 1). There are a total of 11 full time employees in the system. Only the time spent at work based on a normal Danish working year is included (37 hours per week and 47 weeks per year). Working hours are converted to joules by assigning the proportion (1739 working hours per person per year/8760 total hours per person per year) of total food intake of 3000 kcal per day spent during working hours as average over a year (see Appendix A, note 13). The transformity for labor is based on the total emergy flow per person in Denmark in 1999 (Rydberg and Haden, 2006) and again converted to emergy flow per J assuming a 3000 kcal diet per day per person. In this way, the emergy flow is, in fact, not dependent on the choice of diet.

Transformities calculated for labor and services are expected to be particularly variable in the coming years. They are derived based on resource consumption of the entire nation and peak oil and other resource supply constraints will most likely have a dramatic impact on this. These constraints will also have an impact on other purchased inputs, but given that only a smaller part of the emergy flow in goods stems from labor it would in all cases be less distinct. So for the purpose of designing and analyzing visions for the future it would be optimal if all emergy analyses would calculate results and transformities both with and without labor and services, thus giving the opportunity to separate the consequences (see also Ulgiati et al., this volume; Bastianoni and Pulselli, this volume).

In conclusion, the system was designed to take advantage of local renewable resources and this has been quantified by the emergy indices. The input from these resources constitutes 38% (46% without labor and services) of the resources put into the final products (Figure 2). This percentage is similar to the 33% for soybean to diesel in Brazil (Cavelett and Ortega, 2009) but higher than the 22% for sunflower to biodiesel in Italy (Bastianoni et al., 2008).

Another emergy index demonstrating the contribution of local renewable resources is the Environmental Loading Ratio (ELR=1.60 with labor and services; Table 1 bottom). It shows that for each unit of a local renewable source, less than 2 units of non-renewable sources are required to provide the products to be sold. This is a better result than the soybean to biodiesel production with a ratio of 2.02 (Cavalett and Ortega 2009) and even better than the 2.79 for sunflower to biodiesel in Italy (calculated from Bastianoni et al., 2008). In a study of 1st and 2nd generation bioethanol production from wheat in organic and conventional farming systems with or without use of residues, the ELR-figures varied from above 2 to more than 10 (Coppola et al., 2009).

The system was designed to be based on local resources. The Emergy Investment Ratio (EIR=0.80 (0.49 without labor and services)) indicates that in average over the products, a little more local resources are used compared to resources purchased from outside the system of the 5 farms. Further, for 1 input sej from society, more than 2 sej are returned to the society as seen from the Emergy Yield Ratio (EYR=2.25 with labor and services). This is somewhat more than the 1.71 for the soybean system (Cavalett and Ortega, 2009) and 1.43 for the sunflower system (calculated from Bastianoni et al., 2008).

The system is multifunctional and the different products are co-products. When comparing systems with different co-products, it is important to have in mind that the indices calculated are for the specific system and not just for the specific biofuels; they are joint indices as defined by Bastianoni and Marchettini (2000). The joint transformity of the system (the ratio of the sum of all emergy input to the sum of total energy in co-products) is 4.81E+04 sej/J including labor and services which indicates a rather efficient use of resources compared to soybean to biodiesel (Cavalett and Ortega, 2009) with a joint transformity of 1.22E+05 (our calculation of joint transformity for oil, meal and lecithin). A weakness of calculating a joint transformity as we have done, is that different quality of energy are summed based on their energy content (e.g. vegetable oil and heat) even though their ability to do work are in many ways incomparable.

CONCLUSION

Implications of this kind of system based on anaerobic fermenting of green manure are by the agricultural advisors foreseen to be higher yields, better care of nature, less impact on climate, less loss of nitrogen and production of renewable energy. Altogether these advantages may help in increasing the number of farms converting to organic farming and thus supporting a sustainable development of future agriculture. These envisioned consequences were confirmed quantitatively by the emergy assessment using the different emergy indices. In comparison with three selected recent studies of biodiesel and bioethanol production with system boundaries being a crop in one year (biodiesel examples) or over several years with recycling of residues (bioethanol), this system behaves more sustainably. However, this kind of comparisons between systems with different co-products has to be considered with caution.

In future, sustainable agricultural production systems will need to be multifunctional and based on recycling. Emergy accounting can contribute to making decisions about desirable futures by demonstrating the importance of work done by local renewable resources. In this process it is important to have in mind that future labour and service patterns may be very different from those today. A requirement for further progress in emergy methodology is, in addition, that the transparency of transformity calculations and applications is further developed and that the availability of this information is organised.

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APPENDIX A

LOCAL INPUTS			
1	**Solar energy**		DMI (2010)
	Solar radiation	3.73E+13 J ha^{-1} y^{-1}	
2	**Rain (evapotranspiration)**		DMI (2010)
	Rain evapotranspirated	4.20E-01 m y^{-1}	
	Quantity = (area) × (rain) × (water density)	4.20E+09 g ha^{-1} y^{-1}	
3	**Wind**		DMI (2010)
	Density of air	1.30E+00 kg m^{3}	

	Drag coefficient	1.00E-03	
	Wind velocity	4.80E+00 m sec^{-1}	
	Energy = (Energy on land) × (area) × (density) × (drag coeff.) × (wind speed)^3 × (time)	4.53E+10 J ha^{-1} y^{-1}	
4	**Geothermal heat**		
	Heat flow	2.21E+10 J ha^{-1} y^{-1}	Hurter and Schellschmidt (2003)
5	**N deposits (g N)**	1.50E+04 g ha^{-1} y^{-1}	DMU (2005)
6	**Phosphorus loss in exported crops - assuming the straws are left on the fields**		Danish Agricultural Advisory Service (2008)
	Rape seed	1.36E+04 g ha^{-1} y^{-1}	
	Winter wheat	1.51E+04 g ha^{-1} y^{-1}	
	Oats	1.86E+04 g ha^{-1} y^{-1}	
	Peas	1.26E+04 g ha^{-1} y^{-1}	
	Average loss per ha	1.20E+04 g ha^{-1} y^{-1}	
7	**Potassium loss in exported crops - assuming the straws are left on the fields**		Danish Agricultural Advisory Service (2008)
	Rape seed	1.65E+04 g ha^{-1} y^{-1}	
	Winter wheat	2.13E+04 g ha^{-1} y^{-1}	
	Oats	2.28E+04 g ha^{-1} y^{-1}	
	Peas	2.91E+04 g ha^{-1} y^{-1}	
	Average loss per ha	1.79E+04 g ha^{-1} y^{-1}	
PURCHASED INPUT FARMING PHASE			
8	**Lime (2 tons per ha every 5th year)**	4.00E+05 g ha^{-1} y^{-1}	Danish Agricultural Advisory Service (2010)
9	**Grass-clover seed**	2.60E+01 kg ha^{-1} y^{-1}	Danish Agricultural Advisory Service (2008)
	Transformity for seed	1.39E+09 sej/g	This study - using joint transformity cal-culated for grain (converted from J to g)
10	**Lubricants**		
	Quantity (norm) (=1/10 of used diesel)	3.12E+08 J ha^{-1} y^{-1}	Dalgaard et al., (2001)
11	**Maintenance of buildings**		
	Danish agriculture - Cost for maintenance on buildings	5.44E+08 DKK y^{-1}	Haden (2003)
	Quantity of agricultural land	2.64E+06 ha	
	Maintenance of buildings per ha	2.06E+02 DKK y^{-1} h^{-1}	
	Per one farm of 100 ha	2.06E+04 DKK y^{-1}	
	Denmark emergy/DKK-ratio	2.39E+11 SEJ/DKK	Rydberg and Haden (2006)
12	**Steel machinery**	1.98E+03 g $ha^{-1}$$y^{-1}$	Coppola et al., (2009)
13	**Labor Farming phase (per one farm 100 ha)**		
	Full time employees per farm of 100 ha	2.00E+00 prs y^{-1}	
	Working hours per year (37 h)x(47 weeks)x(2 employees)	3.48E+03 h y^{-1}	
	Daily energy metabolism	3.00E+03 kcal day^{-1} prs^{-1}	
	Conversion factor	4.19E+03 J $kcal^{-1}$	
	Energy metabolism per hour	5.23E+05 J h^{-1}	
	Metabolic J per farm	1.82E+09 J y^{-1}	
	Transformity for labor		
	Total emergy used (U in Denmark 1999)	2.93E+23 sej y^{-1}	Rydberg and Haden (2006)
	Population 1999	5.31E+06 prs	Statistics Denmark

	Emergy flow per person per year	5.51E+16 sej prs^{-1} y^{-1}	
	Emergy flow per man-hour	6.29E+12 sej man-$hour^{-1}$	
	Emergy flow per metabolic joule	1.20E+07 sej J^{-1}	
PURCHASED INPUT BIOENERGY PHASE			
14	**Ground water**		
	Quantity needed to make grass-clover biogas feedstock 10% dm	6.13E+03 t y^{-1}	
15	**Oil seed press - one per farm**		
	Weight	1.40E+05 g	VVS-eksperten A/S (2010)
	Assumed turnovertime	1.00E+01 years	
	Yearly input of steel	1.40E+04 g y^{-1}	
16	**Biogas plant investment**		
	Cost DKK	7.00E+06 DKK	
	Turnover time	20 years	
	Cost per year over 20 year	3.50E+05 DKK y^{-1}	
17	**Gas engine - steel machinery**	500 kg	
	Turnover time	20 years	
	Steel per year	2.50E+04 g y^{-1}	
18	**Concrete (biogas plant 100 m^3 reaktor)**	3.14E+06 g y^{-1}	Jungbluth et al., (2007)
19	**Reinforcing steel (biogas plant 100 m^3 reaktor)**	1.08E+05 g y^{-1}	Jungbluth et al., (2007)
20	**Chronium Steel 18/8 (biogas plant 100 m^3 reaktor)**	1.30E+04 g y^{-1}	Jungbluth et al., (2007)
21	**Polystyren, high impact - HIPS (biogas plant 100 m^3 reaktor)**	5.70E+03 g y^{-1}	Jungbluth et al., (2007)
22	**Polyethylene, HDPE Granulate at plante (biogas plant 100 m^3 reaktor)**	4.25E+02 g y^{-1}	Jungbluth et al., (2007)
23	**Synthetic rubber at plant (biogas plant 100 m^3 reaktor)**	3.00E+03 g y^{-1}	Jungbluth et al., (2007)
24	**Glued laminated timber, outdoore use at plant (biogas plant 100 m^3 reaktor)**		
	Quantity	5.54E+00 m^3	Jungbluth et al., (2007)
	Density	600 kg m^{-3}	
	Weight	3.32E+03 kg	
	Heating value (hhv)	1.50E+07 J kg^{-1}	http://en.wikipedia.org/wiki/Heat_of_combustion
	Total heating value	8.31E+08 J y^{-1}	
25	**Labor biogas phase (one full time employee)**	1.74E+03 h y^{-1}	
	Metabolic J per biogas plant (calculated as note 13)	9.10E+08 J y^{-1}	
PRODUCTS			
26	**Grain/food production (metabolic energy) per farm (100 ha)**		
	Data on wheat and oats are for fodder crops but in lack of data for food crops they are applied		
	Winter wheat, net yield (minus saved seeds)	5.00E+03 kg ha^{-1} y^{-1}	Danish Agricultural Advisory Service (2008)
	Oats, net yield (minus saved seeds)	5.13E+03 kg ha^{-1} y^{-1}	
	Total food per farm (area)x(yields)x(14 MJ kg^{-1})	2.84E+12 J y^{-1}	Coppola et al., (2009)
27	**Fodder production (metabolic**		

	energy) per farm (100 ha)			
	Peas, net yield (minus saved seeds)	3.02E+03	SFU ha^{-1} y^{-1}	Danish Agricultural Advisory Service (2008)
	Oilseed rape (seeds)			
	Net Yield per ha (minus saved seeds)	2.20E+03	kg y^{-1}	
	Oil cakes yield (% of oil seed weight)	67	%	Jørgensen and Dalgaard (2004)
	Fodder walue of oil cakes	1.11E+00	SFU kg^{-1}	
	Total fodder value in oil cakes and peas per farm	9.29E+04	SFU y^{-1}	
	Conversion factor (12.5 MJ metabolic energy per SFU)	1.25E+07	J SFU^{-1}	
	Total metabolic energy in oil cakes and peas per farm	1.16E+12	J y^{-1}	
28	**Vegetable oil production per farm (100 ha)**			
	Gross oil yield per farm (1/3 of oil seed weight)x(yield)x(area)x(energy content)	5.42E+11	J y^{-1}	Jørgensen and Dalgaard (2004)
	Net oil yield per farm (gross yield)-(diesel use plant production+diesel use transportation)	2.24E+11	J y^{-1}	
29	**Electricity production per system (500 ha)**			
	Grass clover biogas yield per kg DM	1.06E+07	J kg^{-1}	Berglund and Börjesson (2006)
	Grass clover yield per ha (34.4 % DM)	2.51E+04	kg ha^{-1}	Danish Agricultural Advisory Service (2008)
	Gross biogas yield (system level)	9.17E+12	J y^{-1}	
	Assumed efficiency (% of biogas heating value)	32	%	Jungbluth et al., (2007)
	Gross electricity yield (system level)	2.93E+12	J y^{-1}	
	Electricity use in biogas process (92 MJ t^{-1} lay feedstock)	9.20E+04	J kg^{-1}	Börjesson and Berglund (2006)
	Total electricity use in biogas	2.31E+11	J y^{-1}	
	Electricity use in oil seed press (1.1 kwh per 30 kg seeds. 1 kwh =3.6 MJ)	1.32E+05	J kg^{-1}	Jørgensen and Dalgaard (2004)
	Total electricity use for oil seed presses	2.90E+10	J y^{-1}	
	Net electricity yield (system level)	2.67E+12	J y^{-1}	
30	**Heat production per system (500 ha)**			
	Assumed efficiency (% of biogas heating value	55	%	Jungbluth et al., (2007)
	Gross heat production	5.04E+12	J y^{-1}	
	Used in biogas process (540 MJ t lay^{-1})	1.36E+12	J y^{-1}	Börjesson and Berglund (2006)
	Net heat production	3.68E+12	J y^{-1}	