Energy use efficiency in biomass production systems.

Nonhebel, Sanderine

Published in:
Proceedings conference on Sustainable Energy, New challenges for agriculture and implications for land use.

Publication date:
2002

Citation for published version (APA):
Nonhebel, S. (2002). Energy use efficiency in biomass production systems. In E. van Ierland, A. Oude Ansink, & E. Schieman (Eds.), *Proceedings conference on Sustainable Energy, New challenges for agriculture and implications for land use.* (pp. 75-85). University of Groningen. IVEM, Centre for Energy and Environmental Studies.

Chapter 6

ENERGY USE EFFICIENCY IN BIOMASS PRODUCTION SYSTEMS

Sanderine Nonhebel

1. INTRODUCTION

Over the last three decades, energy use efficiency (kg output /MJ input) in Western agriculture has declined. This decline has been caused by an increase in the number of inputs within agricultural systems. The decline in efficiency observed in agriculture raises the question of what (from the perspective of energy use) is the best system of growing energy crops. Is this a high-input system with high yields per hectare, but with a low energy use efficiency, or a low-input system with low yields per hectare but a high energy use efficiency? Four short-rotation forestry production systems (varying from high-input to low-input systems) will be evaluated with respect to their resource use efficiency (in addition to fossil energy, solar radiation and water will be taken into account.

Plant material is produced within various agricultural systems, ranging from low-input systems in which hardly any external inputs are used to high-input systems which require large quantities of external inputs (fertilisers, pesticides, irrigation, etc.). In general, the yields in low-input systems are much lower than in high-input systems. There is no physiological difference between the production of plant material for food and the production of plant material for energy. Sometimes the same crop is even used for both purposes (rape seed, for instance). The major difference between food crops and energy crops is that energy crops have to yield energy. This implies that the energy that can be obtained from the harvested plant material must be larger than the energy required to produce the inputs. This condition does not hold for food crops: for several crops, the fossil energy required to produce the crop is much higher than the energy that can be obtained from it (*e.g.,* the production of tomatoes in greenhouses). However, since food is not only consumed for the intake of

E.C. van Ierland and A. Oude Lansink (eds.), Economics of Sustainable Energy in Agriculture, 75–85.

energy but also for its nutritional value (vitamins etc.), the value of the harvested material is not determined by its heating value only.

During the last decade, several studies have been done on the use of fossil energy in food crop production systems. These studies have been conducted at various levels of scale (comparison of organic agriculture to high-input agriculture; developments in agriculture over the last 50 years, or between countries (Naylor 1996; Kramer *et al.* 1999; Schroll 1994; Conforti and Giampietro 1997). All authors have come to the conclusion that fossil energy is used most efficiently in the low-input crop production systems.

Since there are no physiological differences between the crops, the input-output relationship for food crops can also be expected for energy crops. This would imply that fossil energy use efficiency of low-input energy crop systems is higher than the energy use efficiency in high-input crop systems. When efficient use of fossil fuels is of importance, energy crops should be grown in so-called low-input systems. However, the studies done by Uhlin (1998; 1999) on the overall (fossil and solar) energy use efficiency of the Swedish agricultural system show that overall, energy use efficiency has increased over the last three decades instead of declined. According to these results, high-input energy crop systems use energy more efficiently.

Based on the existing information on food crops, no conclusions can be drawn with respect to the consequences of choice of a particular production system on anticipated yields. This chapter examines in detail the input-output ratios within four biomass production systems. For all systems, the energy use efficiency is calculated and any differences found between the systems are explained. Finally, the results are compared with previous studies on energy efficiency of food production systems.

2. MATERIAL AND METHODS

In order to determine the efficiency of resource use, information on inputs and outputs (yield) is required. For food producing systems, this information (at various levels of scale) can be obtained from agricultural statistics (KWIN; FAO; LEI). These kinds of data were used in the food studies mentioned earlier. For energy crops, this type of data is lacking, since these crops are presently grown in only a limited number of experimental situations.

The method used here is a different one: the target-oriented approach derived from ecological production research (van Ittersum and Rabbinge 1997). In this approach, the yield level (the output) is defined first, followed by a determination of the required inputs to reach this yield level. Here, both yields and inputs are based on crop growth relations obtained from the literature.

2.1 Description of the biomass production systems studied

In principle, all crops with higher energy yields than energy inputs can be used as energy crops. Comparative studies between various crops have shown that the production of biomass in so-called short-rotation forestry systems seems to be most promising (Lysen *et al.* 1992). This type of biomass production will consequently be evaluated here.

The system studied is a short-rotation forestry system with poplar. The trees are planted in spring with a density of 1 tree/m^2, and every fourth year the crop is harvested by coppicing and is simultaneously chipped. After the harvest, the crop re-sprouts and is harvested again four years later. It is assumed that the plantation will have a total life span of 20 years, and hence five harvests can take place. It is assumed that the production will be the same for every harvest.

The results of a study on the production possibilities for biomass crops in various European regions (Nonhebel 1997) are used as the basis of this study. In that study, yield potentials were determined with the use of a crop growth simulation model. The model was based on the linear relation between intercepted radiation and above-ground biomass production (the so-called light use efficiency derived by Monteith (1978)). A soil water balance was incorporated to simulate the effects of water shortage on crop production. The model requires monthly averages for global radiation, temperature and precipitation to simulate production (for more detailed information on the model, see Nonhebel (1997)). The model simulates potential and water-limited production.

Potential production is defined as the production that can be obtained when a crop is supplied with optimum amounts of water and nutrients and is free from pests and diseases (van Ittersum and Rabbinge 1997). Crop characteristics, air temperature and solar radiation are the only determinants of production considered. The potential yield of a crop is a measure of what can be obtained under optimum growing conditions in a particular region. The actual yields will be much lower. The yield gap (the difference between potential production and actual yields) differs per region. In the Netherlands, actual yield levels are 70% of the potential levels, while in Southern Europe they are 30 % of the potential levels (Nonhebel 1997).

Large difference in potential yields exist across Europe, varying from 12 ton/ha in the North-West to over 40 ton/ha in Portugal. These differences are caused by differences in climate (air temperature and solar radiation). The extremes found in Nonhebel (1997) are used here to evaluate the differences in resource use efficiency between high and low-input systems.

The following production systems were defined:

N_{high}. Potential production of poplar in North Western Europe, with an annual yield of 12 ton/ha of stems and 5 ton/ha of leaves. In this part of Europe, the annual precipitation is sufficient to prevent water shortage and potential production can be achieved without irrigation. Within this production system, the crop is fertilised and crop protection measures are taken.

P_{high}. Potential production of poplar in Portugal may be 43 ton/ha/y for the stems and 18 ton/ha/y for the leaves. However, to obtain this production level, irrigation is required.

Furthermore, two low-input systems in the same climatic regions were recognised (**N_{low}, P_{low}**); the yield of these systems is estimated at 5 ton/ha/y stems (and 2 ton/ha leaves). It is assumed that this yield can be obtained without irrigation and use of pesticides.

2.2 Determination of the required inputs

All systems have to be initiated, which means that for all systems, energy is required for soil cultivation, planting and weeding. Furthermore, after each harvest (every four years) weeding has to be done in all systems. Data required to quantify the energy costs of these actions were obtained from Eriks *et al.* (1991), Lysen *et al.* (1992) and Hall *et al.* (1993).

With respect to fertilisation, only nitrogen is taken into account. Production of this nutrient requires a lot of fossil energy. The amount of nitrogen required is yield-level dependent: all nitrogen in the harvested material (stems) is replaced and some losses are taken into account. The nitrogen in the leaves is expected to remain in the system. Data from Nilson and Eckerston (1983); Eckerston and Slapokas (1990); Eriks *et al.* (1991) and Nonhebel (1997) were used. For the low-input systems, it is only at the start of the plantation that some nitrogen is required (the nitrogen in the leaves). Throughout the rest of the life span of the plantation, the annual nitrogen deposition from the air (about 25 kgN/ha) is sufficient to meet the requirements of the crop.

Furthermore, it is assumed that in high-input systems, crop protection measures take place: the crops will be sprayed with pesticides three times a year. Energy requirements for these measures were derived from Pimentel (1980) and Eriks *et al.* (1991).

In the P_{high} system, irrigation is required (495 mm/year). Energy requirements for this irrigation were determined using data from Stanhil (1981), de Koning *et al.* (1992) and Nonhebel (1997). It should be noted that the values used for nitrogen and water use efficiency are high; in practice, the values are lower.

The energy required for harvesting the crops is yield-level dependent (higher yield implies more costs for harvesting) and data from Hall (1993) were used.

For all systems, the energy requirements of the inputs over the complete life span of the plantation were determined. The energy inputs involve the direct energy required for driving a tractor and the indirect energy required to produce the material used (for instance, the nitrogen in the fertiliser).

3. RESULTS

3.1 Inputs required for various production systems

The main energy source of a crop is solar energy. Solar radiation provides the energy for photosynthesis, which is the basis of crop production. The amount available differs per climatic region. In Table 6.1, an indication is given of the incoming solar radiation for the two regions considered. The annual radiation in Portugal is nearly twice as high as in the Netherlands. Furthermore, it is essential that water be available; the average annual precipitation is also given. The precipitation levels in Portugal are much higher than in the Netherlands, although still not enough to obtain the potential growth level.

Table 6.1. Annual solar radiation and precipitation in the two regions considered

	N-W Europe	Portugal
Solar rad. (MJ/m^2)	3418	6122
Precipitation (mm)	765	1150

Source: Stol (1994); North Western Europe: weather station de Bilt; Portugal: weather station Beja

The fossil energy inputs required for the four production systems studied are summarised in Table 6.2, and involve total inputs over the complete life span of the plantation. The high-input systems require more fossil energy per hectare than the low-input systems. The inputs for planting, weeding and crop protection (when applied) are the same for all production systems, while inputs for fertilisation and harvesting differ. The energy requirements for irrigation are huge. In production systems that are not irrigated, fertilisation and harvest are the largest energy users. The term 'fertilisation' includes the indirect energy in nitrogen and the direct energy required to distribute the nitrogen over the area. The indirect energy is about 10 times as high as the direct energy.

Table 6.2 Total fossil energy inputs (GJ) per hectare for four production systems over 20 years

System	N_{high}	N_{low}	P_{high}	P_{low}
Planting	7	7	7	7
Fertilisation	120	8	382	8
Crop protection	24		24	
Weeding	4	4	4	4
Irrigation			760	
Harvest	144	60	520	60
Total	299	79	1697	79
Per year	15	4	85	4

The main reason for the low energy requirements of the low-input systems is that most of the nitrogen used is free of costs. The crops "grow" on the nitrogen deposition, so that no fossil energy is required for the production of artificial nitrogen and none for the application of it. To produce 25 kg N costs 1.8 GJ. This amount is quite small in comparison with the total fossil energy inputs of high-input production systems (15 to 85 GJ/ha/y), but large in comparison with the inputs in low-input systems (4 GJ/ha/y).

Table 6.3. Inputs required for the production of 1 ton of biomass in the four production systems

System		N_{high}	N_{low}	P_{high}	P_{low}
Acreage	m^2/ton	833	2000	233	2000
solar rad	GJ/ton	2848	6836	1424	12244
Water	m^3/ton	638	1530	383	2300
fossil energy	GJ/ton	1.25	0.79	1.97	0.79

When inputs are recalculated to inputs per output (resource use/ton biomass, Table 6.3), a different picture is obtained. The differences between the production systems in resource use efficiency for land, solar radiation and water are much larger (approximately 8 times) than the differences in resource use efficiency for fossil energy (only twice as large).

The $\mathbf{P_{high}}$ system is efficient with respect to use of land, solar radiation and water, but requires more fossil energy per ton of biomass than the other systems. The more efficient use of land, sun and water in comparison with the $\mathbf{N_{high}}$ system can be explained by the fact that the growing season is longer in Southern Europe. Due to the higher temperatures in that region, the growing season covers the period between March and November, while in the Netherlands, it does not start before May. The longer growing season is the main reason for the higher yields (for more details, see Nonhebel 1997). The crops in Southern Europe use a larger part of the annual solar radiation and precipitation so that their efficiency becomes higher. This high efficiency is the result of climatic conditions, which implies that values found in one region cannot be expected in other regions with other climates. The poor results of the $\mathbf{P_{low}}$ system in comparison with the $\mathbf{N_{low}}$ system can also be explained by high radiation and precipitation levels in Portugal (yields in both systems are the same while inputs are higher).

4. DISCUSSION

The main purpose of this chapter is to quantify and give reasons for varying input-output ratios in different production systems. For this purpose, the yields chosen include the extremes in yields that may occur within Europe. In order to calculate yields and inputs, assumptions are made with respect to growing conditions and so on. The situation in practice will deviate from the assumptions made here, which will lead to other yields and other input requirements. Therefore, data obtained here should not be interpreted as forecasts of input-output ratios for a biomass crop at a specific location (when poplar is grown in Portugal, the actual yields will be lower). Values found for yields and efficiencies should be considered as orders of magnitude and differences should be evaluated in terms of higher and lower and not as absolute values.

The systems chosen cover the whole range of current agricultural practices: with and without use of fertilisers, irrigation or pesticides. The yields cover the potentials attainable over Western Europe. Based on the results found in this chapter, some general remarks can be made with respect to the energy requirements for crops in different production systems.

4.1 Use of fossil energy

The energy required to grow biomass crops is higher for the high-input systems than for the low-input systems. The relative increase of the inputs is larger than the relative increase in yield so that the resource use efficiecy declines (less biomass per input). This picture is in accordance with results found in Naylor (1996), Kramer *et al.* (1999), Schroll (1994) and Conforti and Giampietro (1997).

More detailed study of the inputs shows that 'fertilisation' covers a large amount of the total fossil energy inputs of the crop. This is because of the large energy requirements of artificial fertilisers. Crops can also obtain nitrogen from other sources (for instance, manure or compost) and the energy requirements of this nitrogen are much lower. Production systems using non-artificial nitrogen sources will have a high fossil fuel use efficiency, as is shown in this study for the low-input systems ($\mathbf{N_{low}}$ and $\mathbf{P_{low}}$). This implies that the value of fossil energy use efficiency for a production system is strongly determined by the nitrogen source used in that system. Consequently, high-input systems using manure as nitrogen source will have a high fossil fuel use efficiency (however, since artificial nitrogen is cheap and easy to apply, high-input systems using manure or compost are very scarce and no data exist).

4.2 Use of solar energy

In biomass production systems, solar energy is converted into plant material, which is used later on as an energy carrier. Therefore, the efficiency with which solar energy is converted into plant material is of interest. In Table 6.4, a comparison is made between energy inputs (both fossil and solar) and the energy yield (the heating value of wood: 18 MJ/kg). The solar energy irradiated on a hectare is about 1000 times as high as the fossil energy used for the cultivation of the crops.

Table 6.4. Energy inputs and output of the four production systems

System	Dimension[a]	N_{high}	N_{low}	P_{high}	P_{low}
yield	GJ bm/ha/y	216	90	774	90
input	GJ fos/ha/y	15	4	85	4
net yield	GJ /ha/y	201	86	689	86
solar rad	GJ sol/ha/y	34180	34180	61220	61220
eff fossil		14	23	9	23
eff solar		0.006	0.003	0.013	0.001

[a] bm= biomass, fos=fossil energy, sol= solar radiation.

In Table 6.4, the efficiency of the use of both solar and fossil energy is given. For systems at the same location, it can be concluded that higher yields imply higher solar energy use efficiency. In the $\mathbf{P_{pot}}$ system, energy yield (GJ of biomass) is 1.3% of the incoming solar radiation; in the $\mathbf{P_{low}}$ system, only 0.15%. This does not hold for systems at different locations: both low-input systems have the same yields, while the solar energy use efficiency in the $\mathbf{N_{low}}$ system is higher than in the $\mathbf{P_{low}}$ system. These differences are caused by the different climatic conditions. The $\mathbf{P_{pot}}$ system is the most efficient system for converting solar energy into biomass (in other words, Portugal is the ideal place for growing biomass).

4.3 Energy use in agriculture

Studies on energy use in agriculture were conducted to evaluate the possibilities of reducing energy use in agriculture in general. Energy use can be reduced by more efficient use of this resource. Based on the fact that energy use efficiency in low-input systems is higher, the conclusion can be drawn that a shift to low-input agriculture will lead to an energy use reduction in agriculture (since more food is produced per unit of energy). The choice of a low-input agricultural system, however, will mean that at a higher level of scale, the effect will be reversed, as the following calculation based on data obtained in this chapter shows.

Assume that yields in high and low-input systems differ by a factor of 5 (the average of the Dutch and the Portuguese systems). A change to a low-input agriculture would imply a five-fold increase in the acreage required for food production. For a high-input system, the inputs required will be in the order of magnitude of 50 GJ/ha; for a low-input system, about 5 GJ/ha. When this energy is obtained from biomass (net yield 200 GJ/ha), one hectare of biomass is enough to grow the energy required for 4 ha high-input agriculture. Overall, 5 hectares are required for the production of a certain amount of food.

The low-input system requires 4*5 hectares for the agricultural production and these 20 hectares require (20*5 GJ/ha) 100 GJ for cultivation, which implies 0.5 ha for energy. The low-input system requires 20.5 ha for the production of the same amount of food. (This value is even higher when energy is grown under low-input conditions.) When these (15.5) extra hectares are used for the production of biomass, 15.5*200 GJ of fossil energy can be saved by using high-input agricultural systems.

The results of these simple calculations are in accordance with the data given by Uhlin (1998; 1999) concerning energy use in the entire Swedish agricultural system. This implies that in order to study energy use in agricultural production systems, other indicators than fossil energy use efficiency are required. Knowledge obtained in studies on other sustainable energy sources might be of use and variables such as payback-time or solar energy use efficiency can be incorporated.

4.4 Shift towards low-input agriculture and the consequences for energy crops

Up to now, the choice of a high-input versus a low-input system has only been evaluated in the context of its energy yield/ efficiency. It has been concluded that the high-input systems result in the highest energy yields. In reality, the choice of a high or low-input system is also determined by socio-economic factors. The cost-effectiveness of the system plays a role, as well as the social acceptance of production systems. High-input biomass production systems can be expected to have the same effects on the landscape and environment as high-input agricultural systems. In European agriculture, a shift from high-input to organic farming is observed. Based on this information, the future feasibility of large-scale high-input energy crop farming will be low. The expected shift from high-input to low-input (or organic) production systems will have a major impact on the potential of biomass as an energy source. On one hand, the low-input food production systems will require more land for the production of food, implying a reduction of the land available for energy production. Secondly, energy yields that can be obtained from these areas will be lower, since it is not likely that future production will come from high-input systems.

5. CONCLUSION

Fossil energy use efficiency is higher in low-input crop production systems than in high-input systems. This is caused by the fact that in low-input systems, a relatively large amount of the used nitrogen originates from non-fossil resources. In energy crop production systems, solar energy is converted into plant material (with the aid of fossil energy). The net (output-input) energy yield of high-input systems is much higher than the net yield from the low-input systems. The choice of a particular production system will thus have significant consequences for the energy yields that can be obtained.

REFERENCES

Conforti, P, and M. Giampietro (1997) Fossil energy use in agriculture: an international comparison. *Agriculture, Ecosystems and Environment* 65, 231 -243.

Eckersten, H. and T. Slapokas (1990) Modelling nitrogen and production in an irrigated short-rotation forest. *Agricultural and Forest Meteorology* 50: 99-123.

Eriks, W.A., J.C.V.P. Exel, F.J. Fabler, A. Mager and D. Pietersma (1991) *Energie uit landbouw,* PGO verslag, Vakgroep Agrotechniek en -fysica, LUW, Wageningen.

FAO: Food and Agricultural Organisation of the United Nations (FAO). *FAO Production Yearbook,* annual publication.

Hall, D.O., F. Rosillo-Cale, R.H. Williams and J. Woods (1993) Biomass for energy: supply prospects. In: T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams (eds) Renewable Energy, Island Press, Washington, 593-651.

Ittersum, M.K. van and R. Rabbinge (1997) Concepts in production ecology for analysis and quantification of agricultural input-output combinations. *Field Crops Research* 52: 197-208.

Kramer, K.J., H.C. Moll and S. Nonhebel (1999) Total greenhouse gas emissions related to the Dutch crop production system. *Agriculture, Ecosystems and Environment.* 72:9-16.

Koning G.H.J. de, H. Jansen and H. van Keulen (1992) *Input and output coefficients of various cropping and livestock systems in the European Communities,* Netherlands Scientific Council for Government Policy, The Hague.

KWIN: Informatie- en kenniscentrum voor akkerbouw en groenteteelt in de vollegrond (IKC-AG). *Kwantitatieve informatie voor de akkerbouw en groeneteteelt in de vollegrond.* Lelystad. Annual publication.

LEI: Landbouw-Economisch Instituut (LEI-DLO), Centraal Bureau voor de Statistiek (CBS). *Landbouwcijfers.* Annual publication.

Lysen, E.H, C. Daey Ouwens, M.J.G. Onna, K. Blok, P.A. Okken and J. Goudriaan (1992) *De haalbaarheid van de productie van biomassa voor de Nederlandse energie huishouding.* Novem, Apeldoorn.

Monteith, J.L. (1977) Climate and the efficiency of crop production in Britain. *Philosophical Transactions Royal Society of London* 282: 277-294.

Naylor, R.L. (1996) Energy and resource constraints on agricultural production. *Annual Review of Energy and the Environment* 21: 99-123.

Nilson, L.O. and H. Eckersten (1983) Willow production as a function of radiation and temperature. *Agricultural Meteorology* 30: 49-57.

Nonhebel, S. (1997) Harvesting the sun's energy using agro-ecosystems. *Quantitative Approaches in Systems Analysis* No. 13, AB-DLO, Wageningen.

Pimentel (1980) *Handbook of Energy Utilization in Agriculture,* CRC Press, Boca Raton, Florida, 45-48.

Schroll, H. (1994) Energy-flow and ecological sustainability in Danish agriculture. *Agriculture, Ecosystems and Environment* 51:301-310.

Stanhill, G. (1981) Efficiency of water, solar energy and fossil fuel use in crop production. In: C.B. Johnson (ed) Physiological processes limiting plant productivity, proceedings of the thirtieth University of Nottingham Easter school in agricultural science (2-5 April 1979), Butterworths, London, 39-51.

Stol, W. (1994) Synoptic and climatic data for agro-ecological research. *The AB-Met database. Simulation report CABO-TT nr 37,* Wageningen.

Uhlin, H. E. (1998) Why energy productivity is increasing: an I-O analysis of Swedish agriculture. *Agricultural Systems* 56(4): 443-465.

Uhlin, H. E. (1999) Energy productivity of technological agriculture-lessons from the transition of Swedish agriculture. *Agriculture, Ecosystems and Environment.* 73: 63-81.