

Bioenergy yield from cultivated land in Denmark – competition between food, bioenergy and fossil fuels under physical and environmental constraints

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Abstract

Globally, bioenergy is emphasized as an important contributor to reach strategic goals of energy security. The commodity markets for energy, bioenergy and food are interdependent and interacting through the energy dependency of agriculture, an increasing demand for both food and energy, and the option to replace fossil energy resources with bioenergy resources.

A model for supply of biomass for bioenergy in Denmark was developed using linear programming. The model includes biomass supply from annual crops on arable land, short rotation forestry (willow) and plantation forestry, and minimizes production costs of an energy mix consisting of bioenergy and fossil diesel oil. Here, we analyze the possibilities of substituting domestic bioenergy for fossil energy under the constraint of a given food supply and environmental constraints on land use.

Crop area distributions of a total area of 3200 kha were simulated in two sets of scenarios, each examining a range of fossil oil prices. Both scenarios were based on cost and production data of the year 2005. Scenario (a) required a total food&feed energy yield similar to that produced in the year 2005; scenario (b) addressed high prioritization of dedicated bioenergy crops. This was secured by relaxing the food&feed supply to 50% of the 2005 production level. Further, a maximum limit of 25% cultivation area with willow in short rotation was set, and the area reserved for permanent grassland was set to 275 kha (+100 kha compared to 2005). The trade-based animal husbandry sector was excluded from the analysis and the forest area was fixed to 600 kha.

The crop area distributions were affected by fossil oil prices varying from oil index 25 to 200. Oil index 100~9.4 €GJ⁻¹ corresponded with a crude oil price of 55\$ per barrel in 2005. The woody biofuels, especially high-yielding willow in short rotation, were competitive with fossil oil from around oil index 40 and occupied the maximum allowed area in all crop area distributions, except the model optimized with oil index 25. In contrast, no land was allocated for bioenergy from oil seed rape and sugar beet cultivation at oil prices below oil index 170.

The analysis shows that the potential for replacing fossil energy with bioenergy is lower than 19% of the primary energy demand if the bioenergy is based on domestic biomass production. A further increase in the use of bioenergy relies on imports from world market supplies.

Introduction

Bioenergy is foreseen to be an important part of future energy supply. Following the oil crises in the 70'ies bioenergy products from forestry, and later, agricultural residues have become part of the energy supply. The bioenergy consumption in Denmark reached 100 PJ in 2005 (Danish Energy Agency 2006). Future perspectives of diminishing fossil oil reserves and thus volatile and increasing oil prices have made bioenergy an attractive alternative. The energy efficiency of plant based bioenergy depends on land productivity, cultivation, and conversion methods.

The question now remains in what quantity and at what cost bioenergy from different crop types can be supplied from land cultivation, and how the fossil oilprice interacts with biofuel costs. The question may be analyzed as an optimization problem.

Materials & methods

The analysis is based on a comparative static cost minimization model for bioenergy feedstocks grown in Denmark using currently grown crop classes and yield levels, Table 1. A detailed description of the model and its parameters may be found in Callesen *et al.* (2010). The model uses linear programming for providing solutions to an objective function that minimizes the cost of a fuel mix of bioenergy and fossil oil, represented by diesel oil, by changing the crop area distribution.

Feedstock type	Crop representative	Conversion method and efficiency
Woody lignocellulosic	Norway spruce, yield level PK8 and PK12 in 60 yr rotation Willow in short rotation forest (22 yr) on sandy and loamy soils.	Heat and combined heat and power (69-81%)
Grassy lignocellulosic	Grass-clover ley with 30-50% clover	Biogas (54%)
Oil crops	Oil seed rape on sandy (JB1-3) and loamy soils (JB5-6)	Rape Methyl Ester (70%)
Starch crops	Winter wheat on sandy (JB1-3) and loamy soils (JB5-6)	1 st generation bioethanol (57%), straw used in combustion (90%)
Sugar crops	Sugar beet on loamy soils	1 st and 2 nd g. bioethanol (54%), tops used for biogas (54%)

Table 1: Feedstock types, crop representatives, conversion methods and efficiencies used in the model.

Data on crop yields, input factors and input prices from the year 2005 were used. A key issue in the model is the changes in real fossil fuel prices and its influence on other costs of inputs used in the cultivation. The cost price increase as a share of the real oil price increase was based on an evaluation of the direct and indirect energy used in the production of these input factors: seeds 25%, fertilizers 50% (nitrogen and potassium) or 75% (phosphorus), lime 50%, machines 25%, fuels and lubricants 100%, pesticides 25% .

Constraints on crop area use were delineated based on land data, limitations due to crop rotation requirements, protection of forest area (600 kha evenly distributed on average and low productive soil), permanent grassland (175 kha) and other constraints set by biological requirements of the crops.

In this application of the model we analyzed two sets of scenarios each with fossil oil prices ranging from index 25 to index 200 in intervals of 25 (<oil index 100) or 10 (>oil index 100):

- (a) A set of scenarios based on the food&feed production in 2005 (=100%). Cost levels were as experienced in the year 2005. The food, feed and timber demand was set to 167 PJ starch crop yields, 6 PJ oil crop yields, 11 PJ sugar crop yields, 38 PJ grass for feed based on 2005 crop yields. The reservation of timber for wood products was 5 PJ corresponding to about 25% of wood fellings. The area with willow was 0.2% of the available land area.
- (b) A set of scenarios with only 50% food and feed reservation as a variant of the scenario (a). Constraints on area use were due to prioritization of bioenergy and the environment. The short rotation willow was restricted to a maximum of 25% of the land area.

Results

The feedstock cost reflected the combination of yield level (soil quality) and crop type and the cultivation intensity applied. Figure 1 indicates the cultivation cost in €GJ^{-1} of the various crop types after conversion to biofuel as a function of the fossil oil price. The woody lignocellulosic feedstocks had the lowest cultivation cost per GJ produced, whereas grass and low yielding wheat and oil seed rape on sandy soils showed the highest cost at oil index 100 (Figure 1). The fossil oil price intersected the biofuel costs in the range from about oil index 40 to 200.

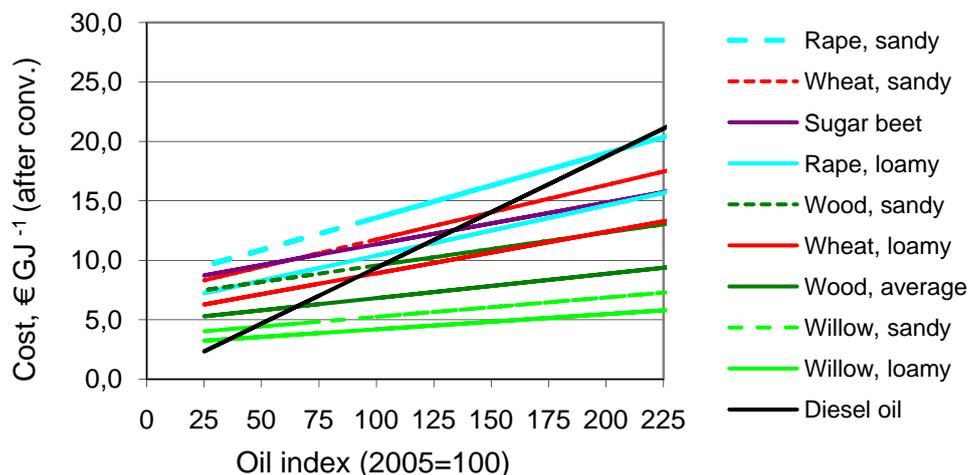


Figure 1: Comparison of costs for producing feedstocks for different biofuels at increasing oil prices (black line, 1:1~ fossil oil index: fossil oil price).

In the (a) scenarios the cost minimized crop area distribution reflected the food constraints laid down in the model and the very limited occurrence of willow plantations. Oilseed rape was grown on a very limited area, and sugar beet was only relevant for bioenergy beyond oil index 160 (Figure 2). In the oil index range from 75 to 150 the biofuel costs for wheat per GJ final energy were quite close to the fossil oil index. Different crop area distributions as

solutions to the cost minimization may therefore result in quite similar values of objective function. The suggested optimized wheat area is a range, since fallow land, wheat and fossil oil compete in this price range.

In the (b) scenarios (Figure 2), no crop area was allocated to willow at oil index 25. With increasing fossil oil index the effect of the low yield level was evident since willow on sandy soil was only present at oil index 50. In the remaining price range the maximum willow area was grown on the high yielding loamy soils. Oilseed rape on sandy soil and sugar beet exceeding the mandatory area reserved for food did occur, but only at a relatively high oil price beyond oil index 160 with a concurrent reduction in wheat on loamy soils.

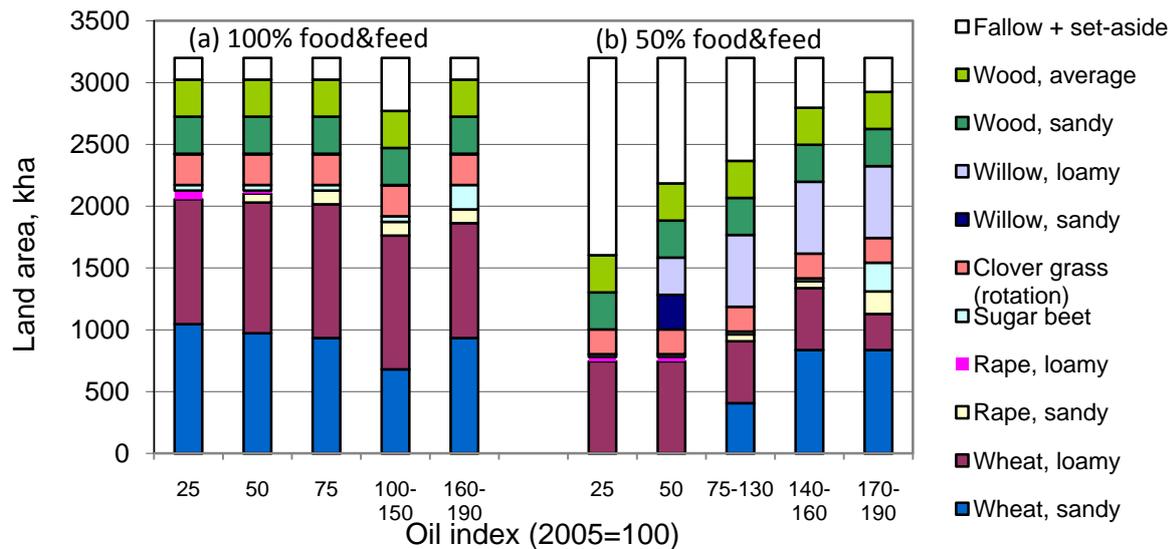


Figure 2: Area distribution of the (a) scenarios with 100% food&feed and the (b) scenarios with 50% food&feed for oil index 25 to oil index 190. Willow is allowed to occupy 25% of the crop area in the (b) scenarios.

The total bioenergy supply across fossil oil prices in the (a) scenarios in Figure 2 ranged between 40 PJ and 60 PJ per year, and the (b) scenarios between 30 PJ and 160 PJ per year. The amount of N fertilizer used in the resulting area distribution of oil index 100 in (a) and (b) (Figure 2) were 375 kt N yr⁻¹ and 229 kt N yr⁻¹ representing a 146 kt difference in N fertilizer use.

Discussion

If the reservation of land for food supply is decreased, much more land would be set-aside or planted with forest in short or long rotation. The environmental benefits for the environment by reducing nitrogen loads (Erismann *et al.*, 2008) through cultivation of perennial woody crops or setting land aside are obvious. Guesses of the potential available area for willow are 100 kha – far lower than the 581 kha that occur in the model result (Figure 2). There is no knowledge base for large-scale willow cultivation in Denmark indicating if the actual yields and costs can be sustained over time, and if it is accepted by the public. Willow plantations may be a way of increasing the forest area in the long term. The energy sector and the agricultural sectors are regulated, taxed and subsidized in numerous ways. The analysis indicates that volatile oil prices are contributing to the uncertainty of price developments for both food&feed and bioenergy markets. The market for solid biofuels such as wood chips and energy grain is well established and flexible. Switching between different biofuels and co-

firing with fossil fuel in both small and large heat and heat and power plants is possible. In comparison with an annual total primary energy use of 800-850 PJ the bioenergy supply would range from 4% to 19%. In addition, there is an unused bioenergy potential, especially from waste in the animal husbandry sector.

In the competition for biomass feedstock, solid woody biofuels had an advantage over liquid biofuels. This may call for market incentives for liquid biofuels (OECD-FAO, 2009). Mandatory blending of biofuel in petrol in the EU27 has been decided by the European Union. Targets are 5,75% in 2010 and 10% in 2020 (European Commission, 2003). Our analysis shows that liquid biofuels will rely on policy mandates, e.g. biofuel blending requirements in petrol.

Long term increases in oil prices speak in favour of biofuels, since most feedstocks can be produced at a competitive cost above the fossil oil index 190. Fossil oil dependent price increases deviating from our assumptions may change the picture. The competitive strength of liquid biofuels will rely on world market supplies of low cost sugar cane or corn based ethanol. The domestic crop land is available provided that feed supplies at a large scale can shift from primary feed to processed by-products such as dried distillers grains with solubles (DDGS).

Conclusion

Domestic bioenergy feedstock production is very limited in comparison with the energy consumption. The possibilities of a substantial increase e.g. by cultivation of willow, even up to 25% of the available crop area, will not increase the bioenergy supply substantially, but the landscape would change dramatically. Biomass imports are needed if the contribution of bioenergy to the total energy production is to increase above current levels.

Apparently, willow in short rotation is a cost effective solid biofuel alternative to annual crops, but the actual future yields, landscape planning perspectives, the environmental performance, and landuse flexibility issues needs further consideration.

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