Modeling and Analysis

Biofpr Biofuels Bioproducts & Biorefining

Energy, feed and land-use balances of refining winter wheat to ethanol

Niclas S. Bentsen*, Bo J. Thorsen, Claus Felby, University of Copenhagen, Denmark

Received May 20, 2009; revised version received July 12, 2009; accepted July 14, 2009
Published online in Wiley InterScience (www.interscience.wiley.com); DOI: 10.1002/bbb.170;
***Biofuels, Bioprod, Bioref.* (2009)**

Abstract: Five conversion routes in winter wheat to first- and second-generation ethanol production systems under north European conditions are analyzed subject to energy efficiency, feed energy production, feed protein production and land use. The impact of integrating a bioethanol plant with combined heat and power generation, taking advantage of excess heat available, is analyzed for the same five scenarios. They are based on empirical data from large-scale processing of starch and lignocellulose to ethanol. We show that integrating technologies can improve the system energy efficiency by more than 30 percentage points. A technology-integrated wheat-to-ethanol system may exhibit energy efficiencies almost comparable to those seen for conversion of petroleum into gasoline. We also show that it is possible to utilize crops for energy purposes without substantially changing the global appropriation of land for agriculture. © 2009 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: bioethanol; energy loss; energy system performance; land use

Introduction

In a world of climate change, depleting fossil resources, and energy supply security, the use of biomass for energy has become an area of strategic importance. Biomass is the most versatile renewable energy resource: it can provide heat, power or transportation by solid, liquid and gaseous energy carriers.

New energy carriers for the transport sector, such as electricity and hydrogen, are not compatible with the present car pool and fuel distribution system, and a long transition period is to be expected. For decades, the majority of cars and trucks will use gasoline or diesel, and a link between alternative energy sources and the present transport sector is needed. Furthermore, the long-term transportation fuel demand for large trucks, airplanes and ships will most likely still need to be met by liquid fuels.

Bioethanol based on biomass has the potential to link the current dependence on fossil fuels to alternative energy carriers and transport technologies. Provided that the biomass is sustainable, bioethanol can be used in today's cars and serve as a means of mitigating non-reversible CO_2 emissions and reducing the pressure on the fossil reserve.

Correspondence to: Niclas S. Bentsen, Centre for Forest, Landscape and Planning, Faculty of Life Sciences University of Copenhagen, Denmark.
E-mail: nb@life.ku.dk

Within the last 10–15 years, the energy efficiency of bioethanol production has been subject to numerous studies with various results. Studies have been conducted on bioethanol based on corn,[1–7] switchgrass,[2,6] wheat,[8–13] sugarbeet,[9] sweet sorghum,[14] and wood.[2] Published studies yield different results on the energy efficiency of bioethanol production, and utmost care should be taken when comparing results directly, as assessment methodology, temporal and geographical scope, byproduct inclusion or allocation, and boundary conditions differ. Recent attempts to compare energy and sustainability indicators across different studies have been made by Farrell *et al.*[15] and von Blottnitz *et al.*[16]

The conversion of an energy carrier into a liquid transport fuel has an energy cost. This holds for both fossil and renewable energy carriers. Thus society loses work potential when it chooses to support the transport sector with liquid transport fuels. Considering the value and importance of transport, this loss of work potential is a price society is willing to pay, but it is in society's interest to minimize the price.

The recent dramatic fluctuations in food prices (FAO (www.fao.org [April 2009])) has drawn attention to the use of agricultural commodities in the energy sector and the increase in the demand for biofuels has been identified as a significant driver of the rapid increase in food prices.[17] It is shown that biofuels do not by default mitigate greenhouse gas (GHG) emissions[18,19] as the impact depend on changes in land use. Furthermore, biofuels may have negative impacts on other parts of society, especially with regard to food security.[20,21]

The aim of this paper is to explore the impact of integrating combined heat and power with bioethanol production on the performance of first- and second-generation processes, using winter wheat as feedstock. Furthermore, we study how the technologies perform subject to criteria relevant to food security and land use, feed energy and protein production, and land-use changes. This study is unique as it is based on empirical data from demonstration-scale processing of lignocellulose to ethanol.

Our analyses are done with reference to agricultural area, not to quantities of input resources. We find this to be the correct approach, as agricultural area, being the ultimately limiting factor, is the proper operational unit.

Methods and models

The conceptual starting point of this study is 1ha of winter wheat. The cases reflect central to northern European conditions in terms of the relation between energy consumption and yield in agriculture.

The conversion process considered is the Integrated Biomass Utilisation System (IBUS).[22,23] IBUS is capable of converting both starch (first generation) and lignocellulose (second generation) into fermentable sugars and subsequently into ethanol. Furthermore, the IBUS plant is integrated with a combined heat and power (CHP) plant utilizing excess steam for pre-treatment of the bioethanol feedstock.

The systems considered are multiple input/multiple output systems and hence evaluating performance using one parameter only is inadequate. Utilization of primary biomass for energy purposes is inevitably linked to feed production and land use. To demonstrate some of the potential impacts induced by using a wheat field for feedstock-to-ethanol production instead of feed production, we analyze five integrated technology scenarios subject to three additional key characteristics: (i) feed energy; (ii) feed protein production; and (iii) land use.

Data input to the study is a quantitative and qualitative analysis of material and energy flows to and from the system of producing and converting winter wheat into ethanol. We use the concept of life-cycle thinking in data acquisition, tracking energy and resource consumption upstream in the production system as far as possible. Data for the analyses are collected from literature, Statistics Denmark, and FAO. Most data are publicly available.

Input and output parameters in a production system covering biorefining, agriculture, transport and further upstream processes vary greatly due to differences in capacity, area, technology, location, purpose and more. We express, when available, system parameters by distributions rather than by single figures, and as such we provide not only central estimates of system performance, but also measures of variability and uncertainty. Calculation of energy loss and impacts on feed and land-use balance is done by Monte Carlo simulation applying 100 000 iterations.

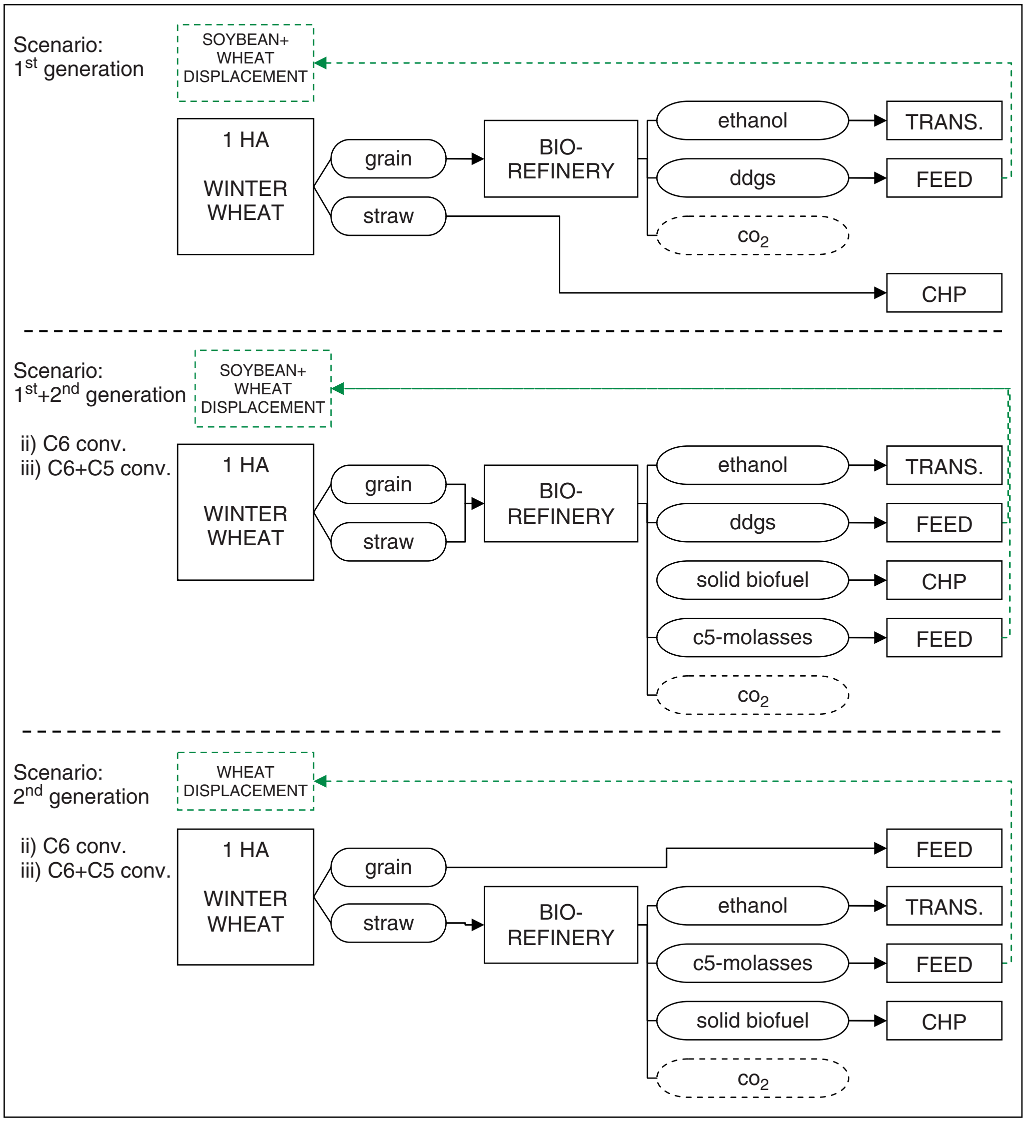

Figure 1. Illustration and flow diagram of the five scenarios analysed. The product encircled with a dotted line (CO_2) is not included in the analyses.

Scenarios

The energy requirement in wheat farming is a constant distribution in all scenario analyses. Different conversion routes in IBUS[22,23] make up the scenarios. We use data for three different conversion routes building on the current terminology of first- and second-generation biofuels: (i) conversion of starch only; (ii) conversion of C6 sugars; and (iii) conversion of C6 and C5 sugars (Scenario 'Case 1', 'C2' and 'D2b' in Morgen[22]). All scenarios assume C6 or C5 yeast for fermentation to ethanol. We combine this with the choice of utilizing grain only, straw only or both in the process. The five scenarios are shown in Fig. 1.

Alternative scenarios

A key element in the baseline scenarios is the integration of the biorefinery with CHP generation, taking advantage of available excess heat. As alternative scenarios we consider the situation where a refinery cannot be integrated with CHP, thus having to produce process steam in a natural gas boiler.

System boundaries

We include processes upstream in the production system as far as possible, including raw material extraction, production of materials, agriculture and refinery processes.

Simulation data

Agriculture

By fitting a logistic curve to data from Rosenberger *et al.*[12] we find a relation between yield and energy consumption in winter wheat production, which is combined with reported yields of winter wheat (Statistics Denmark (www.statistikbanken.dk [March 2009])).

Biorefining

Data used in simulating the energy consumption in refining winter wheat into ethanol and byproducts are given in Table 1.

Outputs

Refining whole-crop winter wheat into ethanol leads to a range of other products, all of which are exploitable in society, either in the energy sector or in other sectors. Data used in modeling the output from agriculture and refinery processes are shown in Table 2.

Energy values of displaced feed products

Non-energy products – for example, fertilizers – are attributed energy values according to the energy required for their procurement or for the procurement of a product they displace. Conversion of grain and straw into ethanol yields four non-energy products: (i) distillers' dried grains with solubles (DDGS); (ii) a protein-rich feed product that may substitute other protein feeds; (iii) C5-molasses, an energy-rich feed product; and (iv) pure CO_2, which has been disregarded here. Table 3 shows the displacement factors we use for DDGS and C5 molasses. These are calculated on the basis of protein and digestible energy contents of the feed products.

Metrics

The results are expressed in four metrics: (i) relative energy loss; (ii) feed energy balance; (iii) feed protein balance; and (iv) land-use balance. Metrics are defined as follows.

Relative energy loss ($E_{l,rel}$):

$$E_{l,rel} = 1 - \frac{\sum E_{out}}{\sum E_{in}}$$

With E_{out} = energy value of outputs from the system and E_{in} = energy value of inputs to the system.

Feed energy balance ($E_{f,\,balance}$):

$$E_{f,balance} = \frac{\sum Q_{out,i} E_{f,i}}{\sum Q_{in,i} E_{f,i}}$$
$$= \frac{\left(Q_{grain} \cdot E_{f,wheat}\right) + \left(Q_{straw} \cdot E_{f,straw}\right) + \left(Q_{DDGS} \cdot E_{f,DDGS}\right) + \left(Q_{mol} \cdot E_{f,mol}\right)}{\left(Q_{grain} \cdot E_{f,wheat}\right) + \left(Q_{straw} \cdot E_{f,straw}\right)}$$

With $Q_{out,i}$ = output quantity of product i, $E_{f,i}$ = content of digestible energy of product i, and $Q_{in,i}$ = input quantity of product i.

Feed protein balance ($P_{f,balance}$):

$$P_{f,balance} = \frac{\sum Q_{out,i} P_{f,i}}{\sum Q_{in,i} P_{f,i}}$$

With $P_{f,i}$ = protein content of product i.

Land-use balance ($LU_{balance}$):

$$LU_{balance} = \left(Q_{DDGS}\left(\frac{D_{DDGS,wheat}}{Q_{grain}} + \frac{D_{DDGS,say}}{Q_{say}}\right) + Q_{mol}\left(\frac{D_{mol,wheat}}{Q_{grain}}\right)\right) - \left(\frac{\Sigma Q_{in,i} E_{f,i} - \Sigma Q_{out,i} E_{f,i}}{E_{f,wheat}} \cdot \frac{1}{Q_{grain}}\right)$$

With $D_{j,k}$ = displacement factor between feed product j and k, Q_{grain} = Danish yield of winter wheat and Q_{soy} = US yield of soybean.

Results

Energy Input

Inputs of energy to the system are partly from material inputs and partly from process energy inputs (Fig.2).

Table 1. Quantities and attributed energy values of process inputs to bioethanol production.

Input	Conversion route	Quantity	Unit	Dist.[1)]	Reference	Attributed energy values	Unit	Dist.	Reference
Grain		7135 (± 244)	Kg ha^{-1}	N	(24)	1.7(± 0.02)	MJ kg^{-1}	N	†
Straw		4188 (± 228)		N		14.5			(25)
Steam	i) Grain	3.653	MJ kg^{-1}		(22)	0.65-0.90 (1.34)[2)]	MJ MJ^{-1}	U	† (26)
	ii) Straw (C6)	3.646							
	iii) Straw (C6 and C5)	3.832							
Electricity	i) Grain	0.106	KWh kg^{-1}			9.8	MJ KWh^{-1}		† (27-29)
	ii) Straw (C6)	0.167							
	iii) Straw (C6 and C5)	0.174							
Water	i) Grain	0.213	Kg kg^{-1}			0.004	MJ kg^{-1}		† (27-30)
	ii) Straw (C6)	0.071							
	iii) Straw (C6 and C5)	0.018							
Enzymes and additives						0.07	MJ kg^{-1} ethanol		(11)
Construction						0.067-0.332	MJ kg^{-1} ethanol	U	(11)
Transport						308-2015	MJ ha^{-1}	U	‡

1): Distribution of simulation data; N = normal and U = uniform distribution.

2): The energy value attributed to steam generation in scenarios without technology integration.

†: data are calculated by the authors on basis of listed references. If no references are listed, data are a result of the current study.

‡: A preliminary study has shown that transport of agricultural products from field to biorefinery and of ethanol to blending with gasoline and of byproducts to farms or power plants concerning distances in Denmark take up only a limited share of the total energy consumption in the analyzed system. We attribute 308-2,015 MJ to all transport activities in this study.

Table 2. Quantities and attributed energy values of process outputs from bioethanol production.

Product	Conversion efficiency (% of dry weight) Conversion route i) Grain	 ii) Straw (C6)	 iii) Straw (C6 and C5)	Reference	Attributed energy values (MJ kg^{-1})	Reference
Ethanol	34.39	17.23	25.24	(22)	26.7	(25)
DDGS	39.35				2.8	† (31;32)
C5 molasses		36.35	20.68		1.4	† (33)
Biofuel		37.29	36.91		17.5	† (26)
CO2 ‡	32.85	16.46	24.11		-	

†: data are calculated by the authors on basis of listed references. If no references are listed, data are a result of the current study.
‡: The output of CO_2 is calculated by the authors based on the molar mass relation between ethanol (46.07 g mol^{-1}) and CO_2 (44.01 g mol^{-1}).
When the conversion percentages adds up to more than 100 is it because the dry matter content in the components of biomass feedstock increases during enzymatic hydrolysis.

Table 3. Displacement factors between IBUS feed products in first column and alternative feed products in first row; and energy values attributed to displaced feed products. Factors are based on dry weight.

	Soybean				Wheat			
		Unit	Dist.	Reference		Unit	Dist.	Reference
DDGS	0.770	Kg kg^{-1}		† (33)	0.032	Kg kg^{-1}		† (33)
C5 molasses	0	Kg kg^{-1}		† (33)	0.769	Kg kg^{-1}		† (33)
Yield	2374 (± 222)	Kg ha^{-1}	N	† (34)	6065 (± 207)	Kg ha^{-1}	N	† (24)
Attributed energy value	3.9	MJ kg^{-1}		† (31;33;34)	2.0 (± 0.02)	MJ kg^{-1}		†

1) The energy value attributed to wheat production is based on the simulations done in this study.
Example: 1kg of DDGS displaces 0.77kg soybean and 0.032kg wheat.

Agricultural production makes up a significant process energy input, ranging from 10 000 to 14 400 MJ ha^{-1}. As materials, grain and straw represent a major input of energy to the system: 9900 to 15 200 and 46 100 to 77 300 MJ ha^{-1} respectively.

Agriculture and feedstock inputs to the system are equal across all scenarios, but differences occur when agricultural produce is processed. Energy consuming processes considered in this study are: (i) steam generation; (ii) electricity generation; (iii) water consumption; (iv) additive and enzyme consumption; (v) refinery construction; and (vi) transport. Steam generation is the predominant contributor to energy inputs, followed by electricity generation. Other energy inputs are relatively insignificant at the system level considered here.

Energy output

Ethanol is the reason for converting biomass in these scenarios and represents a main contribution to the energy output (Fig. 2), but in pure second-generation scenarios, ethanol does not represent the biggest contribution. Solid biofuel represents an equal or bigger share of the energy output, which shows the importance of including all products in the analyses.

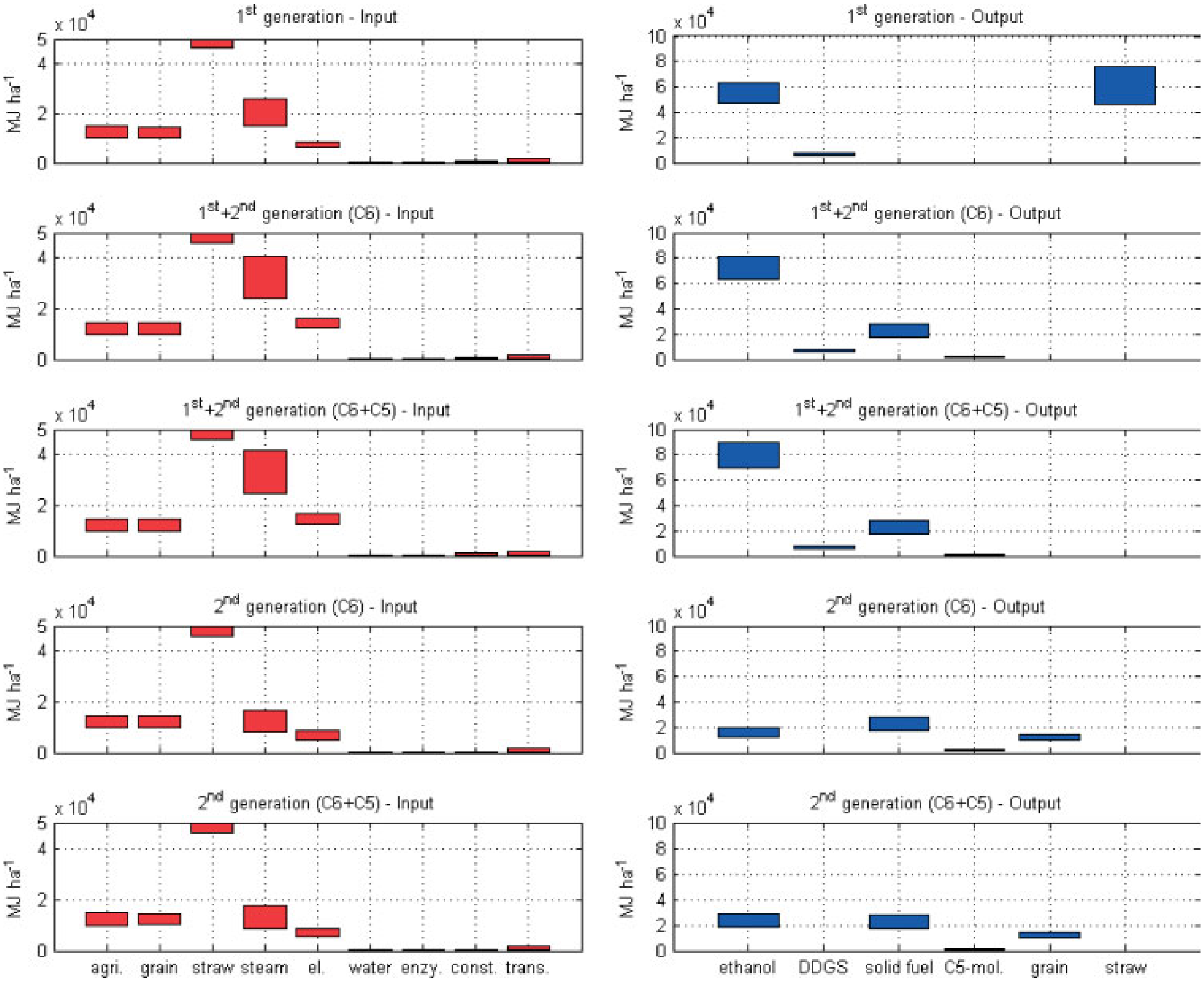

Figure 2. Contribution to the systems total energy input and output from individual processes and materials.The length of bars represent the simulated range of contributions to input and output. The energy input from straw represent 46000 – 74000 MJ ha-1 in all scenarios. agri. = Agricultural processes, el. = electricity and its generation, enz. = production of enzymes and additives, const. = bio-refinery construction, trans. = transportation. C5-mol. = C5 molasses.

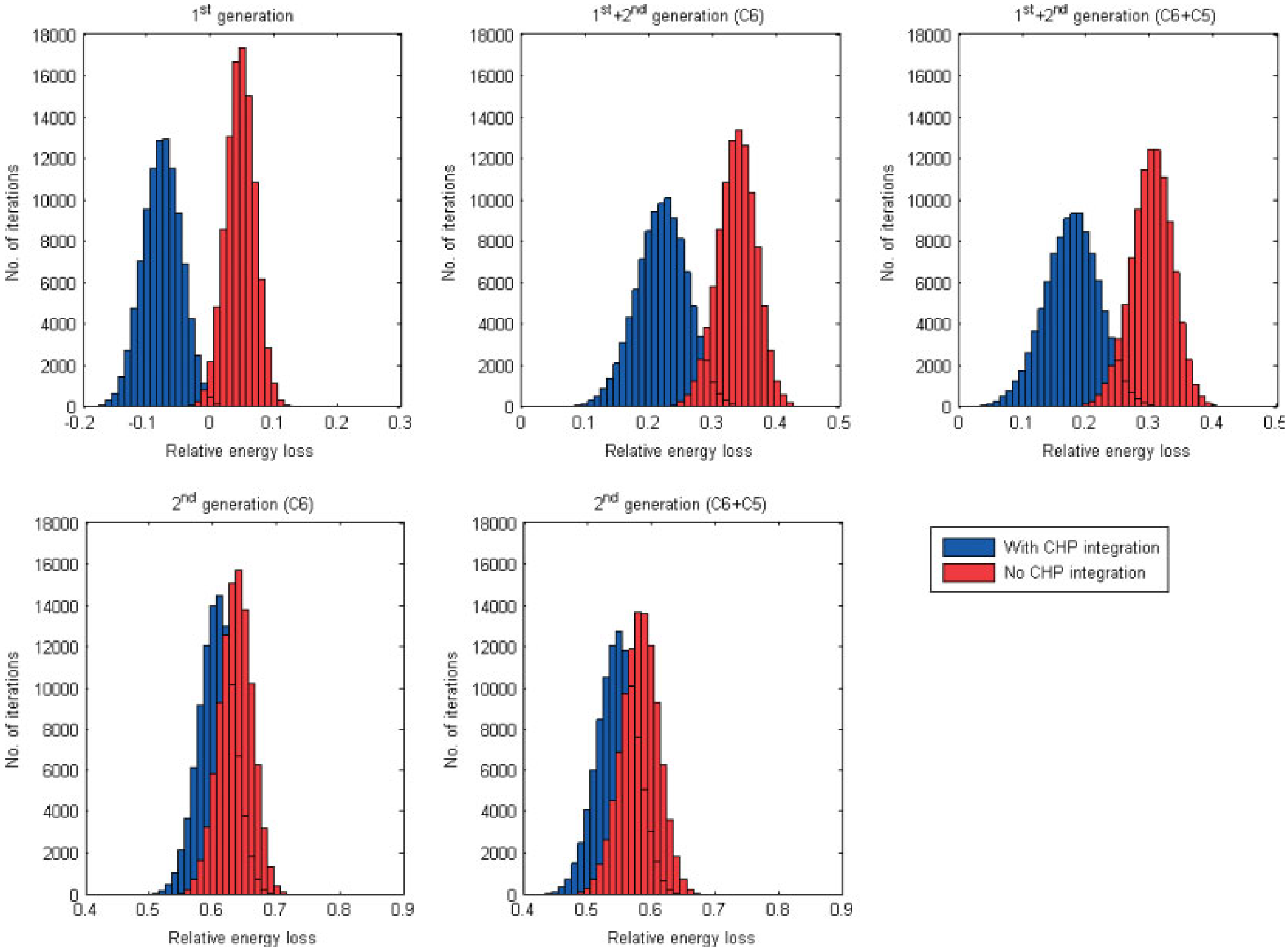

Figure 3. Simulated relative energy loss in scenarios where technology integration is not an option (blue histograms) compared to relative energy loss when technology integration is an option (red histograms). Notice that the x-axis differs between sub-plots.

System integration

Relative energy loss is considered as a measure of performance or the energy efficiency of the scenarios (Fig. 3). The impact on energy efficiency of technology integration can be viewed as the horizontal distance between red and blue distributions in Fig. 3.

In non-integrated scenarios we find a simulated mean energy loss of 5% in first generation; 34% in first and second generation (C6); 30% in first and second generation (C6+C5); 63% in second generation (C6); and 58% in second generation (C6+C5). Technology integration significantly improves the system performance: the corresponding simulated energy losses are -8% in first generation; 22% in first and second generation (C6); 18% in first and second generation (C6+C5); 60% in second generation (C6); and 55 % in second generation (C6+C5).

Multicriteria characteristics

Technology integrated scenarios evaluated on four key characteristics show that the scenarios exhibit different performance patterns (Fig. 4). First generation is superior to other scenarios in terms of relative energy imbalance or energy efficiency and in terms of feed protein imbalance. On the other hand, second generation exhibits superior performance when it comes to feed energy imbalance. Regarding land-use imbalance, first- and first- and second-generation scenarios appear better than pure second-generation scenarios.

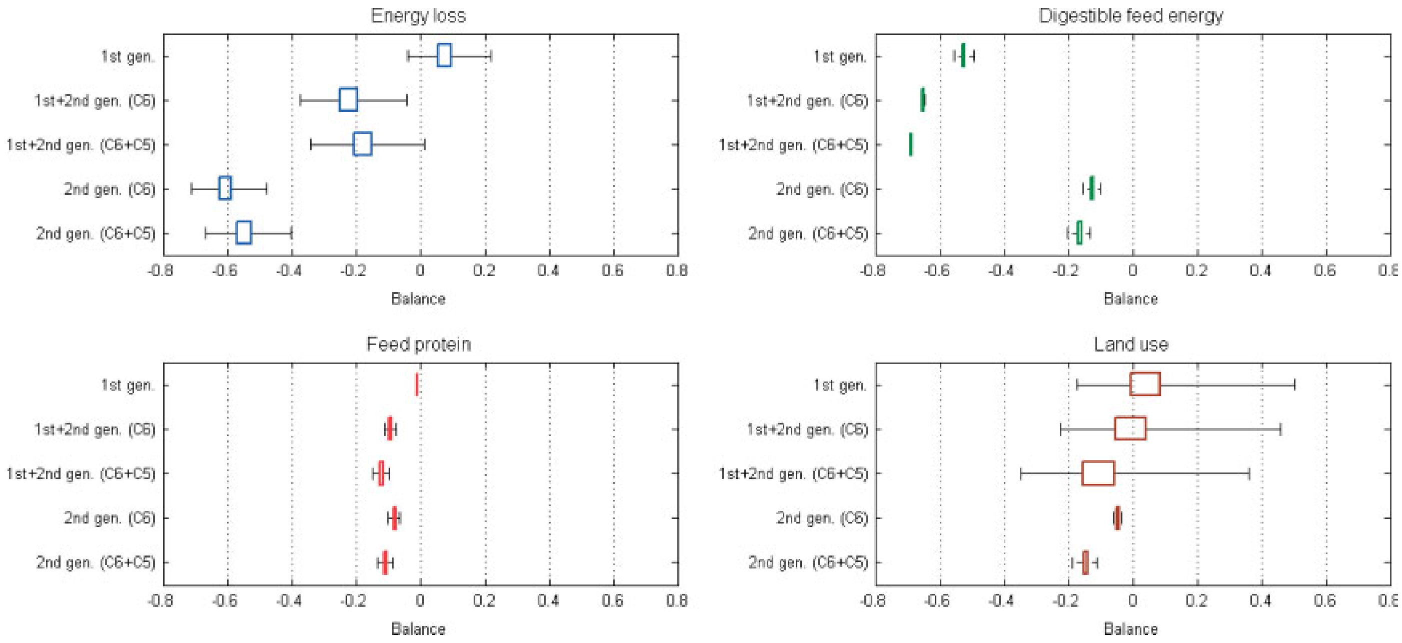

Figure 4. Multi criteria characteristics of the five integrated scenarios. The four characteristics are i) energy balance (equivalent to fig. 3), ii) digestible feed energy balance, iii) digestible protein balance and iv) agricultural land use balance. Boxes represent first and third quartile and whiskers represent the range of simulated values.

Discussion

Material input

When used in a biorefinery, grain and straw cannot be used elsewhere in society. Thus there is an opportunity cost. Thirty per cent of straw from cereals in Denmark is utilized for fuel heat or CHP generation. Analyzing the energy efficiency, we attribute the lower heating value (14.5 MJ kg^{-1}) to the straw input. In principle, grain could be used for fuel heat and power generation as well. However, according to Danish regulation, grain and other food commodities cannot be used in public heat supply.[24] Thus, the grain input is attributed an energy value equal to the energy required to produce grain to substitute the quantity used in the processes (μ = 1.7 MJ kg^{-1} based on this study).

Agriculture

Energy consumption in wheat production varies a lot between references. Börjesson[25] reports energy consumption in Sweden of 16–19.5 GJha^{-1}, whereas Refsgaard *et al.* [26] report energy consumption of 10–10.1 GJha^{-1} under Danish conditions. In Germany, Kuesters *et al.* [27] find the figures to be ~7–~18 GJha^{-1}. The figures upon which we build our study are 5.1–14.4 GJha^{-1}.[12] Our simulations return an energy consumption of 10–14.4 GJha-1, which is within the variation of other studies under European conditions.

Energy loss

In all scenarios we have two inputs: (i) a product with no access to the energy sector (grain); and (ii) a product traditionally used in the energy sector (straw). In the first-generation scenario, straw is still utilized for energy and induces no imbalances. Grain, on the other side, is transformed from pure non-energy purposes into combined energy and feed purposes. From an energy point of view, biomass has a higher value as an energy carrier than as a feed. This relation is the reason why the first-generation scenario apparently contests thermodynamic theory. Could grain be considered as an energy carrier and thus be attributed an energy value equal to its lower heating value (15 MJ kg^{-1}), then the first-generation scenario would also exhibit an energy loss.

At the other end of the energy balance spectrum, the second-generation scenarios are located and exhibit major energy losses. Here the argumentation is the opposite. The high-value energy product (straw) is converted into even higher-value energy products (ethanol and lignin-rich biofuel) but also into a low-value feed product (C5 molasses). As the first- and second-generation scenarios are combinations of first and second generation, they are located in between on the energy imbalance spectre.

Direct comparison of our study with other studies on wheat to ethanol is difficult as our approach takes a systems point of view with land being the limiting factor. Many papers analyze biofuel's potential to displace fossil fuels and consider the input – grain and straw – as 'free' (i.e., they do not attribute energy values to the biomass feedstock). [8,12–14,28,29] We find this approach inadequate when analyzing options for utilizing agricultural crops for energy purposes, as all these products have alternative uses. Laser *et al.*[30] provide a comprehensive overview of second-generation technology options and find system efficiencies up to 70 to 80% (i.e., far higher than we do (40 to 50%)). However, they do not include energy consumption in agriculture and attribute a higher energy value to feed protein than we do.

Any conversion of any energy carrier from one form to another leads to a loss of energy. This is a consequence of basic thermodynamics and the lack of thermodynamic reversible processes.

Using the systems approach in our first- and second-generation scenarios, we find relative energy losses of 18–22%, a level slightly above findings for gasoline production. Farrell[15] and Elsayed[13] find for gasoline production relative energy losses of 16%.

System integration

We show that integration of technologies that allows one technology to utilize the other's waste has significant positive impact on energy efficiency. In this case, a biorefinery can utilize excess steam from CHP generation that would otherwise partly be cooled by seawater. We find that the relative energy loss is reduced by 11 to 12 percentage points for first- and first- and second-generation scenarios and by 3 to 4 percentage points for pure second-generation scenarios, when systems are integrated.

The results could indicate that second-generation technologies benefit less from system integration than do first-generation. This is a consequence of system configurations in the analyses. Our functional unit is 1ha and the produce thereof follows different routes inside and outside the energy sector, leading to differences in the magnitude of energy involved and in the relative importance of individual processes. In scenarios applying the second-generation conversion route, ethanol production accounts for only a minor part of the entire production system, which also includes grain that passes through the system unprocessed.

Isolating biorefinery processes from the rest of the system shows that the energy requirement in integrated scenarios is reduced 34% following the first-generation conversion route and 31% for the second-generation route. Thus both conversion routes benefit greatly from the integration of technologies.

Feed energy and protein balances

Feed production is the main purpose of Danish cereal production. In 2007, 72% of the Danish cereal production was used for feed. For wheat alone the figure was 80% (Statistics Denmark (www.statistikbanken.dk [March 2009]).

Utilization of a feed product for energy purposes induces changes in the feed market. Analyzing this metric, we now consider the input to the system (grain and straw) as purely feed products. We have done so for grain hitherto, but now also straw is considered as feed; in doing so we depict the worst case of potential impacts on feed production. In a society where straw has no utilization as feed, this approach would lead to erroneous conclusions. In the case of Denmark, however, 17–19 % of the collected wheat straw resource is used as feed.

All scenarios lead to a significant drop in available digestible (for cattle) energy. This is expected, as the whole idea of the system is to ferment carbohydrates into ethanol. The first-generation scenario leads to a significantly higher drop in available feed energy than do second-generation scenarios. As most of the digestible energy is found in starch, first-generation technology obviously has a bigger negative impact on feed energy than have second-generation technologies. First- and second-generation scenarios are multiples of first and second generation, and this is why they exhibit the highest drop in feed energy availability.

On the protein side, the picture is different. Conversion of grain into ethanol has only a slight impact on the proteins in the grain, whereas conversion of straw into ethanol destroys more than 50% of the proteins in straw. A probable cause of this is the steam treatment of straw prior to fermentation.

Land-use balance

The fourth metric we apply in the analysis of system performance is the impact on agricultural land use. All scenarios lead to a loss of feed energy and/or protein and that needs to be compensated if status quo is to be maintained. All scenarios also produce feed products, and these will displace other feed products and will *ceteris paribus* decrease demands on agricultural land occupancy elsewhere. Land-use imbalance is calculated as the ratio between land liberated from agriculture due to byproducts from the refinery process entering the market, and land occupied by agriculture to compensate feed and protein not entering the market but utilized in refinery processes. As we work at a system level and do not distinguish between localities, this metric can be considered as a global impact, whereas feed and protein imbalances can be considered as local/national impacts.

Conversion of marginal lands into agriculture may have large impact on the carbon emission profile of such a land-use change, depending on which kind of marginal lands are converted. If native ecosystems are converted into biofuel production, large net carbon emissions are possible depending of the specific circumstances.[18] The demand for biofuel does not change the global feed demand, and thus increased production of biofuel will increase the pressure on land, which may vary from virgin rain forest to degraded cropland. We find that due to the feed products, applying first- and first- and second-generation scenarios can *ceteris paribus* potentially reduce the pressure on marginal lands in a global scope.

The most important factor is how feed products change in characteristics through conversion processes. Grain is converted into DDGS and as 53% of the feed energy is lost but only 1% of the proteins, the resulting product is very different in feed characteristics than is the input, going from a medium energy/medium protein product into a lower energy/high protein product. Likewise, straw is transformed from a low energy/low protein product to a medium energy/low protein product.

We consider that 1kg of DDGS displaces 770g of soybean produced in the USA and 32g of wheat produced in Denmark, and 1kg of C5 molasses displaces 769g of wheat. The displacement rate for DDGS must be considered as conservative; a recent report from IEA Bioenergy finds that 1kg of corn DDGS displaces 0.68kg of corn and 0.60kg of soybean meal due to higher nutritional quality of proteins in DDGS than in soybean.[31]

Our results indicate that the first- and first- and second-generation scenarios potentially release land occupancy even though they, in the national scope, induce feed energy deficits. Our results also indicate the huge uncertainty in quantifying land-use changes. In the first-generation scenario we find as mean values 0.67ha of land additionally occupied in Denmark to cover feed energy deficits and 0.71ha liberated predominantly in the USA due to the entrance of the protein-rich feed product on the market. A reason for this result is that 1 ha of soybean in the USA yields 976kg of protein and 44 GJ of digestible (for cattle) energy, whereas 1ha of Danish wheat yields only ~70% the quantity of protein (697kg) but ~220 % the digestible energy (97 GJ) (calculations based on FAO (www.faostat.fao.org [April 2009]) and Møller *et al.* [32]). A Danish wheat field thus produces more than double in feed energy units than does a US soy field.

The other scenarios result in the following simulated mean values for liberated/occupied land. First and second generation (C6): 0.83/0.83; first and second generation (C6+C5): 0.78/0.88; second generation (C6): 0.12/0.16; and second generation (C6+C5): 0.07/0.21. There is a close correlation between land-use balance and the ratio between feed energy balance and protein balance, indicating the importance of not destroying proteins during biomass processing. The simulations yield a large variability in the results for first- and second-generation scenarios as compared with pure second-generation scenarios. This is because DDGS displaces soybean and the yield of soybean in the USA is much more volatile than the yield of winter wheat in Denmark (FAO (www.faostat.fao.org [April 2009]) and Statistics Denmark (www.statistikbanken.dk [April 2009])).

The assumptions on feed substitution are only valid at the system level and when considering marginal changes in the feed market. At farm level, DDGS can substitute various portions of other diets up to ~25 % for dairy cattle.[33]

Resource utilization in reference case

In analyzing performance of a bioenergy system, it is of paramount importance how the resource input is considered. In our view ‘there is no such thing as a free lunch’, but determination of the right price for that ‘lunch’ may be problematic. Utilization of a resource has the consequence that the resources cannot be utilized elsewhere and as such there must be a cost associated with utilizing any resource. Here the term cost is not considered as a monetary cost but as an energy cost. In 2007, 38% of the Danish straw resource was utilized for energy generation, 12% for feed and 10% for bedding. The rest (40%) was left in the field (Statistics Denmark (www.statistikbanken.dk [March 2009])). Even the unutilized part of the straw resource has a function as it provides nutrients and organic matter to the soil.

Here we attribute the highest possible cost to the straw resource. Analyzing the performance of the production systems subject to energy, we consider straw as an energy carrier, and as a feed product when looking at the systems’ performance subject to feed energy and proteins.

Sustainability

Quantitative analysis of the sustainability of a wheat-to-ethanol production system is not the issue of this paper. Attempts at such analysis have been made by Hedegaard *et al.* [34] Attention must, nevertheless, be drawn to soil organic carbon (SOC) and the potential mining thereof, as liquid biofuels are viewed as a way to mitigate CO_2 emissions from transport. The SOC balance in agriculture is a delicate interplay between soil type, crop, crop rotation, agricultural practice (e.g., ploughing, tilling and straw removal), initial SOC status and much more. In general, and in the long run, removal of straw will reduce SOC by up to 15% as compared with not removing straw.[35] Recent attempts to quantify the impact of GHG emissions from a corn-to-ethanol system derived from land-use changes in the USA find that changes in land use may play a significant role in the systems performance on GHG emissions.[18,19,31]

Conclusions

We have shown a large variability in energy efficiency within and between different scenarios for a wheat-to-ethanol production system. First-generation technology exhibits the best performance in terms of energy efficiency, protein preservation and global land occupancy. Second-generation technology exhibits better performance in terms of feed energy preservation and local/national land occupancy.

Technology integration is a key element in improving the performance of a wheat-to-ethanol production system. Reducing the energy needed for steam generation can dramatically reduce the energy loss from the system. We have shown that the energy efficiency of a wheat-to-ethanol production system can be almost comparable to the energy efficiency of a petroleum-to-gasoline production system.

From the points of view of land use and agriculture, we have shown that protein preservation is very important. Proteins are the plant components hardest to synthesize and must be preserved if intelligent stewardship of inherent solar radiation is an issue.

Applying relatively crude assumptions and simple modeling, we find that there are strong interactions between bioenergy systems and agriculture and land use, and that these may be both positive and negative from a land-use-efficiency point of view. This emphasizes the importance of integrating energy models with land-use models to improve the basis of decision support regarding future energy systems based on biomass.

Acknowledgements

The work behind this paper was supported financially by the Danish Council for Strategic Research and was carried out under the umbrella of the CEESA project (www.ceesa.dk).

References

1. Nielsen PH and Wenzel H, Environmental assessment of ethanol produced from corn starch and used as an alternative to conventional gasoline for car driving. The Institute for Product Development Technical University of Denmark (2005). Available at: www.ipu.dk/upload/publikationer/bio-ethanol-report.pdf [May 2009].
2. Pimentel D and Patzek TW, Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. *Natural Resources Research* **14**:65–76 (2005).
3. Shapouri H, Duffield JA and Graboski MS, Estimating the net energy balance of corn ethanol. *Agricultural Economic Report*, United States Department of Agriculture, Report No. 721 (1995).
4. Shapouri H, Duffield JA and Wang M, The energy balance of corn ethanol: An update. *Agricultural Economic Report*, United States Department of Agriculture, Report No. 814 (2002).
5. Ulgiati S, A comprehensive energy and economic assessment of biofuels: When green is not enough. *Crit Rev Plant Sci* **20:**71–106 (2001).
6. McLauchlin SB and Walsh ME, Evaluating environmental consequences of producing herbaceous crops for bioenergy. *Biomass Bioenerg* **14:** 317–324 (1988).
7. Kim S and Dale BE, Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel. *Biomass Bioenerg* **29**: 426–439 (2005).

8. Venendaal R, Jørgensen U and Foster CA, European energy crops: A synthesis. *Biomass Bioenerg* **13**: 147–185 (1997).
9. Armstrong AP, Baro J, Dartoy J, Groves AP, Nikkinen J and Rickeard DJ, Energy and greenhouse gas balance of biofuels for Europe – an update. CONCAWE Report No. 2/02 (2002).
10. Börjesson P, Energianalys av drivmedel från spannmål og vall [In Swedish]. Lunds Tekniska Högskola, Report No. 54 (2004).
11. Bernesson S, Life cycle assessment of rapeseed oil, rape methyl ester and ethanol as fuels - a comparison between large- and small-scale production. Swedish University of Agricultural Sciences, Uppsala, Report No. 2004:01 (2004).
12. Rosenberger A, Kaul H-P, Senn T and Aufhammer W, Improving the energy balance of bioethanol production from winter cereals: the effect of crop production intensity. *Appl Energ* **68**: 51–67 (2001).
13. Elsayed MA, Matthews R and Mortimer ND, Carbon and energy balances for a range of biofuels options. Sheffield Hallam University, Sheffield, UK (2003).
14. Venturi P and Venturi G. Analysis of energy comparison for crops in European agricultural systems. *Biomass Bioenerg* **25**: 235–255 (2003).
15. Farrel AE, Plevin RJ, Turner BT, Jones AD, O'Hare M and Kammen DM, Ethanol can contribute to energy and environmental goals. *Science* **311**: 506–508 (2006).
16. von Blottnitz H and Curran MA. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *J Clean Prod* **15**: 607–619 (2007).
17. FAO, *The state of food and agriculture*. Food and Agriculture Organisation of the United Nations, Rome (2008).
18. Fargione J, Hill J, Tilman D, Polasky S and Hawthorne P, Land clearing and the biofuel carbon debt. *Science* **319**: 1235–1238 (2008).
19. Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J *et al*., Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319: 1238–1240 (2008).
20. D Rajagopal, S E Sexton, D Roland-Holst and Zilberman D, Challenge of biofuel: Filling the tank without emptying the stomach? *Eur J Agron* **2**: 1–9 (2007).
21. Cassman KG and Liska AJ, Food and fuel for all: realistic or foolish? Biofuels Bioprod Bioref 1:18–23 (2007).
22. Morgen C, Integrated Biomass Utilisation System. DONG Energy (2006).
23. Larsen J, Petersen MØ, Thirup L, Li HW and Iversen FK, The IBUS process –lignocellulosic bioethanol close to a commercial reality. *Chem Eng Technol* **31**: 765–772 (2008).
24. Bekendtgørelse om godkendelse af projekter for kollektive varmeforsyningsanlæg [in Danish], Transport og Energiministeriet (2005).
25. Borjesson PII, Energy analysis of biomass production and transportation. *Biomass Bioenerg* **11**: 305–318 (1996).
26. Refsgaard K, Halberg N and Kristensen ES, Energy utilization in crop and dairy production in organic and conventional livestock production systems. *Agr Syst* **57**: 599–630 (1998).
27. Kuesters J and Lammel J, Investigations of the energy efficiency of the production of winter wheat and sugar beet in Europe. *Eur J Agron* **11**: 35–43 (1999).
28. Kaltschmitt M, Reinhardt GA and Stelzer T, Life cycle analysis of biofuels under different environmental aspects. *Biomass Bioenerg* **12**:121–134 (1997).
29. Hill J, Nelson E, Tilman D, Polasky S and Tiffany D, Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *P Nat Acad Sci USA* **103**: 11206–11210 (2006).
30. Laser M, Larson E, Dale B, Wang M, Greene N and Lynd L, Comparative analysis of efficiency, environmental impact, and process economic for mature biomass refining scenarios. *Biofuels Bioprod Bioref* **3**: 247–270 (2009).
31. (S&T)^2 Consultants Inc., An examination of the potential for improving carbon/energy balance of bioethanol. IEA Bioenergy, Report No. IEA Task 39 Report T39–TR1 (2009).
32. Møller J, Thøgersen R, Helleshøj ME, Weisbjerg MR, Søegaard K and Hvelplund T, Fodermiddeltabel [In Danish]. Dansk Kvæg, Report No. 112 (2005).
33. Akayezu J-M, Linn J, Harty S and Cassady J, Use of distillers grains and co-products in ruminant diets. University of Minnesota, Department of Animal Science (1998).
34. Hedegaard K, Thyø KA and Wenzel H, Life cycle assessment of an advanced bioethanol technology in the perspective of constrained biomass availability. *Environ Sci Techno*l 42: 7992–7999 (2008).
35. Christensen BT, Kulstofindhold i dyrket jord [In Danish] in *Biomasseudtag til energiformål*, ed by Christensen BT. Danish Institute for Agricultural Sciences. Report No. 72 (2002).

Niclas Scott Bentsen

Niclas Scott Bentsen is a PhD-student at the Centre for Forest, Landscape and Planning, at the University of Copenhagen. His research focuses on the production of biomass for energy and includes work on optimal resource allocation in and sustainability impact assessment of bioenergy systems.

Bo Jellesmark Thorsen

Bo Jellesmark Thorsen is Professor in Applied Economics at the Centre for Forest, Landscape and Planning at the University of Copenhagen. He holds a PhD in Forest and Natural Resource Economics and a DSc in Stochastic Decision Analysis in Resource Economics. He heads the Division of Economics, Policy and Management Planning.

Claus Felby

Claus Felby is Professor in Wood and Biomass Technology. His research includes work in biocatalytic tools for industrial processes, conversion of lignocellulosic carbohydrates to fermentable sugars, and fundamental studies on the structure and properties of lignin in wood and plant cell walls.