ENERGY BALANCE OF 2nd GENERATION BIOETHANOL PRODUCTION IN DENMARK

Niclas Scott Bentsen[1] Claus Felby[1] Karen Hvid Ipsen[2]

[1] Royal Veterinary and Agricultural University
Danish Centre for Forest, Landscape and Planning
[2] Elsam Engineering A/S
Present occupation: Energinet.dk

Executive summary

This report will study the energy balance of ethanol production using Danish winter wheat as feedstock. The focus of the report is a 2nd generation ethanol process where the whole crop is used as feedstock. The specific process studied is the Integrated Biomass Utilisation System (IBUS) where ethanol production is integrated with a power plant for combined heat and power.

Biomass based fuels for the transportation sector has become one of the most promising short to medium term technologies for substitution of fossil fuels. The use of ethanol as gasoline replacement has been known for more than 3 decades. The main advantages of ethanol are a high compatibility with current gasoline engines, a full substitution of additives used for lead free gasoline and the possibility of using renewable biomass as feedstock for a large scale production and supply.

Production of bio-based ethanol (bioethanol) is done by fermentation of the sugars which typically constitutes 70% of all plant biomass. Present bioethanol production has been based on kernels only using the starch as sugar source. Recent technological development done by Danish industry and research has made it possible to include the whole plant i.e. straw, kernel and leaves as sugar feedstock. The overall potential of ethanol has been increased to a level where it can have a large impact as an alternative transportation fuel.

The impact of ethanol as transportation fuel depends upon the energy efficiency of the whole process. This includes all process steps from agricultural production to processing and refining of the final ethanol product. Higher energy efficiency may be obtained by integrating a bioethanol production facility with a power plant and using low pressure steam from the power plant as steam source for the ethanol process.

This report shows the energy balance on conversion of a whole crop winter wheat into ethanol under Danish conditions. The process technologies included are a traditional process based on kernels only combined with the IBUS 2nd generation process, where the wheat straw is processed to ethanol.
Data for the calculations are collected from literature, agricultural extension services and from Statistics Denmark, as well as data obtained during pilot- and full-scale processing of biomass to ethanol in the IBUS demonstration plant. All data has been verified on pilot- or large-scale level.

The concept of life cycle thinking in data acquisition, tracking energy and resource consumption up-stream in the production system is applied as far as possible. Quantifying the total energy input into a potential Danish cereal to ethanol production system is done by quantifying both direct energy inputs as diesel use in field operations and indirect energy inputs in the production system as energy inputs in fertiliser production or in the production of chemicals used in ethanol plants.

The integration between an ethanol production facility and a power plant for combined heat and power increases the energy efficiency by at least 30%. The IBUS process has a good ratio between energy-input and –output, as 2.03 times the energy input is produced by the process. The output energy is a mix of pure energy carriers and substitution of other products and productions. A comparable production system based on green field generation of steam delivers only 1.53 times the energy input.

A whole crop winter wheat to ethanol production system is multifunctional and delivers a range of bi-products together with ethanol. Based on 1 ha the production system delivers in average 2,987 kg ethanol, 2,510 kg protein fodder (DDGS) for ruminants or pigs, 561 kg C5 molasses also for fodder, 1,674 kg lignin rich biomass for combustion and 2,897 kg pure CO_2 with multiple appliances.

For 1 ha of winter wheat the total energy input for agriculture and processing is 66,000 MJ.
For the agricultural production 14,500 MJ is needed mainly for diesel and fertilizers. The refining of feedstock to ethanol, feed and solid fuels requires for the IBUS process 50,300 MJ mainly in the form of steam and electricity, whereas an equivalent green field plant will require 71,900 MJ.

Within the IBUS process the nutrients in straw and kernels are recycled to the eco-system in order to obtain maximum sustainability. This will not give the maximum energy output of the process, but the recycling of nutrients for eco-system stability is a pre-requisite for large scale implementation of ethanol as transportation fuel.

Based on the current agricultural production a maximum of 125,400 ha of average wheat land is needed to meet the 2010 obligation of the biofuels Directive 2003/30/EC, which states that 5.75 % of the transportation fuels i.e. both gasoline and diesel, must be based on biomass.
However, with the recent development of biomass conversion technologies a much wider range of crops and crop types are now available for bioethanol production, and winter wheat should only be included as feedstock in the short term. The use of other biomass feedstocks will markedly increase energy input/output ratio as well as multiply the production potential.

Introduction

The growing consumption of the limited available resource fossil oil has led to intensive research in alternative energy sources. A number of technologies within the field of renewable energy (RE) for heat and electricity have been developed and implemented in practice such as wind mills, hydro power, biomass combustion etc. No similar development of alternative energy sources has happened in the ever-growing transport sector.

Although a lot of research is done on new energy sources for transport such as electricity and hydrogen only few of these technologies has been implemented, nor are they applicable with the present car pool and distribution system. The vast majority of cars and trucks still run on gasoline or diesel, and a link between alternative energy sources and the present transport sector is needed. Fuel ethanol based on biomass has the potential of being not only a link between the present dependence of fossil fuels and future energy sources, it may also be used as a future fuel sources in a number of fuel cell types. Biomass based ethanol may serve as a mean of reducing non-reversible CO_2 emissions and reducing the pressure on the fossil reserve. Ethanol can be used in today's cars with only minor changes, and it can be distributed using the present infrastructure, as seen in several countries around the world with Brazil being the prime example. Also USA, Germany and Sweden has implemented bio ethanol as an alternative to petrol in various scales.

The purpose of this study is to analyse bio ethanol as an alternative fuel for today's car pool. Based on latest technologies for fuel ethanol production and averages agricultural production, the study will explore whether it is reasonable from an energy point of view to use the produce of 1 ha of winter wheat in Denmark as a source of energy for cars. Other factors and concerns about supply security and ecological sustainability is included. The purpose is not necessarily to explore the best possible use of 1 ha of agricultural land.

The process for conversion of whole crop used in this study is the Integrated Biomass Utilisation System (IBUS) developed by Elsam, KVL, Risø, SICCO and TMO. In this process the whole crop ethanol production is integrated with a power plant for combined heat and power.

Background
The Danish energy consumption is rising year by year. From 1990 to 2003 the climate corrected final consumption rose from 605 PJ to 646 PJ, an increase of 6.7 % (Energistyrelsen 2004).

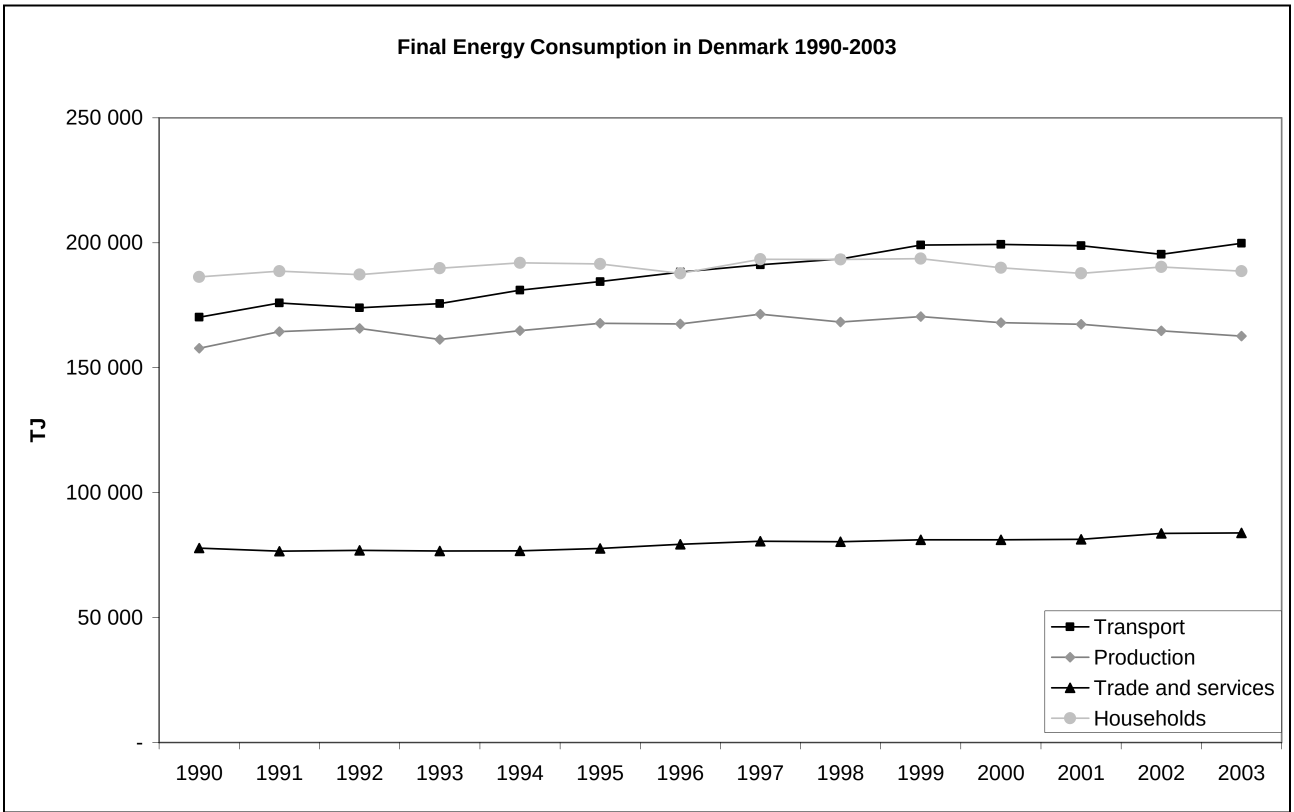


Figure 1. Final energy consumption in Dnamark in 1975-2003 in transport, production, trade and the household sectors (Energistyrelsen 2004).

Growth in the energy consumption is highest in the transport sector totalling 17.4 % in the period 1990-2003 (Energistyrelsen 2004), whereas growth in other sectors has been moderate with increases between 1.2 and 7.7 %. Within the transport sector the main contributors to the increased energy consumption are road transport (20.8 %) and international air traffic (24.5 %). Rail transport, domestic sea transport and domestic air traffic have seen decreases in energy consumption (Energistyrelsen 2004).

In the period from 1990 to 2003 the transport sector's share of the total energy consumption rose from 28 % to 31 %.

As road transport is a large contributor to the total growth in the transport sector consumption a subsequent increase in consumption of fuels for road transport vehicles (e.g. diesel and gasoline) is seen (Fig. 2).

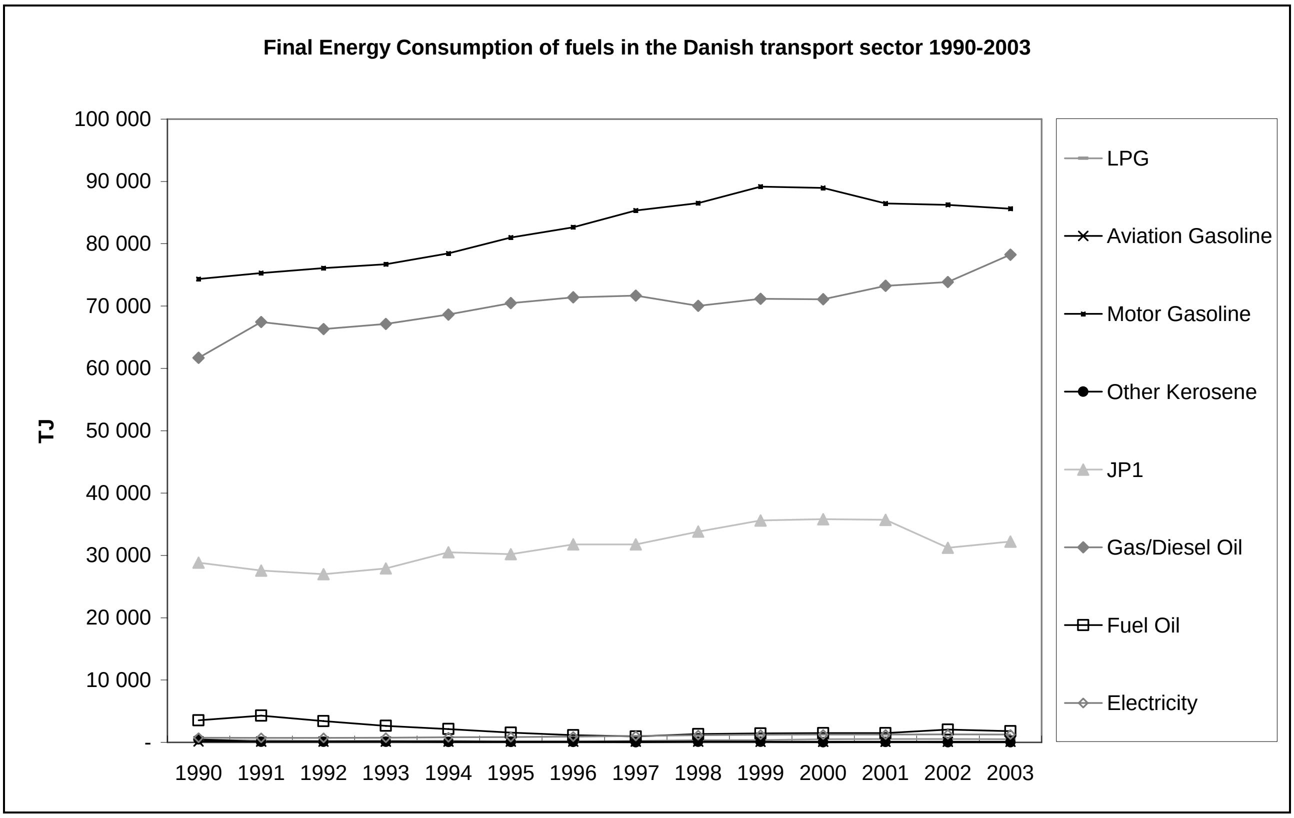


Figure 2. Final energy consumption of fuels in the Danish transport sector in the period 1990-2003 (Energistyrelsen 2005).

This trend is not exclusive to Denmark. To focus on both the environment and security of supply, the European Union launched in 2003 a directive on increased use of renewable resources in transport. By 2005 2 % (based on energy content) of fuels used in transport must be based on biomass. In 2010 the proportion is 5.75 % (European Parliament 2003). Denmark has recently put forward a target by the end of 2006 of basing 0.1 % of transport energy on biofuels (Transport- og Energiministeriet 2005). Denmark already has a production of liquid biofuels (RME) amounting to 1.7 PJ in 2003 (Energistyrelsen 2005) corresponding to 0.8 % of the Danish transport energy need in 2003. Practically all RME was exported and local consumption is insignificant.
Using biomass and other renewable sources for energy purposes other than transport is an area where Denmark is in the top-league internationally (Energistyrelsen 2004). In 2003 13.6 % of the Danish gross energy consumption was based on renewable sources. The corresponding figures for 1990 and 1980 are 6.4 % and 3.4 % (Energistyrelsen 2004). Biomass and waste amounted to more than 70 % of the renewable energy production in 2003 in Denmark.

Transport being the fastest increasing energy consumer has focused improvement or development for increased use of biomass based fuels. Several technologies have been developed and are in use today. Rapeseed oil can be used as a substitute for diesel oil, and can be converted to rape methyl ester (RME) also known as biodiesel. In the Americas biomass is used for the production of ethanol used alone or in an admixture with gasoline as car fuel. In Latin America 7.1 % of the energy used for transport in 2000 was based on liquid bio fuels (Fulton & Eads 2004), and in Brazil alone 11-17 % of the transport energy consumption in 1995 - 2004 was based on bio-ethanol (Ministerio de

Minas e Energia 2005). In USA app. 1.1 % (2004) of the transportation sector energy consumption came from corn based ethanol (U.S. Department of Energy 2005). Several countries in Europe produce ethanol for fuel from biomass.

The energy efficiency of bioethanol has been subject to numerous studies with various results. The table below gives an overview of studies conducted within the last 10-15 years on the energy balance in bioethanol production systems.

Reference	Year	Feed stock	Region/ country	Energy output/input	By-product credits included
Marland and Turhollow	1991	Corn	U.S.	1.14	No
				1.28	Yes
Pimentel	1991	Corn	U.S.	0.58	No
				0.69	Yes
Keeney and DeLuca	1992	Corn	U.S.	0.83	No
				0.92	Yes
Morris and Ahmed	1992	Corn	U.S.	1.01	No
				1.51	Yes
Lorenz and Morris	1995	Corn	U.S.	1.04	No
				1.33	Yes
Shapouri et al.	1995	Corn	U.S.	1.01	No
				1.24	Yes
Venendaal et al.	1997	Winter wheat	Germany	1.1-1.7	No
				4.0-5-0	Yes
	1997	Winter wheat	Belgium	1.1-5.9	?
	1997	Winter wheat	France	1.3	?
Macedo	1998	Sugarcane	Brazil	9.2	No
McLaughlin et al.	1998	Corn	U.S.	1.21	Yes
		Switchgrass	U.S.	4.43	Yes
Prakash et al.	1998	Sugarcane	India	~ 2	?
Wang et al.	1999	Corn	U.S.	1.11	No
				1.42	Yes
Pimentel	2001	Corn	U.S.	0.58	No
				0.69	Yes
Ulgiati	2001	Corn	Italy	0.59	No
				1.36	Yes
Armstrong et al.	2002	Wheat	Belgium	1.04	No
		Sugar beet	Belgium	0.93	No
Shapouri et al.	2002	Corn	U.S.	1.08	No
				1.33	Yes
Pimentel	2003	Corn	U.S.	0.78	No
				~ 0.83	Yes
Venturi et al.	2003	Sweet sorghum	Italy	1.20	No
				1.21	Yes
Bernesson	2004	Winter wheat	Sweden	1.1-1.13	No
Börjesson	2004	Winter wheat	Sweden	1.31	No
				2.05	Yes
Punter et al.	2004	Winter wheat	U.K.	0.68-2.22	No
Pimentel and Patzek	2005	Switchgrass	U.S.	0.69	?
		Wood cellulose	U.S.	0.64	?
Nielsen et al.	2005	Corn	U.S.	1.9	Yes

The figures presented above are not directly comparable due to differences in assumptions and decisions regarding production system settings and delimitations. These studies do not necessarily analyse the same thing, but it underlines the importance of transparency in analyses of this kind. One general lesson to be learned from the studies is the impact of including energy credits for by-products in the calculations. For the studies shown above inclusion “improves” the output-input ratio with up to 51 % as compared to no inclusion.

Methodology
The aim of this paper is to study the energy balance on conversion of a Danish winter wheat crop into ethanol. Data for the calculations are collected from literature, agricultural extension services and from Statistics Denmark.
The study uses the concept of life cycle thinking in data acquisition, tracking energy and resource consumption up-stream in the production system as far as possible. Quantifying the total energy input into a potential Danish cereal to ethanol production system is done by quantifying both direct energy inputs as diesel use in field operations and indirect energy inputs in the production system as energy inputs in fertiliser production or in the production of chemicals used in ethanol plants.

Calculation of energy consumption in agricultural production is done by simulation. Production systems and settings vary a lot due to differences in capacity, area, technology, location, purpose and more. We acknowledge these variations and attempt to express production system parameters by a reasonable range rather than by a single figure.

Base line scenario
The base line scenario of this study is an agricultural production of winter wheat under Danish conditions using good agricultural practices. Farming is done in a conventional manner using commercial fertilisers and pesticides within the rules and regulations imposed on Danish agriculture. Technology used is considered as average, and data are considered valid in a time scale of 0 – 10 years from present.

The outputs from the field, grain and straw, are both used as sugar source in the bio refinery. The by-products distillers dried grain with solubles (DDGS) and C5-molases are returned to the agricultural business as feed for cows or pigs. Another by-product, biomass, is incinerated for energy generation. CO_2, which also is a by-product, is not dealt with in this study.

System boundaries
The figure below show the main processes included in this study. Allocation of energy consumption between different co-products is to a large extent avoided by expanding the delimitations of the product system.

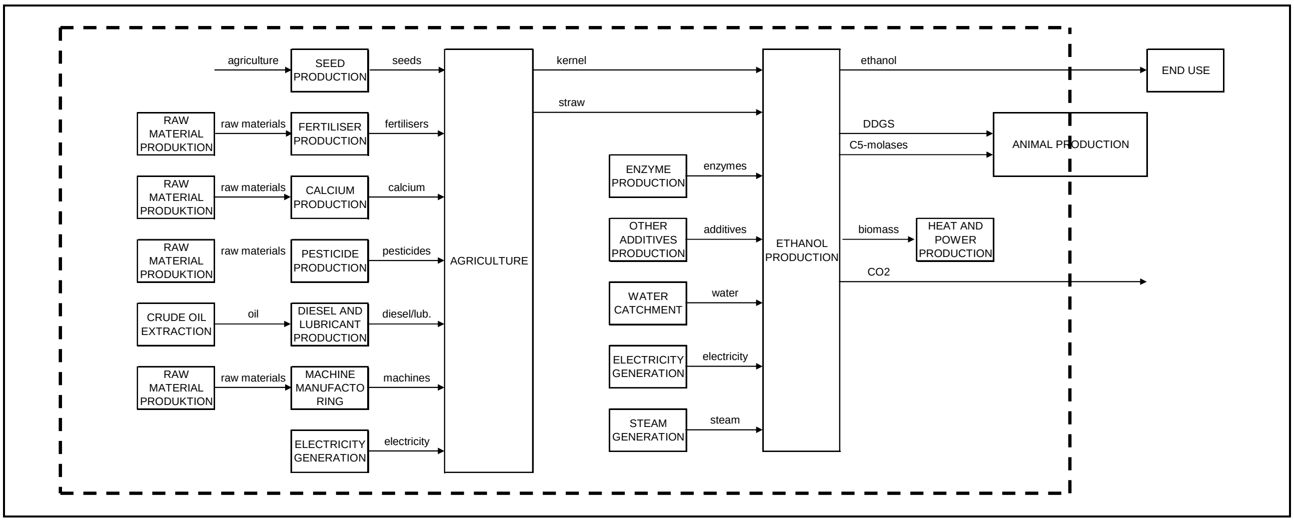


Figure 3. Main processes included in the analysis of energy consumption and generation in the production system of producing ethanol from winter wheat.

Data on energy input

Findings on resource and energy consumption on single processes in the production system are shown in the tables below.

Seeds

Seeds are needed to produce a cereal crop. For winter wheat seeds are usually a sub stream of a previous crop. The target number of germinated seedlings depends on time of seeding and varies between 200 and 400 seedlings pr ha (Dansk Landbrugsrådgivning 2003). In this study we have chosen target number on 350 seedlings pr m^2 in accordance with seed source tests by the Danish Agricultural Advisory Service (Dansk Landbrugsrådgivning 2004). This gives a seed input range (Q_{seed}) of 136 to 221 kg/ha. The energy consumption related to distribution of seeds (EC_{seed}) is based on estimates by Kuesters et al. (1999) and Rosenberger (2001).

Table 1. Input data for seeds used in the simulations.

Abbreviation	Input	Unit	Input range	Reference	Abbreviation	Unit	Specific energy input range	Reference
Q_{seed}	Seeds	Kg/ha	136 - 221	Dansk landbrugs-rådgivning 2004	EC_{seed}	MJ/kg	2.5 – 3.5	Kuesters 1999; Rosenberger 2001

The total energy consumption for the production and handling of seed is calculated as:

$$EC_{SEED} = [Q_{seed}] * [EC_{seed}]$$

Chemical inputs to agriculture

Modern agricultural production of winter wheat in Denmark is highly dependent on chemical inputs as nitrogen, phosphorus and potassium fertiliser or plant protection agents. Input levels are highly variable and dependent on soil, crop and previous crop.

Fertilisers

The allowable input of nutrients to agricultural crops is defined by norms from the Danish Plant Direktorate (Plantedirektoratet). For winter wheat the nitrogen norm is 157-179 kg/ha (Plantedirektoratet 2004). Since winter wheat is most suitable for better soils, soil class 6-7 (Dansk Landbrugsrådgivning 2003), we use the norms for class 5-6 and 7-9 in the modelled application rates, 169-179 kg/ha (Q_N). The guiding norm for phosphorus is 20 kg P/ha and correspondingly for potassium is 70 kg K/ha. From 2000 to 2002 only 43 % to 49 % of the total nitrogen application to agricultural land in Denmark came from commercial fertilisers (Danmarks Statistik 2004). The rest came from manure. In this study we assume the same proportion ($P_{N\text{-}com}$). The commercial fertiliser share of P and K nutrients is lower, but we chose to use nitrogen as reference because that norm is obligatory where the P and K norms are guiding.

Manure

As supplement to commercial nitrogen fertilisers manure is the primary nitrogen supplier. The nitrogen content varies in different manures. We assume that manure is applied to the soil in the form of slurry from pigs or cows. The nitrogen content in slurry from pigs and milking cows ranges from 3.93 to 6.93 kg N/ton slurry (Danmarks JordbrugsForskning 2005). Due to differences in nutrient availability in the slurry, the Danish regulation on the application of manure on agricultural land says that 75 % of the N-content in pig slurry has to be accounted for and correspondingly 70 %

of the N-content in cow slurry (Ministeriet for Fødevarer, Landbrug og Fiskeri 2005). Thus the application of 1 ton of manure corresponds to the application of 2.75 - 4.85 kg nitrogen leading to application rates of manure (Q_{man}) of 17,732 – 37,091 kg/ha.

Table 2. Input data for fertilisers and manure used in the simulations.

Abbreviation	Input	Unit	Input range	Reference	Abbreviation	Unit	Specific energy input range	Reference
Q_N	Nitrogen	Kg/ha	169-179	Dansk Landbrugsråd givning 2003; Plantedirektor atet 2004				
$P_{N\text{-}com}$	Proportion on commercial N-fertiliser	%	43-49	Danmarks Statistik 2004	$EC_{N\text{-}com}$	MJ/Kg N	38.0-76.7	Borjesson 1996; Rosenberger et al. 2001; EFMA; Feldvoss et al. 2002; Dalgaard et al. 2001, 2002; Refsgaard et al. 1998
$C_{N\text{-}man}$	N-content in manure accounted for	Kg N/t	2.75 – 4.85	Danmarks JordbrugsFors kning 2005	EC_{man}	MJ/T	7.39 – 77.03	Clements et al. 1995; Dalgaard et al. 2001, 2002; Refsgaard et al. 1998; Sørensen 2005
$Q_{P\text{-}com}$	Commercial P-fertiliser	Kg P/ha	0.00-7.24	Plantedirektor atet 2004; Danmarks JordbrugsFors kning 2005	$EC_{P\text{-}com}$	MJ/Kg P	6.8 – 33.0	Rosenberger et al. 2001; Feldvoss et al. 2002; Dalgaard et al. 2001, 2002; Refsgaard et al. 1998
$Q_{K\text{-}com}$	Commercial P-fertiliser	Kg K/ha	0.00-38.44	Plantedirektor atet 2004; Danmarks JordbrugsFors kning 2005	$EC_{K\text{-}com}$	MJ/Kg K	2.9-12.6	Rosenberger et al. 2001; Borjesson 1996; Feldvoss et al. 2002; Dalgaard et al. 2001, 2002; Refsgaard et al. 1998

Slurry also contains phosphorus and potassium, and the application rates of commercial P and K fertilisers must be adjusted according to the P and K content in slurry. The P content in slurry ranges from 0.72 to 1.91 kg P/t slurry and the content of K ranges from 1.78 to 6.47 kg K/t slurry (Danmarks JordbrugsForskning 2005).

Given application rates of manure as described above the application of P from manure will be in the range of 12.76 - 70.84 kg P/ha and correspondingly the application of K will be in the range of 31.56 - 239.98 kg K/ha. The application rates of commercial P and K fertilisers to the crop used in the modelled energy consumption are calculated as the norm deducted the content of P and K in the applied slurry. Thus the need for commercial fertilisers thus amount to 0.00 - 7.24 kg P/ha ($Q_{P\text{-}com}$) and 0.00 - 38.44 kg K/ha ($Q_{K\text{-}com}$).

The average application rates of commercial P and K fertiliser on all agricultural land in Denmark as reported by the agricultural statistics (Danmarks Statistik 2004) are 5 – 7 kg P/ha and 23-27 kg K/ha in the period 2000-2003. Our figures comprise that range.

The direct energy consumption by handling and applying manures amounts to 0.006 l diesel pr ton for slurry stirring, 0.01 l diesel pr ton for pumping (Sørensen 2005) and 0.3 l. pr ton for application (Dalgaard et al. 2001, 2002; Sørensen 2005). Direct energy consumption for transport between slurry tank and field is calculated as

*1.5 * distance (km) * 0.2 (l/t*km)* (Sørensen 2005)

Distance between slurry tank and field is assumed to be between 0.5 and 5.0 km giving a total direct energy consumption for slurry transport in the range of 0.15 to 1.5 l diesel pr ton.
The total (direct and indirect) energy consumption is assumed to be 40.9 – 45.11 MJ/l diesel (see below part on diesel and lubricants) and additional 3.6-5.7 MJ/l diesel for lubricants (Dalgaard et al. 2001; Refsgaard et al. 1998) totalling a range of 7.39 – 77.03 MJ/ton slurry (EC_{man}).

The energy consumption associated with the application of commercial fertilisers is calculated as:

$$EC_{FERT} = ([Q_N]*[P_{N-com}]*[EC_{N-com}]) + ([Q_{P-com}]*[EC_{P-com}]) + ([Q_{K-com}]*[EC_{K-com}])$$

The total energy consumption associated with the application of manure is calculated as:

$$EC_{MAN} = \frac{[Q_N]*(1-[P_{N-com}])}{[C_{N-man}]} * [EC_{man}]$$

Calcium
Also the need for calcium is highly dependent on soil type and crop rotation. A rule of thump recommends application of up to 1000 kg calcium pr ha pr year (Landbrugets Rådgivningscenter 2002). I this study we calculate with application rates of 0 – 1000 kg/ha (Q_{ca}).

Table 3. Input data for calcium used in the simulations.

Abbreviation	Input	Unit	Input range	Reference	Abbreviation	Unit	Specific energy input range	Reference
Q_{Ca}	Lime	Kg Ca/ha	0 – 1000	Landbrugets Rådgivningscenter 2002	EC_{Ca}	MJ/Kg Ca	0.021-0.030	Dalgaard et al. 2001, 2002; Rosenberger et al. 2001; Refsgaard et al. 1998

The total energy consumption associated with the application of calcium is calculated as:

$$EC_{CA} = [Q_{Ca}]*[EC_{Ca}]$$

Pesticides
In conventional farming pesticides are applied to protect the crop against weed competition, insect damage or fungal deceases. The application rate estimate (Q_{pest}) is based on sales statistics (Danmarks Statistik 2005). For the period 2000-2004 sales corresponded to an average application on all agricultural land ranging from 1.34-1.42 kg active ingredient (ai) pr ha. This calculation principle is based on an essential assumption that stocks of pesticides do not differ from year to year. The Danish EPA use this principle in their reports on the use of pesticides in Denmark (Miljøstyrelsen 2005).

The target for pesticide use in Danish agriculture in 2009 is an average "treatment frequency" (the treatment of agricultural land with one standard dose once with a relevant pesticide) on 1.7 (Pesticidhandlingplan 2004-2009). The crop specific target for winter wheat is 1.75. We find it reasonable to assume that the consumption of pesticides in winter wheat does not differ significantly from the average consumption in agriculture and no adjustments to the figures above are made.

Energy consumption for production of pesticides (EC_{pest}) varies a lot between references. In this study we calculate with the range 40.3-580.0 MJ/Kg active ingredient.

Table 4. Input data for pesticides used in the simulations.

Abbreviation	Input	Unit	Input range	Reference	Abbreviation	Unit	Specific energy input range	Reference
Q_{pest}	Pesticides	Kg ai/ha	1.34 – 1.42	Danmarks Statistik 2005	EC_{pest}	MJ/Kg ai	40.3-580.0	Feldvoss et al. 2002; Refsgaard et al. 1998; Kuesters et al. 1999; Dalgaard et al. 2001, 2002; Clements et al. 1995

The total energy consumption associated with the application of pesticides is calculated as:

$$EC_{PEST} = [Q_{pest}]*[EC_{pest}]$$

Diesel and lubricant inputs in agriculture

Agricultural machines run on diesel oil and require lubricants. Diesel has a net calorific value of 42.7 MJ/kg and a density of 0.83 kg/l (Energistyrelsen 2005) giving a direct energy input to agriculture of 35.44 MJ/l diesel consumed. The indirect energy consumption associated to the manufacturing and distribution of diesel varies among references. Based on Dalgaard et al. (2001, 2002) and Clements et al. (1995) the total energy consumption is estimated to be 40.9 – 45.11 MJ/l diesel consumed. The consumption of lubricants (Q_{lub}) is closely correlated to the consumption of diesel (Q_{diesel}), hence the relation between diesel and lubricant consumption assuming a total energy consumption from lubricants of 3.6 - 5.7 MJ/l diesel consumed.

Table 5. Input data for diesel and lubricants used in the simulations.

Abbreviation	Input	Unit	Input range	Reference	Abbreviation	Unit	Specific energy input range	Reference
Q_{diesel}	Diesel oil	l diesel/ha	90.0-132.9	Dalgaard et al. 2001, 2002; Bernesson 2004	EC_{diesel}	MJ/l diesel	40.9-45.11	Dalgaard et al. 2001, 2002; Clements et al. 1995
Q_{lub}	Lubricants				EC_{lub}	MJ/l diesel	3.6-5.7	Dalgaard et al. 2001, 2002; Refsgaard et al. 1998

The total energy consumption associated with the use of diesel oil and lubricants is calculated as:

$$EC_{FUEL} = [Q_{diesel}] * ([EC_{diesel}] + [EC_{\text{lub}}])$$

Machine manufacturing
Machines and tools as tractors, harvesters and ploughs are used in industrial agriculture. Machines and tools have to be manufactured, steel and other metals and materials have to be produced and ore to be extracted in order to produce the machines and tools needed. All these operations require energy. Data used in this study is based on Dalgaard et al. (2000), Börjesson (1996), Refsgaard et al. 1998 and estimated to be 1366 – 1916 MJ/ha.

Table 6. Input data for machine manufacturing used in the simulations.

Abbreviation	Input	Unit	Input range	Reference
EC_{mach}	Machinery	MJ/ha	1366-1916	Dalgaard et al. 2000; Börjesson 1996; Refsgaard et al. 1998

Other references relate the energy requirements for machine manufacturing to the diesel consumption estimating a total energy requirement on 12 MJ/l diesel used. Given a total use of diesel to produce 1 ha of winter wheat on 90.0 – 132.9 l/ha, the energy consumption range between 1.080 and 1,487 MJ/ha. This range is lower than the range used in this study whereas our range is far lower than that reported by Patzek (2005) for corn farming in the United States approximating 6,000 MJ/ha. One explanation of the huge difference could be that Patzek (2005) apparently do not include the scrap value of iron in his calculations.

Electricity input in agriculture
Agricultural production consumes electricity for heat, light, ventilation etc. The energy consumption from using electricity has to cover not only the direct use, but also the conversion of energy carriers to electricity and the transmission loss. Dalgaard et al. (2000) reports a primary energy consumption for electricity on 866 MJ/ha. Bernesson (2004) reports electricity consumption on 66.7 kWh. Giving a primary energy consumption for conversion and distribution on 9.8 MJ/kWh the estimated energy consumption ranges from 654 - 866 MJ/ha.

Table 7. Input data for electricity use in agriculture used in the simulations.

Abbreviation	Input	Unit	Input range	Reference
EC_{elec}	Electricity	MJ/ha	654-866	Dalgaard et al. 2000; Bernesson 2004

Total energy consumption in winter wheat production
The total quantity of primary energy required to produce a hectare of winter wheat is calculated by simulation using the application rates and energy consumption ranges presented in the tables above. For all input ranges an even distribution within the range is assumed. The model for primary energy consumption in agricultural production is:

$$EC_{AGRI} = EC_{SEED} + EC_{FERT} + EC_{MAN} + EC_{CA} + EC_{PEST} + EC_{FUEL} + EC_{mach} + EC_{elec}$$

Simulation is done by the Monte Carlo method with SAS software using 10.000 iterations. The result of the simulation is shown in fig. 4.

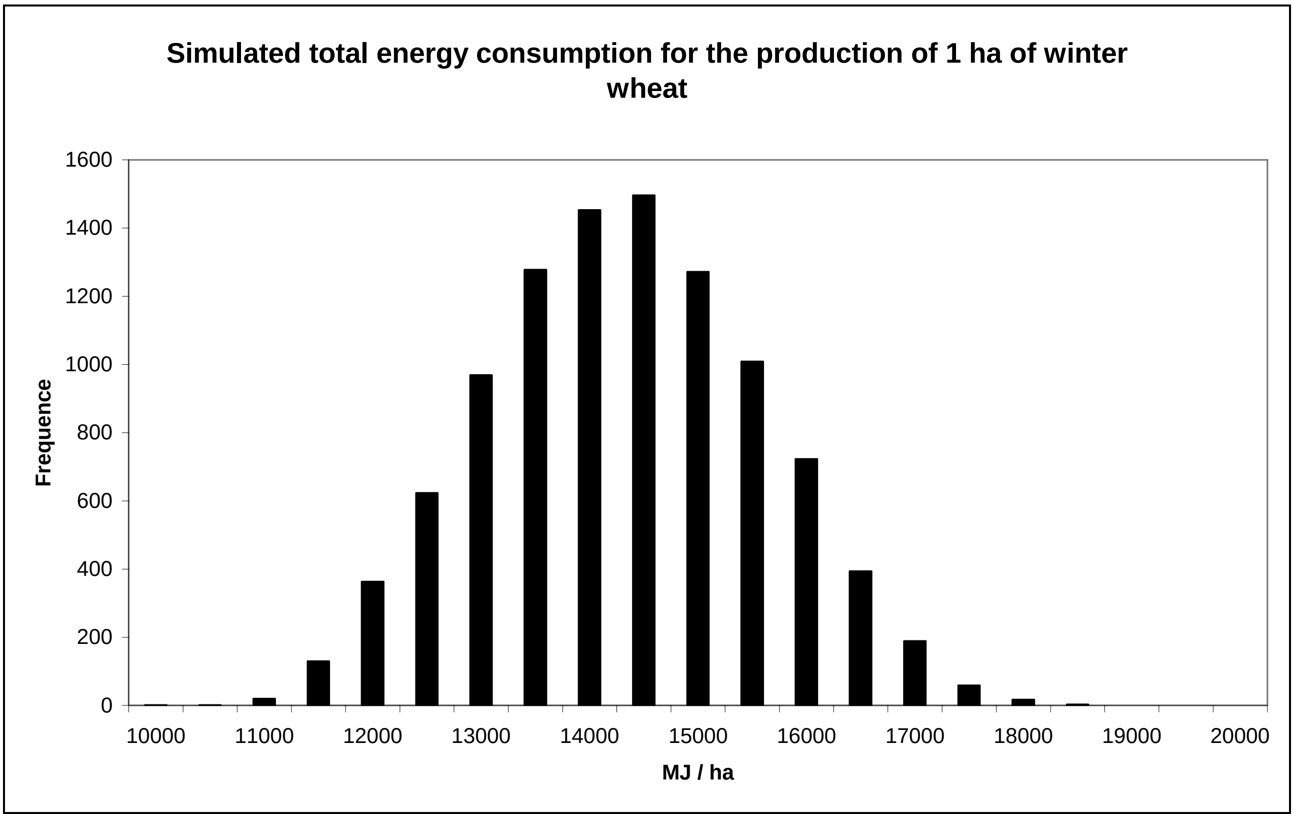


Figure 4. Simulated total energy consumption for the production of 1 ha of winter wheat under Danish conditions.

Simulation of the primary energy consumption returns a bell shaped distribution around a median of 14,560 MJ/ha. The lower quartile is 13,673 and the upper quartile 15,458 showing that in 50 % of the iterations of the simulated energy consumption for producing a hectare of a cereal crop is between 13,673 and 15,458 MJ/ha.
The minimum and maximum values from the simulation are 10,275 and 18,776 MJ/ha respectively.

As the production system behind growing winter wheat constitutes of several single processes it is relevant to analyse the contribution from each process to the total energy consumption. The result is shown in fig. 5 below. It is seen that the two major contributors are the use of commercial fertilisers and the consumption of diesel oil and lubricants. Their contribution to the total energy consumption is 33 % and 37 % respectively. Within the commercial fertilisers nitrogen is by far the most energy consuming.

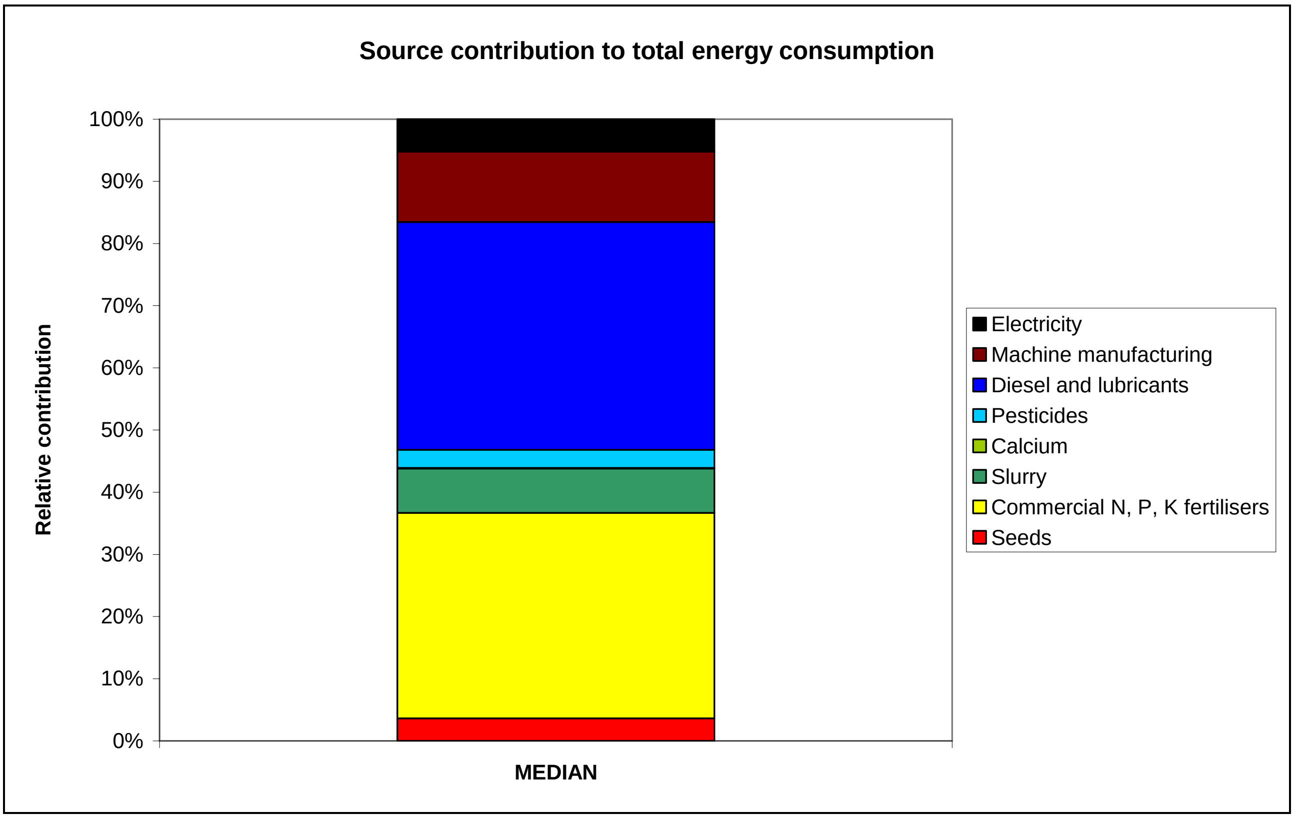


Figure 5. Relative importance of single processes' contribution to the total energy consumption for growing 1 ha of winter wheat.

Agricultural outputs

Outputs from agricultural production are estimated on basis of national statistics for the period 1990 to 2003. These statistics are based on the total production of winter wheat in Denmark and cover all intensities, soil types and agricultural practices. Mean annual yield of winter wheat in Denmark (Q_{kern}) is 7,057 kg/ha (σ = 359) at 15 % moisture content, corresponding to 5,998 kg/ha dry weight (DW) (Danmarks Statistik 2005).
For the same period mean annual yield of straw (Q_{straw}) from winter wheat is 4,232 kg/ha (σ = 198) at 15 % MC or 3,597 kg/ha DW (Danmarks Statistik 2005). Since the estimate on ethanol output from straw (see below) is based on a study where the straw by nature had a moisture content of 14 % we correct the straw yield to 4,183 kg/ha (σ = 196)

Table 8. Output data from 1 ha of winter wheat used in the simulations.

Abbreviation	Input	Unit	Input range	Reference
Q_{kern}	Kernel	kg/ha	μ = 7,057 σ = 359	Danmarks Statistik 2005
Q_{straw}	Straw	kg/ha	μ = 4,183 σ = 196	Danmarks Statistik 2005

Ethanol production and by-products

During the refinement of kernel and straw to ethanol the feed stock runs through a series of processes for liquifaction, enzymatic hydrolysis, fermentation, distillation and drying. The processes and mass balance is shown in fig. 6 below.
The outputs from the refining processes are pure water free ethanol, DDGS (Distillers Dried Grain with Solubles), C5-molasses, biomass and pure CO_2.

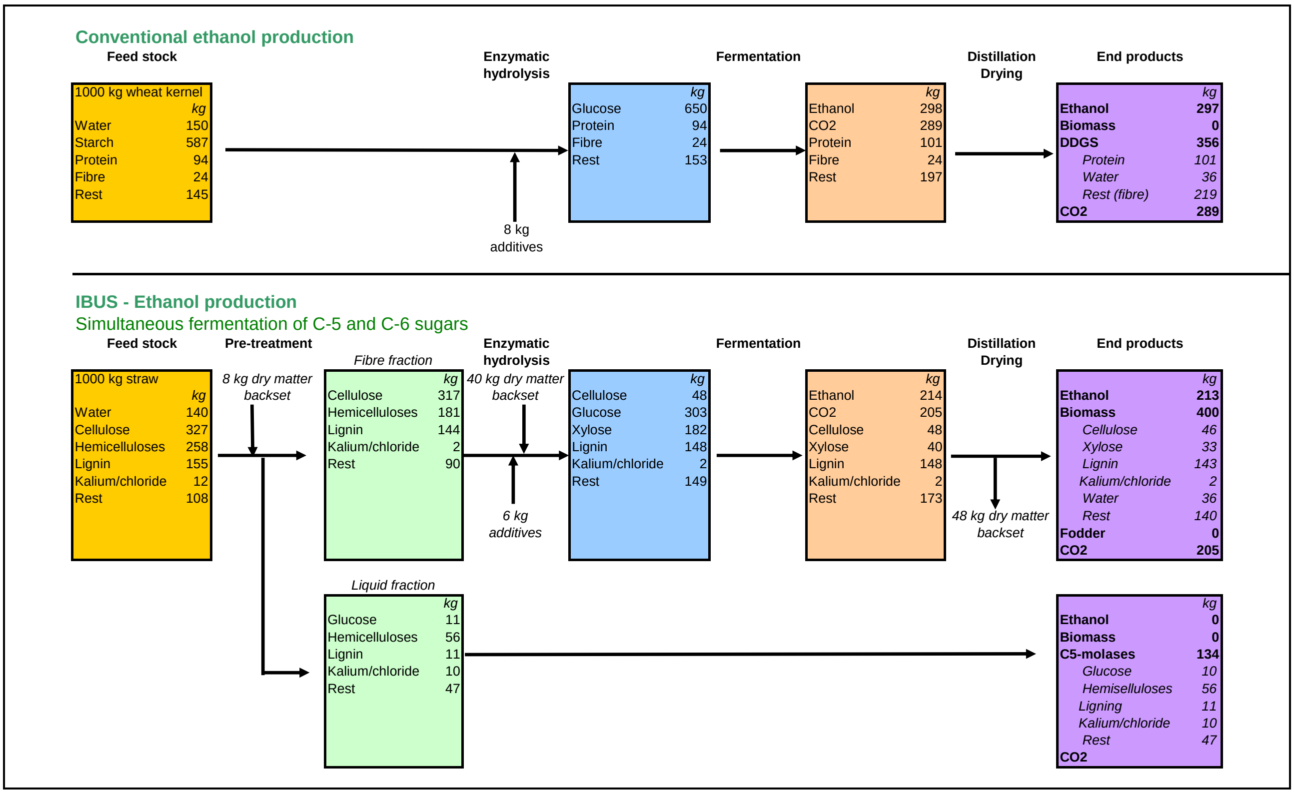


Figure 6. Mass balance of conventional ethanol production from winter wheat kernels and the IBUS processes refining winter wheat straw to ethanol. (From Iversen 2005).

Outputs from the conversion of grain and straw to ethanol are based on the results from the IBUS project, where the Danish energy company Elsam A/S in co-operation with universities, research centres and other companies has created the worlds largest demonstration plant for processing lignocellulosic biomass to fermentable sugars Elsam (2005).

Ethanol
The estimated ethanol output from grain is based on traditional technology and is in accordance with a recent feasibility study from the southern part of Denmark (Sønderjysk Landboforening 2004). The output of ethanol from straw is based on the assumption that C-5 and C-6 sugars are co-fermented. It is believed to be possible within 2-5 years.
The output from 1 ha of wheat land can on average produce 2,987 kg water free ethanol. With a lower heating value of 26.7 MJ/kg ethanol (ORNL 2006) the area based output in form of car fuel is 79,761 MJ/ha. Fuel ethanol has many possible appliances as car fuel, either in blends or pure, but no actual application in Denmark. In this study we haven't considered any specific application of the ethanol.

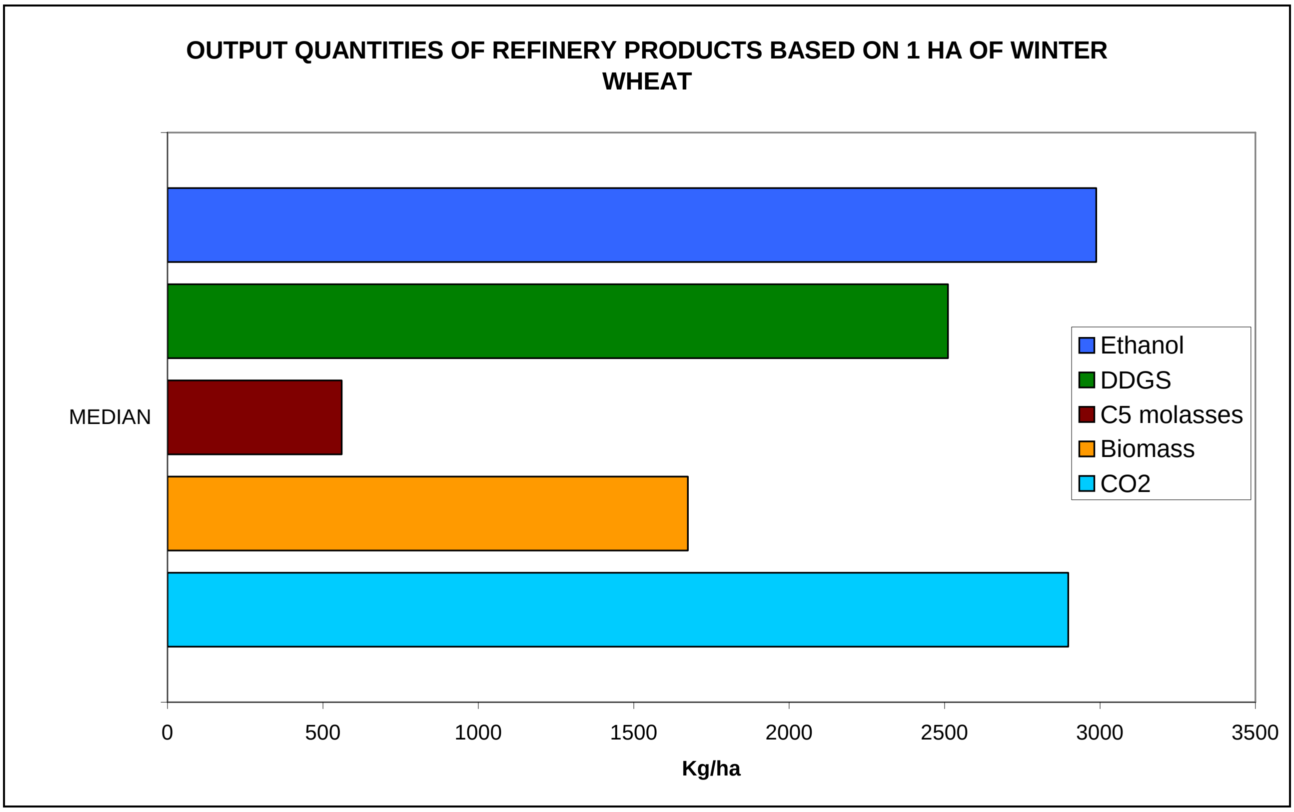
DDGS
In the production system considered we extract 5,998 kg DW wheat kernel pr ha corresponding to 5,998*1.21=7,258 Scandinavian Food Units (SFU_{cattle}, the equivalent feeding value of 1 kg rye) based on its feed value for cattle (Møller et al. 2005). If the DDGS from the bio refinery is returned as feed we return 2,259 kg DW DDGS corresponding to 2,257*1.08=2,437 SFU_{cattle} (Møller et al. 2005) Thus 34 % of the feed value in the grain can be returned. DDGS is valuable protein and vitamin rich feed for animals as ruminants, pigs and poultry (www.ddgs.umn.edu), but is has other feed properties than wheat grain, so grain is not the obvious feed to be substituted by DDGS. More likely other protein rich feed stuffs as rape seed cake or sesame cake is to be substituted. According to the agricultural statistics only 1.7-3.4 % of oil cake consumed by Danish animals in 2000/01 – 2002/03 originated from Danish agriculture (Danmarks Statisik 2004). Thus 96.6-98.3 % was imported. In quantifying the energy credits to be attributed to the DDGS we assume that DDGS from the ethanol production will substitute imported fodder concentrates. Dalgaard et al. (2001) estimate the total energy consumption from imported fodder to 5.7 MJ/SFU. The estimated mean energy credits in this study is calculated to 5.7*2,437=13,891 MJ/ha.

C5-molasses
13.4 % of the straw input is extracted as C5-molasses, amounting to 561 kg/ha. This substance contains a lot of organic acids and is well suited as fodder. The feeding values is assumed equal to sugar beet molasses 0.98 SFU/kg dry weight (Møller et al. 2005) and the substitution of other fodder products equal to that of DDGS.

Biomass
The area based median output of biomass from the refinery processes is 1,674 kg/ha with a moisture content of 10 % and an estimated lower heating value (LHV) of 17.5 MJ/kg. In the base line scenario of this study we assume that the refinery processes take place at a CHP plant. The residual biomass can thus be used internally as fuel.

CO_2
CO_2 is a major by-product from the production of ethanol. The area-based output is 2,897 kg/ha. Pure CO_2 can be used in the production of beer and soft drinks, but it also has a potential as carbon source for the chemical industry. If emitted, it will have no effect on the carbon balance. Due to its origin from biomass it is considered CO_2 neutral. If used as carbon source it may substitute CO_2 from other sources, usually fossil. In this study we haven't included the substitution potential in the calculations, but it is an obvious task for further research activities.

Output quantities of products and by-products from the production system are shown in figure 7 below.



Figur 7. Output of different products from refining the produce of 1 ha of winter wheat.

Energy inputs into ethanol production

Steam and electricity

Steam and electricity requirements for the processing of kernels and straw are based on the results from the IBUS project (Elsam 2005). Steam ($Q_{steam\ kern}$) and electricity ($Q_{elec\ kern}$) requirements for the conversion of kernels to ethanol and by products are estimated to 3.6 GJ steam and 100 kWh electricity pr ton kernels (15 % moisture content) (Elsam 2005). Correspondingly the requirements for processing straw are estimated to 3.8 GJ steam ($Q_{steam\ straw}$) and 220 kWh electricity ($Q_{elec\ straw}$) pr ton of straw (14 % MC) (Elsam 2005; Iversen 2005).

Electricity generation

Electricity is drawn from the existing infrastructure. For the purpose of this study, it is assumed to be at mix produced by the various generating facilities in Denmark, base year 2004, as reported by the Danish Energy Authority, DEA. (Energistyrelsen 2005b) The electricity is generated from fossil fuels (4% oil, 25% natural gas and 46% coal) and renewables (9% biomass and waste, 16% wind and hydro).

DEA also reports the direct energy inputs for electricity generation, where the fuel used for heat production in co-generating units has been subtracted assuming a 200% conversion efficiency for co-generated heat. The direct energy input for Danish electricity is thus 2.06 MJ of primary energy

per MJ of electricity produced. This figure, however, does not include all energy inputs in the full fuel cycle.
The whole life cycle inventory for Danish electricity is estimated using a large LCA study of generation technologies (Elsam et al. 2000). The results of this study were, that using a correction-factor on the direct energy inputs would yield a fairly precise estimate of the required energy input for electricity for the full life cycle. Correction-factors were 1.3 for coal, 1.2 for oil, 1.3 for natural gas and 1.03 for renewables. Recalculating the electricity mix for 2004 using the above correction factors yield a full fuel cycle input of 2.56 MJ/MJ_{el}.

Finally, to correct for losses in the transmission and distribution grids, which vary slightly from year to year depending on grid balancing, import and export and capacity adjustments, a grid loss estimate of 1 % in the transmission grid and 5% in the distribution grid was assumed (Eltra 2005). This results in a primary energy input at the point of use of 2.71 MJ/MJ_{el} or 9.8 MJ pr. kWh of electricity.

Steam generation
Two different scenarios for steam generation are examined.

The baseline scenario – the integrated scenario – assumes that surplus steam at the appropriate pressure and temperature levels is available at low cost. This is certainly the case if the bio refinery is integrated with the large power plants. Here large amounts of energy are removed as a waste stream by cooling with sea water, when the plants run in full condensing mode. This waste energy is already partially harvested during winter for district heating purposes, but there is still a large surplus in summer.

In large condensing power plants, steam is expanded through the turbine and the electric energy produced corresponds to the loss in enthalpy in the steam from the expansion. Some of the best electric efficiencies, up to 45% for conventional condensing power plants, are seen in Denmark. However, some 55% of the input energy is still lost in the condenser. This loss may largely be recovered and converted to process steam for a bio refinery, with a minimal need for additional fuel. In the best integration scenario, steam is available from the turbine at precisely the pressure level required by the bio refinery in practice it is likely that the steam pressure will be slightly higher than required depending on the physical design and lay-out of boiler and turbine at the power plant and the annual load profiles.

By integrating a biorefinery with a large power plant, the additional fuel required for steam production, assuming a constant electricity production for the power plant irrespectively of whether or not a biorefinery is added has been estimated. The required energy is in the range of 0.5-0.7 MJ of additional primary fuel per MJ of steam required.
The large power plants in Denmark are typically based on coal or natural gas. Using the life cycle correction factor (see below) of 1.3 for both these fuels, leads to a life cycle based input range estimate of 0.65-0.90 MJ of primary energy per MJ of steam required.

The alternative scenario – the greenfield scenario – assumes that surplus steam is not available for an ethanol plant, and that a separate steam boiler will have to be erected at the bio refinery. The preferred fuel for separate steam generation in Denmark is natural gas. With a boiler efficiency of 97% (Danish Energy Authority, 2005), and full fuel cycle correction factor of 1.3 for natural gas yields a primary energy need of 1.34 MJ/MJ_{steam}.

This means, that there is an energy saving potential for steam production of between 50%-65% by integrating a bio refinery with a power plant.

Table 9. Data used in simulations relating to processing kernels and straw to ethanol and by-products.

Abbreviation	Input	Unit	Input range	Reference	Abbreviation	Unit	Specific energy input range	Reference
$P_{etoh\ kern}$	Ethanol proportion	kg/kg kernel	0.297	Elsam 2005	EC_{etoh}	MJ/kg	26.7	ORNL 2006
$P_{etoh\ straw}$	Ethanol proportion	kg/kg straw	0.213	Elsam 2005				
P_{ddgs}	DDGS proportion	kg/kg kernel	0.356	Elsam 2005	EC_{ddgs}	MJ/kg	5.7	Dalgaard et al. 2001
$P_{molasses}$	C5-molasses proportion	Kg/kg straw	0.134	Elsam 2005	$EC_{molasses}$	MJ/kg	5.7	Assumption
$P_{biomass}$	Bio mass proportion	kg/kg straw	0.40	Elsam 2005	$EC_{biomass\ straw}$	MJ/kg	17.5	Elsam 2005
$Q_{steam\ kern}$	Steam	MJ/kg kernel	3.6	Elsam 2005	EC_{steam} integrated	MJ/MJ	0.65 – 0.90	Own calculations
$Q_{steam\ straw}$	Steam	MJ/kg straw	3.8	Elsam 2005	EC_{steam} green field	MJ/MJ	1.34	Own calculations
$Q_{elec\ kern}$	Electricity	kWh/kg kernel	0.10	Elsam 2005	EC_{elec}	MJ/kWh	9.8	Own calculations
$Q_{elec\ straw}$	Electricity	kWh/kg straw	0.22	Elsam 2005				

The total energy input from steam generation for refinery processes is calculated by:

$$EC_{STEAM} = [Q_{kern}]*Q_{steam\ kern}*EC_{steam} + [Q_{straw}]*Q_{steam\ straw}*EC_{steam}$$

The total energy input from electricity generation for refinery processes is calculated by:

$$EC_{ELECTRICITY} = [Q_{kern}]*Q_{elec\ kern}*EC_{elec} + [Q_{straw}]*Q_{elec\ straw}*EC_{elec}$$

Additives

The processes in bio ethanol synthesis demand a range of additives during different steps in the production process. The table below list the additives needed for converting kernels to ethanol (Elsam 2005). In this study we assume that the same additives and approximately same quantities are needed for converting straw to ethanol.

Table 10. Additives used in refinery processes and their relating energy values used in the simulations.

Additive	Quantity (Elsam 2005)	Energy consumption		
	Kg/ton Etoh	MJ/kg additive	MJ/ton Etoh	Reference
A-amylase	1.2	6.32	7.58	Bernesson 2004
AMG	2.4	6.32	15.17	Bernesson 2004
Protease	1.1	6.32	6.95	Bernesson 2004
Sulphuric acid (93 %)	25	3.00	75.00	Bernesson 2004
$CaCl_2$ (68 %)	1.2	1.55	1.86	Bernesson 2004
Urea (45%)	5.8	6.2	35.96	GaBi LCA database
Phosphorous acid (74%)	5.8	20	116.00	Bernesson 2004
NaOH (49 %)	3.6	10.4 – 49.2	37.44 - 177.12	Bernesson 2004 GaBi LCA database
Ammonia water (25%)	12	5,2	62.4	GaBi LCA database
Water	~2000	0.005	10.00	Feldvoss 2002
Sum			~ 369 – 508	

Table 11. Data on energy input from the production of additives to ethanol production.

Abbreviation	Unit	Specific energy input range	Reference
$EC_{additives}$	MJ/kg ethanol	0.369-0.508	ORNL 2006

The total energy input for production of additives is calculated as:

$$EC_{ADDITIVES} = [EC_{additives}]*([Q_{kern}]*P_{etoh\ kern} + [Q_{straw}]*P_{etoh\ straw})$$

Biorefinery construction

Utilising winter wheat as feed stock for ethanol production requires the construction of a bio-refinery. Bernesson (2004) reports for Swedish conditions (winter wheat) total energy consumption for the construction of buildings and machinery to be 0.332 MJ/kg EtOH for small scale production and 0.067 MJ/kg EtOH for large scale production. Patzek (2005) reports for USA (corn) somewhat higher energy consumption on 4,363 Btu/Gallon EtOH corresponding to 0.96 MJ/kg EtOH.
We assume the Swedish conditions to be more comparable to Danish than the American.

Table 12. Energy input data from construction of bio refineries.

Abbreviation	Unit	Specific energy input range	Reference
$EC_{construction}$	MJ/kg EtOH	0.067 – 0.332	Bernesson 2004

The total energy input for constructing biorefineries is calculated as:

$$EC_{CONSTRUCTION} = [EC_{construction}]*([Q_{kern}]*P_{etoh\ kern} + [Q_{straw}]*P_{etoh\ straw})$$

Transport scenarios
No bio ethanol plant has been erected in Denmark yet (2006), so actual transport scenarios can not be analysed and estimated. We base the following analysis on the assumption that 3 bio ethanol plants would be appropriate for producing the quantity needed to meet the Directive 2003/30/EC obligations (5.75 % of transport energy based on bio fuels).

The Danish production of winter wheat is highly regionalised. 61 % of the winter wheat produced in 1990-2004 was produced in the counties of Nordjylland, Århus, Fyn, Vestsjælland and Storstrøm (Danmarks Statistik 2005).

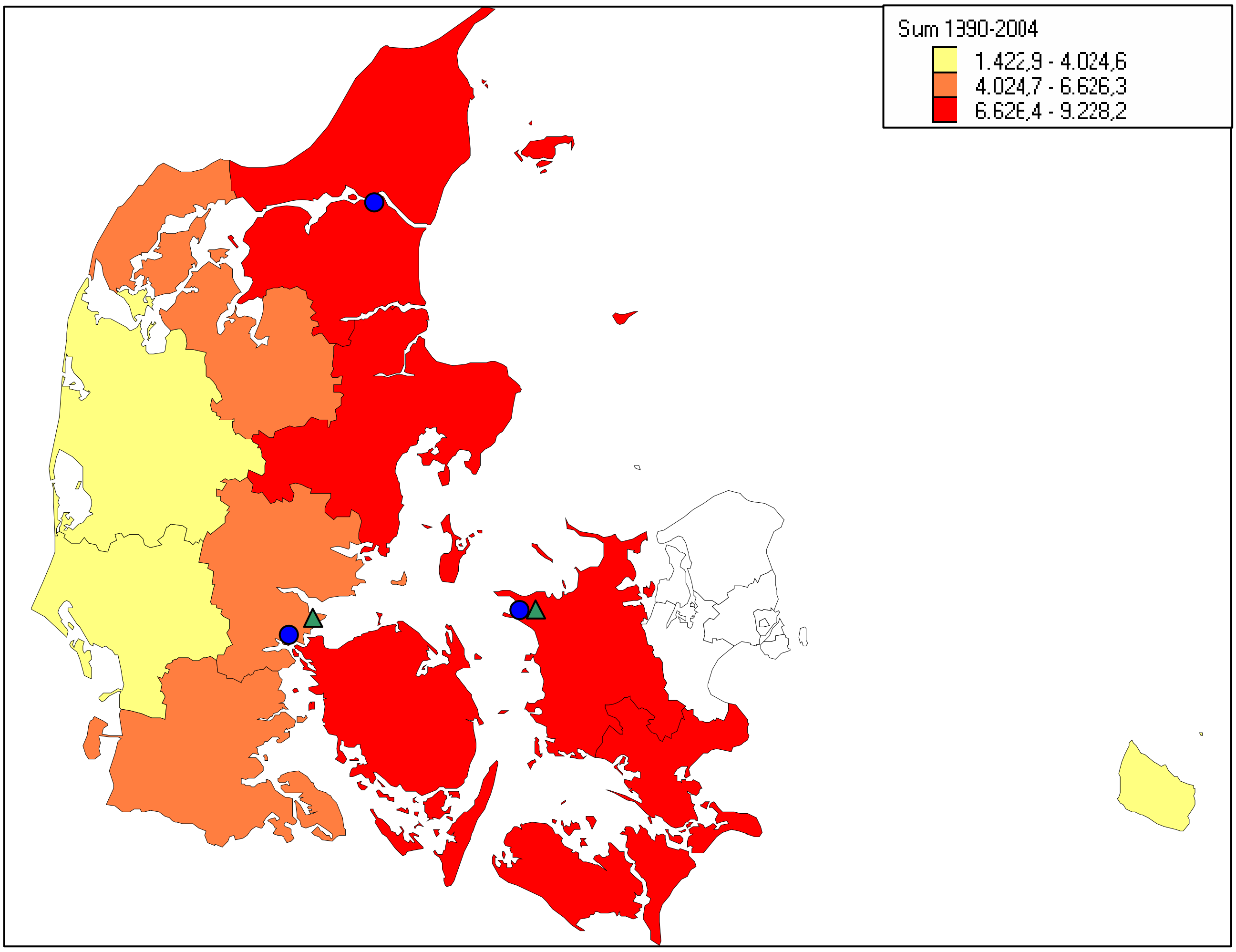


Figure 8. County wise production of winter wheat in Denmark from 1990 through 2004 in Mio. kg's. The Capitol Region (white region on the map) is not included, but has no significant production. Blue circles mark a potential location of bio refineries. Green triangles mark existing location of oil refineries.

In the base line scenario of this study we assume that bio refineries would be located in conjunction with existing CHP plants. An obvious location hence the spatial distribution of winter wheat production would then be at the power plants in Asnæs, Skærbæk and Ålborg.

Assuming that each plant produces the same quantity of ethanol distances for transport of kernel and straw from field to bio refinery are simulated by the following:

1/3*[1, 180] km + 1/3*[1, 136] km + 1/3*[1, 142] km

Ranges in brackets are the transport distance ranges in the catchment areas of the potential plants in Stigsnæs, Skærbæk and Ålborg respectively.
25 % of the transport is assumed to be on motorway and the rest on highway.

Distribution of ethanol from bio refinery to consumer is assumed to go via the 2 existing oil refineries in Denmark in Fredericia and Kalundborg. The distance for transport of ethanol from potential bio refineries to oil refineries is estimatd by the following.

1/3*[0] km + 1/3*[10] km + 1/3*[202] km

With 85 % of the transport on motorway and 15 % on highway.

DDGS produced at the refinery is especially usable for pig or ruminant fodder. This is a conservative consideration since this transportation will substitute transportation of other foodstuffs. Ruminant rearing in Denmark is regionalised, but not in the same regions as winter wheat farming. The counties of Nordjylland, Viborg, Ringkøbing, Ribe and Sønderjylland has in the period 1990 to 2004 hosted more than 71 % of the cows in Denmark (Danmarks Statistik 2005). Pig rearing is also regionalised with a major part (more than 63 % from 1990 through 2004) of the pigs in the counties of Nordjylland, Viborg, Århus, Ringkøbing and Sønderjylland (Danmarks Statistik 2005).

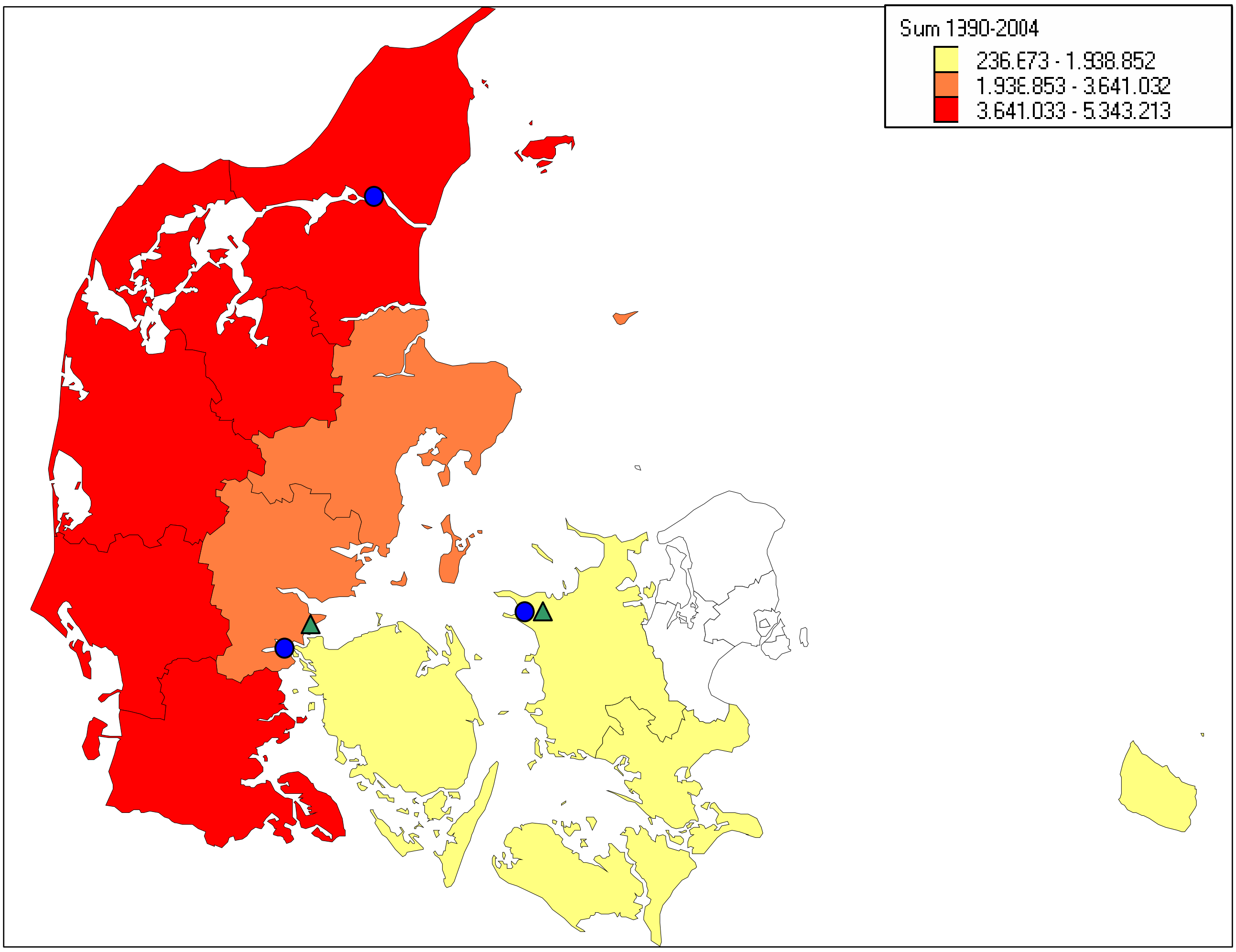


Figure 9. County wise distribution of cows in Denmark from 1990 through 2004 in number of animals. The Capitol Region is not included in the map, but has hosted less than 2 % of the cows in the period. Blue circles mark the potential location of bio refineries. Green triangles mark the location of existing oil refineries.

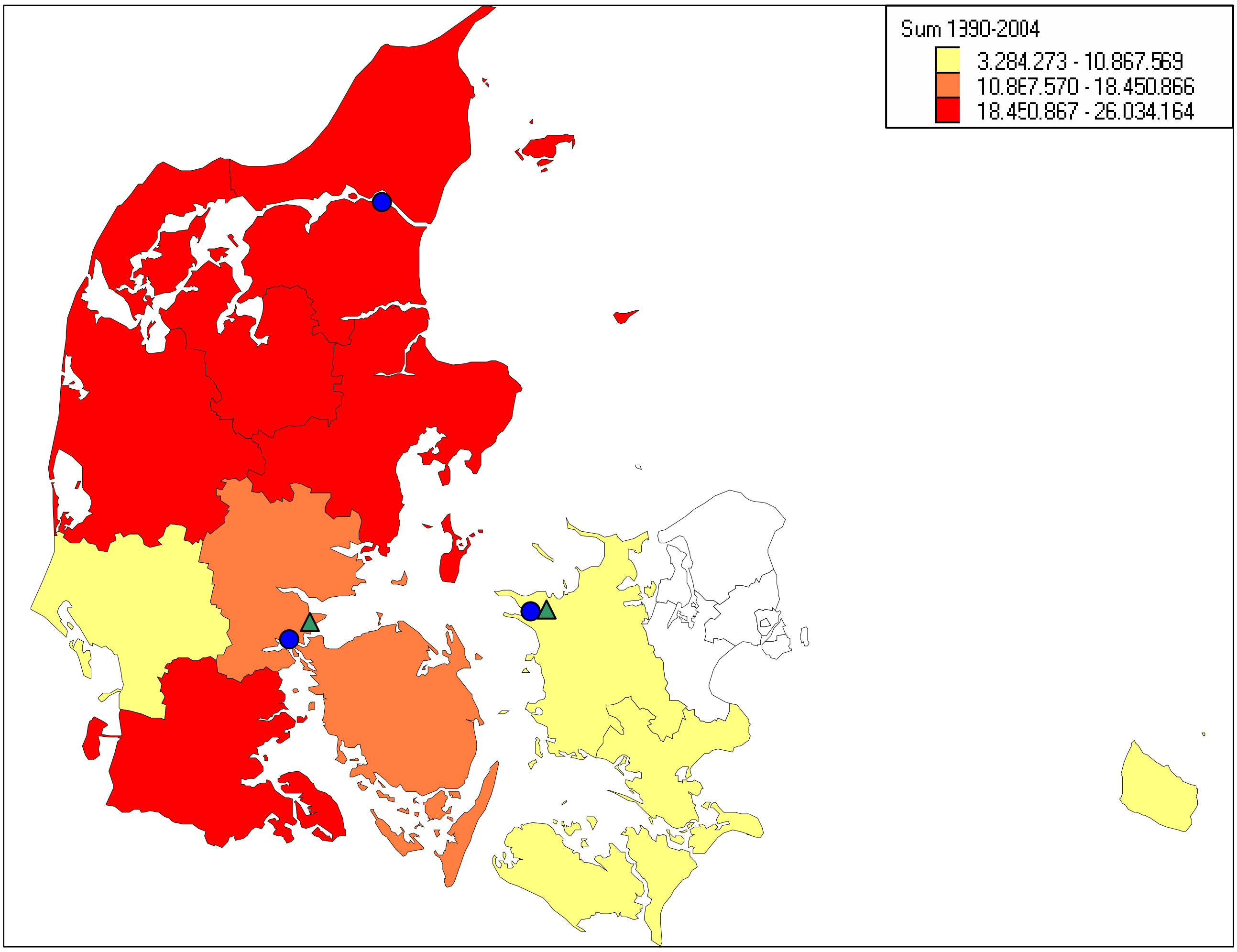


Figure 10. County wise distribution of pigs in Denmark from 1990 through 2004 in number of animals. The Capitol Region is not included in the map, but has hosted less than 2 % of the pigs in the period. Blue circles mark the potential location of bio refineries. Green triangles mark the location of existing oil refineries.

Hence the distribution of winter wheat, cows and pigs in Denmark transport of DDGS can not be assumed as reversed to the transport of grain and straw.
Transport distances of DDGS from the potential bio refineries to farms are simulated by.

1/3*[1, 299] km + 1/3*[1, 128] km + 1/3*[1, 182] km

With 25 % on motorway and 75 % on highway.

Residual biomass outputs from the ethanol production are assumed incinerated at the plant and no transportation is accounted for.
All transportation is done by lorry and transportation energy is based on GaBi LCA data base.

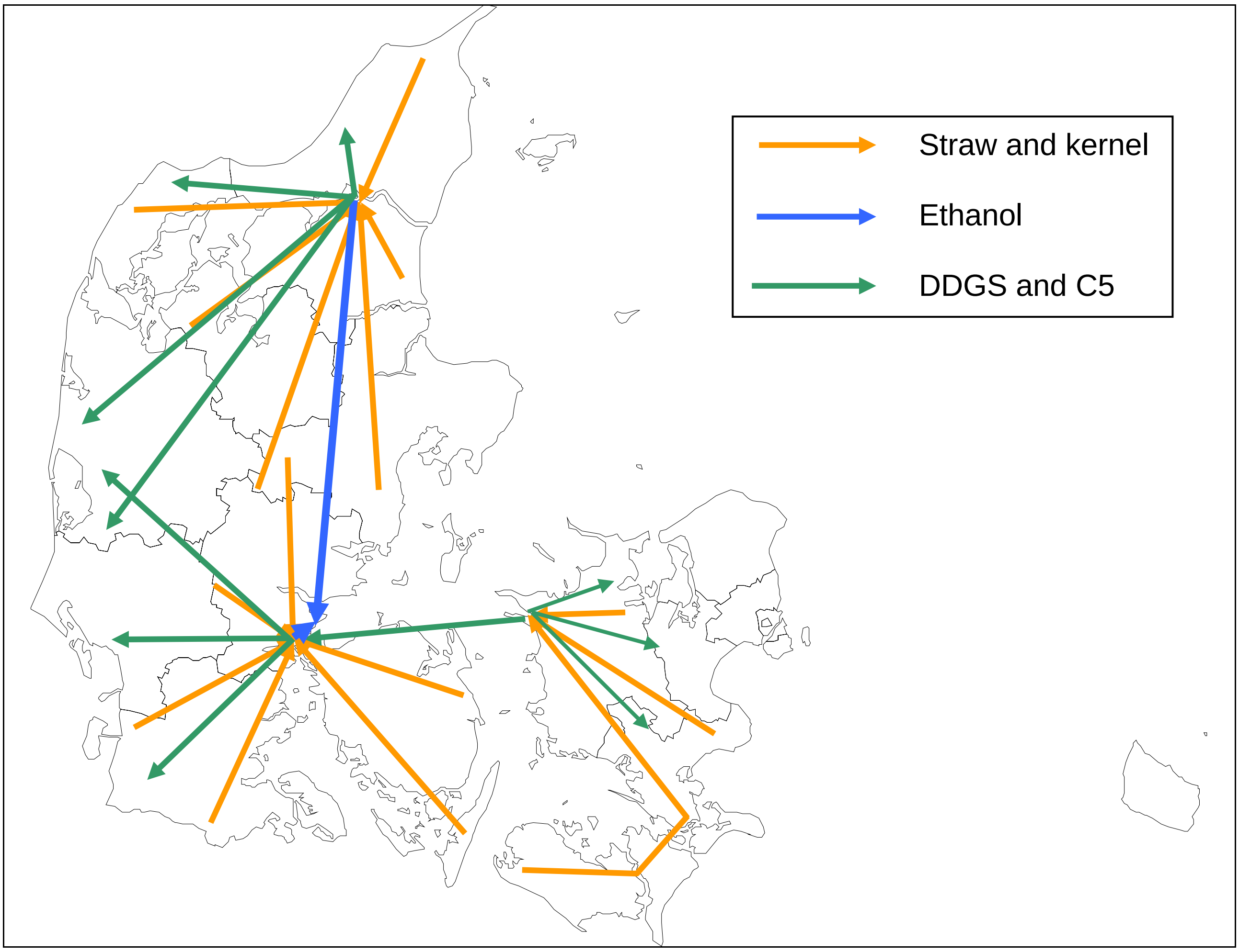


Figure 11. Obvious major transport routes of feed stock and by-products from a Danish bio ethanol production system.

Sensitivity of transport scenarios

The transport scenarios are based on several sensitive scenarios. All transport of material and products is assumed to be road transport by truck, but all power plants, and thus potential biorefineries, are placed in conjunction with a harbour. This facilitates sea transport and in some cases and for some products sea transport must be considered more likely. In general sea transport is less energy consuming than road transport so our estimates of transport energy consumption must be considered as conservative.

Furthermore these scenarios are based on an assumption that production and consumption in the product system is local, meaning Denmark. We fully acknowledge that most of the products in the system are global commodities that are transported over wide distances. The transport scenarios analysed are only likely scenarios among others.

Table 13. Data used in simulations relating to transport of bio refinery feed stock and refinery products.

Abbreviation	Input	Unit	Input range	Reference	Abbreviation	Unit	Specific energy input range	Reference
$Q_{trans\ kern}$	Trans-portation of kernel and straw	Km	1/3[1, 180] 1/3[1, 136] 1/3[1, 142]	Own calculations	$EC_{trans\ m}$ Motorway	MJ/kg*km	0.00077	Gabi LCA database
$Q_{trans\ etoh}$	Trans-portation of ethanol	Km	1/3[0] 1/3[10] 1/3[202]	Own calculations	$EC_{trans\ h}$ Highway	MJ/kg*km	0.00086	Gabi LCA database
$Q_{trans\ ddgs}$	Trans-portation of DDGS and C5-molasses	Km	1/3[1, 299] 1/3[1, 128] 1/3[1,182]	Own calculations				

The total energy input from transportation of kernels, straw, ethanol, DDGS and C5-molasses is calculated as:

$$EC_{TRANSPORT} = (0.75*[Q_{trans\ kern}] + 0.15*[Q_{trans\ etoh}] + 0.75*(Q_{trans\ ddgs} + Q_{trans\ molasses}))*EC_{trans\ h}$$
$$+(0.25*[Q_{trans\ kern}] + 0.85*[Q_{trans\ etoh}] + 0.25*(Q_{trans\ ddgs} + Q_{trans\ molasses}))* EC_{trans\ m}$$

Total energy input

The total energy input to the production system is calculated as:

$$EC_{IN} = EC_{AGRI} + EC_{TRANSPORT} + EC_{STEAM} + EC_{ELECTRICITY} + EC_{ADDITIVES} + EC_{CONSTRUCTION}$$

Energy outputs from ethanol production

The energy outputs from the ethanol production are simulated on basis of the parameters shown in the tables 8 and 9.

The total energy output as ethanol is calculated as:

$$EC_{ETOH} = ([Q_{kern}]*P_{etoh\ kern} + [Q_{straw}]*P_{etoh\ straw})*EC_{etoh}$$

The total energy output as biomass for combustion. The factor "1.3" is added because the biomass combustion will substitute energy generation based on fossil fuels, mainly coal:

$$EC_{BIOMASS} = [Q_{straw}]*P_{biomass\ straw}*EC_{biomass}*1.3$$

The energy value allocated to DDGS due to its substitution of other fodder products is calculated as:

$$EC_{DDGS} = [Q_{kern}]*P_{ddgs\ kern}*EC_{ddgs}$$

The energy value allocated to C5-molasses due to its substitution of other fodder products is calculated as:

$$EC_{MOLASSES} = [Q_{straw}]*P_{molasses}*EC_{molasses}$$

Total energy output
The total energy output from the production system is calculated as:

$$EC_{OUT} = EC_{ETOH} + EC_{BIOMASS} + EC_{DDGS} + EC_{MOLASSES}$$

Production system energy input/output
The analysis of the total energy consumption and production in the winter wheat to ethanol production system is based on Monte Carlo simulations using 10,000 iterations. Most results are reported on area basis, meaning the simulated energy input or output for processing, transporting etc. the physical output from 1 ha of winter wheat.

The simulated total energy input and output from the entire wheat to ethanol cycle is shown in figure 12 below.

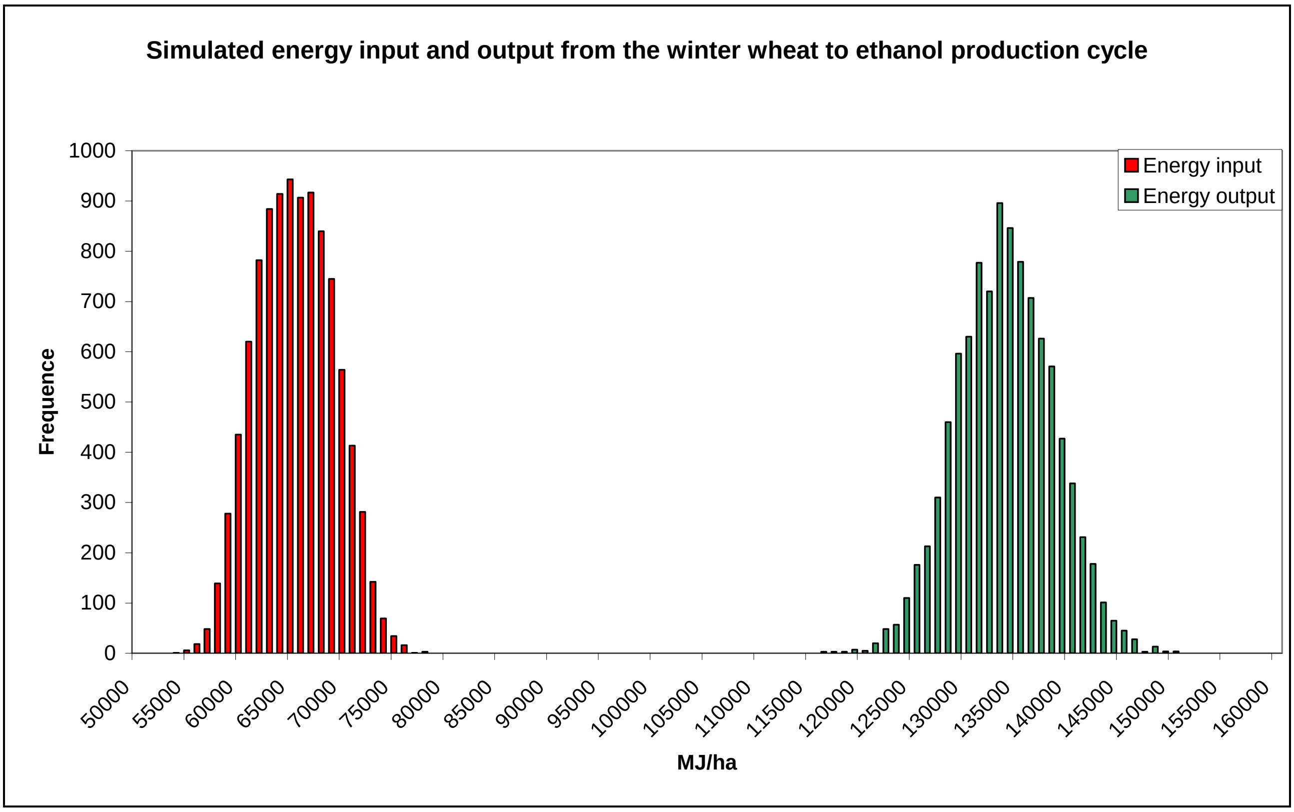


Figure 12. Simulated energy consumption and energy output of refining the produce of one ha of winter wheat to ethanol.

The simulation returns an area based median input to the production system of 65,927 MJ/ha. The lower and higher quartiles are 63,230 MJ/ha and 68,732 MJ/ha respectively. Minimum simulated input is 54,598 MJ/ha and maximum is 78,811 MJ/ha. On the output side we find a median of

133,962 MJ/ha, and lower and higher quartiles of 130,791 MJ/ha and 137,201 MJ/ha respectively. Minimum value is 116,548 MJ/ha and maximum is 150,211 MJ/ha.

Output-Input ratio
The ratio between total energy output and total energy input is calculated as:

$$EC_{OUT-IN} = \frac{EC_{OUT}}{EC_{IN}}$$

The output-input ratio for the production system is shown in figure 13 below.

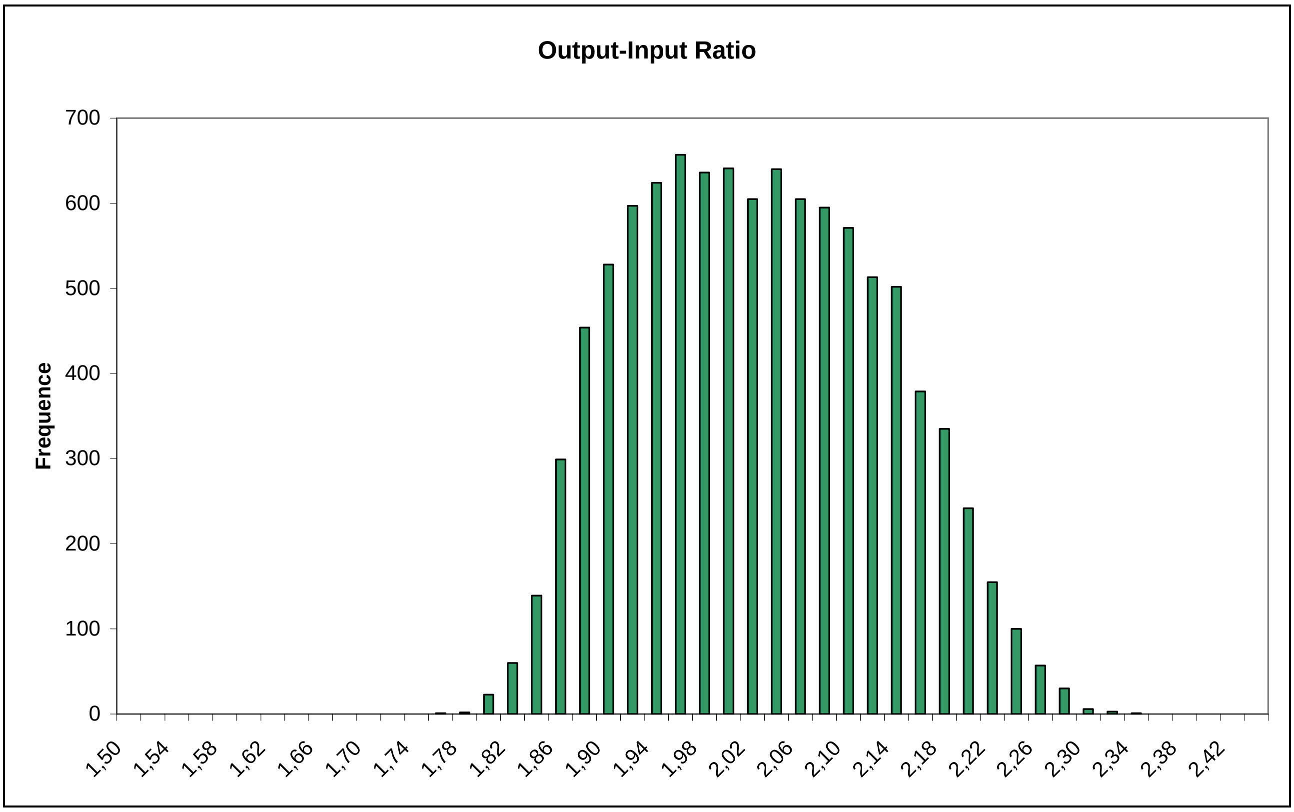


Figure13. Output-input ratio of the IBUS winter wheat to ethanol production system.

The simulated median ratio is 2.03 meaning that one may harvest 2.03 times the energy sown in the production system analysed. This does not mean that energy can be created out of nothing, but we haven't included the solar radiation on the input side, and it exceeds by far the difference between input and output.
Lower and higher quartiles of the simulated ratio are 1.95 and 2.11 respectively showing that there is a high probability of reaching an output-input ratio close to 2. Simulated minimum ratio is 1.78 and maximum ratio is 2.34.

The energy output-input ratio is constructed by contributions from a number of single processes. In figure xx below it is seen that for the input side refinery processes (steam and electricity generation)

and construction contribute with 76 % of the total energy consumption. The agricultural production contributes with 22 %.
On the output side the energy carriers (ethanol and biomass) contributes with 88 % of the energy output. The remaining 12 % are gained by substitution of other fodder products.

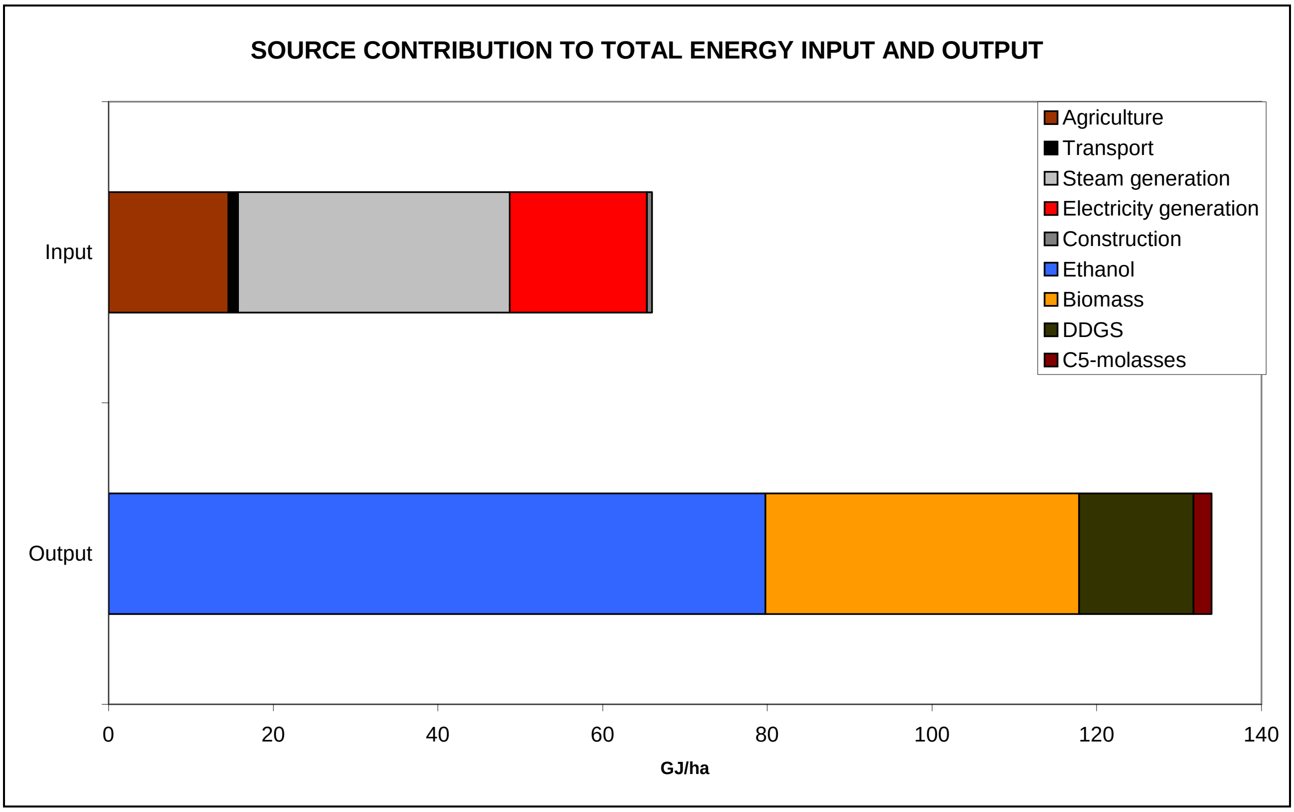


Figure 14. Contributions from different sources to the total energy input to and output from the IBUS winter wheat to ethanol productions system.

Sensitivity analysis

The results presented above all relate to the base line scenario of the study assuming that both kernel and straw is used as input in the ethanol production, that process steam is delivered through an integration of the bio refinery and combined heat and power production. An actual production of bio ethanol in Denmark needn't necessarily fit in to these assumptions and in the following we analyse the sensitivity of some of the critical assumptions.

Source of grain
As default in this study grain, straw and agricultural land is considered as unlimited resources. This is, off course, not the case, but considerable quantities can be shifted from one utilisation to others if decided. The table below shows the Danish production, consumption, import and export of wheat grain in the period from 2000 through 2004 (Statistikbanken 2005) and the calculated mean.

Table 14. Production, consumption, imports, exports and stocks of wheat grain from 2000-2004.

Mio tons	2000	2001	2002	2003	2004	Calculated mean
Harvest	4.553	4.524	3.937	4.560	4.643	4.443
Import	0.184	0.229	0.416	0.380	0.274	0.297
Stocks primo	2.775	2.776	2.965	2.685	2.755	2.791
Seed	0.123	0.126	0.114	0.130	0.129	0.124
Export	0.934	0.762	0.747	0.791	0.238	0.694
Processed to flour etc.	0.345	0.399	0.406	0.420	0.409	0.398
Industrial purposes	0.015	0.011	0.011	0.011	0.011	0.012
Stocks ultimo	2.776	2.965	2.685	2.755	3.314	2.899
Feed	3.310	3.266	3.355	3.519	3.571	3.404

Drawing resources from any fraction above would cause changes in society either in Denmark or elsewhere. It has not been with in the scope of this study to determine what fractions most likely would be tolled for bio ethanol production in Denmark. Alone the net export of 0.397 Mio tons (MT) would be able to produce app. 3,148 TJ of ethanol corresponding to 2.01 % of energy consumed by road transport in 2003, or equal the Danish obligation for 2005 according to Directive 2003/30/EC.

Source of straw

Straw is an important resource in Danish energy production and if straw where to be used as input in ethanol production it might be drawn from other energy production. This is to some extend true. The consumption of straw for energy has increased almost constantly over the last 30 years and in 2003 16,719 TJ was generated on straw (Energistyrelsen 2005). With a calorific value of 14.5 MJ/kg the energy sector consumed app. 1.15 MT straw in 2003. I 1993 Denmark launched a political target of using 1.2 MT straw in distributed energy generation (Regeringen 1993, 1997). It is expected that the target will be fully reached in 2005 (Miljø & Energiministeriet 2000) According to the agricultural statistics 1.44 MT straw was used for energy in 2003 (Statisikbanken 2005). The balance covers local energy generation at farms. The same statistics show, also for 2003, that 1.002 MT straw from winter wheat and a total of 1.997 MT straw from agriculture as a whole was not gathered. A total of 0.788 MT straw was used for animal feed and a total of 1.188 MT straw was used for bedding. Of a potential resource of 5.413 MT straw 27 % is already allocated to energy purposes. For winter wheat straw alone 36 % of the 2.557 MT produced in 2003 was allocated to energy generation. Which fraction would then be used as supply for a potential bio ethanol production is in our view a question of price on the straw, price on the products that could substitute straw as feed and bedding and political incentives.

The non-gathered fraction of winter wheat straw alone would, based on the base line scenario assumption, be able to produce 213 Mio kg ethanol or 5,698 TJ.

Source of agricultural land

On average (2000-2004) 2.66 Mio ha was cultivated as agriculture in Denmark. Hereof was 0.62 Mio ha occupied with winter wheat and the figure in growing (Statistikbanken 2005). 0.22 Mio ha or 8 % of the cultivated area was set aside as fallow land or otherwise taken out of cultivation. A reasonable estimate is that up to 20% of the agricultural land may be used for energy production, if as is the case for ethanol, other products such as feed are produced by the same agricultural land. Presently such a use of the area might be restricted by Danish and EU legislation.

Based on the assumptions for the base line scenario as described above an average ethanol yield from winter wheat would be 2,987 kg/ha or 80 GJ/ha. The Danish Energy Authority predicts an energy use for road transport in 2010 of 173,930 TJ (Energistyrelsen 2005). Meeting the obligation of Directive 2003/30/EC, that 5.75 % of transport energy i.e. both diesel and gasoline must be based on biomass, would require app. 10,000 TJ. If that quantity where to come from bio ethanol alone 125,420 ha of average wheat land would be needed. This includes the additional transport induced by the production of bio ethanol. Including all additional transport is a very conservative assumption since part of it would substitute other transports. If all set aside lands were cultivated for this production 52 % of the average yield of winter wheat would be required. The lowest county wise yield reported for 2000 – 2004 is 5,850 kg/ha obtained in the county of Nordjylland in 2003 (Statistikbanken 2005). This yield corresponds to 83 % of the mean yield used in the base line scenario of this study.

By-product energy credits

Since the production of ethanol from winter wheat produces several by-products the question of energy credits is important to address. From other studies it is discussed whether credits should be given or not. Patzek (2005) oppose to credits with the perception that every biological by-product should be returned to the field in order to maintain ecological sustainability for a longer period. This is, however not in good agreement with practice applied in many agricultural production systems. Other studies favour the use of credits because the by-products potentially can substitute the use of fossil fuels. In the base line scenario of this study we have chosen to include energy credits from the by-products.

Green field vs. integrated production

The analyses so far build on the assumption that biorefineries are integrated with combined heat and power production. A project designed by the farmers association in southern Jylland (Sønderjysk Landboforening 2004) builds on an idea of steam generation by a natural gas boiler at the biorefinery. This enables a more optimal location of the biorefinery close to the production of the feed stock.

The production system modelled in the base line scenario of this study includes 3 rounds of transport: From field to bio refinery with kernel and straw, from bio refinery to oil refinery with ethanol, and from bio refinery to farms with DDGS and C5-molasses. Transport of ethanol-petrol blends from oil refineries to gas stations not included.
The median of the total energy consumption is 1,161 MJ/ha and the analysis shows that 63 % of the total energy consumption is used on the transportation of kernel and straw from field to biorefinery (figure 15 below). It is obvious that this energy consumption can be reduced by a more optimal location.

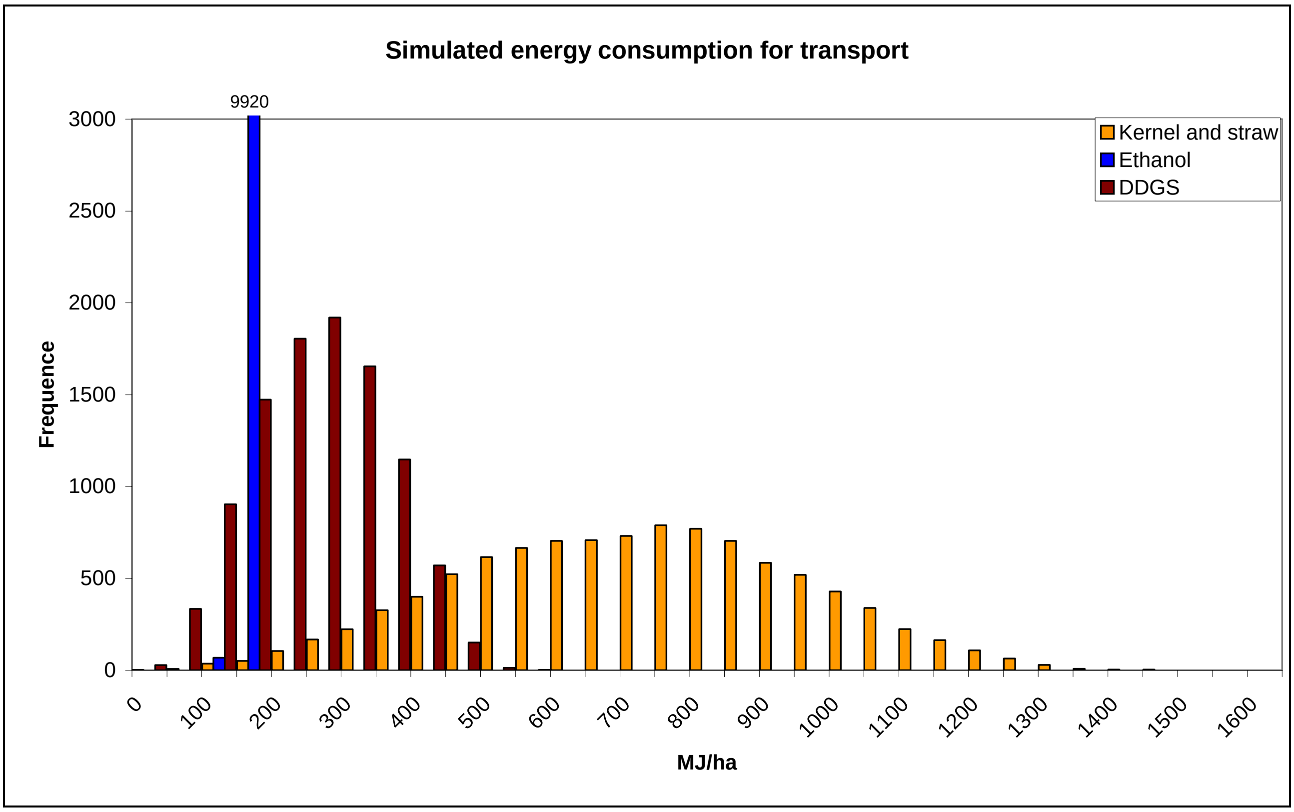


Figure 15. Total energy consumption for transport in the IBUS winter wheat to ethanol production system.

As an alternative scenario to the base line scenario analysed above we have modelled a production system based on an ethanol production not integrated with CHP and placed more optimal in relation to the production of winter wheat.
The alternative production system differs on energy consumption for transport and for steam generation at the biorefinery.

Energy consumption for transport
The simulation shows that the energy consumption for transport can be reduced. A location of the biorefinery closer to the fields have reduced the area based total energy consumption for transport to 1,028 MJ/ha in comparison to the 1,161 MJ/ha in the baseline scenario. This is an 11 % reduction.

Energy consumption for steam generation
Generating the steam required for refinery processes turns out much more expensive energy wise in the greenfield scenario than in the baseline scenario. Where the baseline scenario showed an area-based energy cost for steam generation of 33 GJ/ha, the greenfield scenario shows an energy cost for the same process of 55.4 GJ/ha (figure 16).

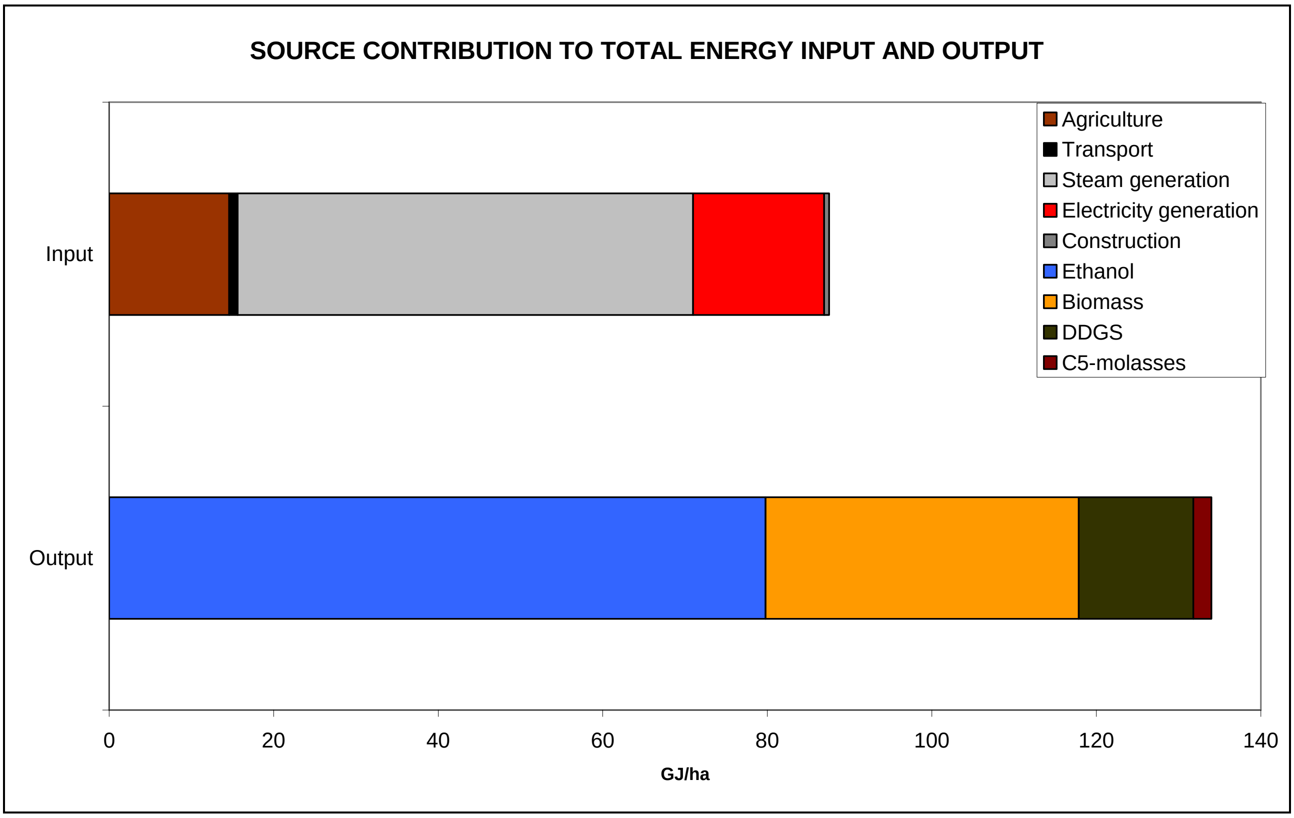


Figure 16. Contributions from different sources to the total energy input to and output from the greenfield scenario of a winter wheat to ethanol productions system.

Energy balance

The higher energy consumption for steam generation overrules the savings on transport multiple times, and consequently the output-input ratio for the greenfield scenario is lower than for the baseline scenario with integration between ethanol refining and CHP (figure 17).

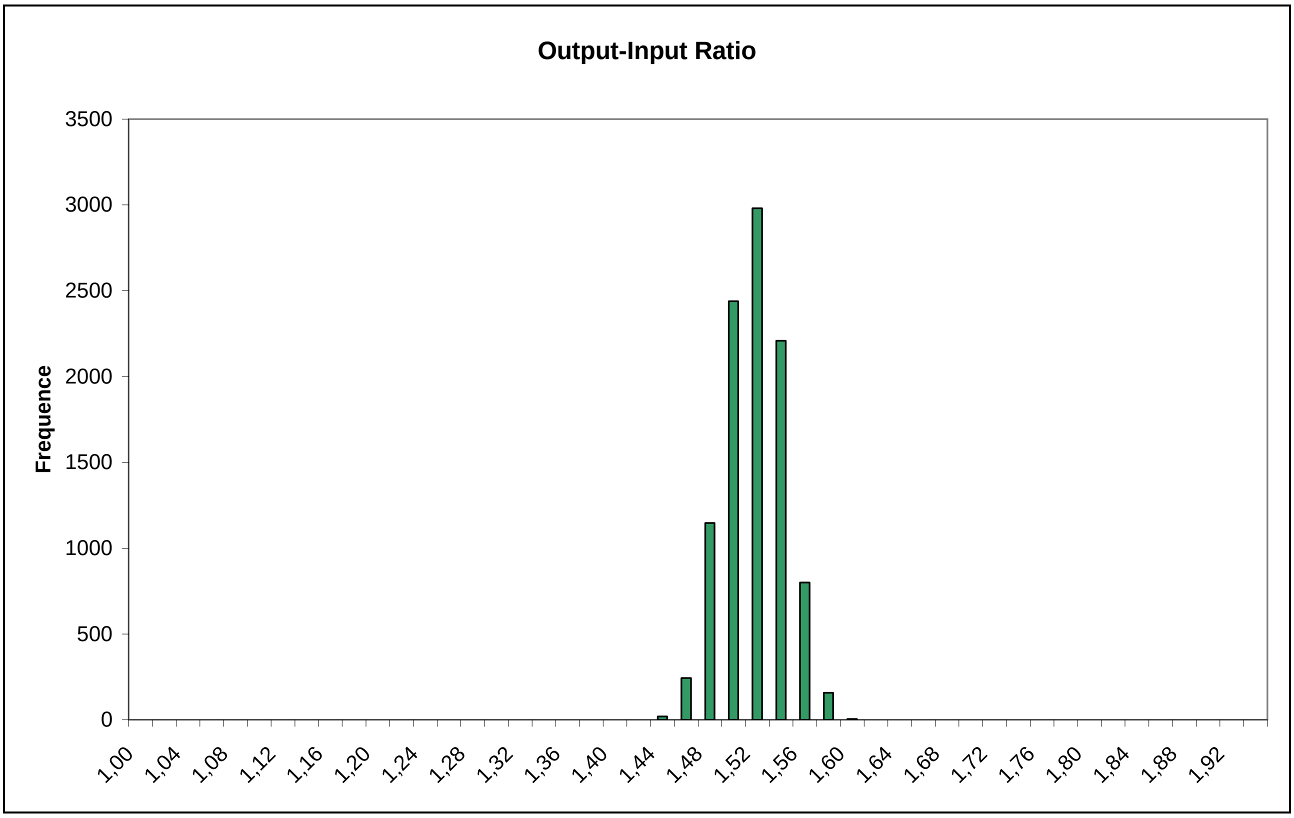


Figure 17. Output-input ratio in the greenfield scenario in a winter wheat to ethanol production system.

The median of the simulated output-input ratio is 1.53. Lower and higher quartiles are 1.51 and 1.54 respectively. Minimum ratio is 1.44 and maximum is 1.61.

Discussion

Model assumptions

Several studies on the energy consumption in agricultural production have been published. These studies show a huge variation in the energy input needed to produce a cereal crop. Reported energy input in wheat production range from 4.300 MJ/ha to 18.000 MJ/ha (Bailey 2003; Clements 1995; Börjesson 1996; Rosenberger 2001). Within this range reported energy input on non specified cereal production also fits (Dalgaard 2000; Kuemmel 1998; Refsgaard 1998; Halberg et al. 2000). Many factors can cause the huge variation in energy input. Some of the references studies agricultural production at different intensities (Bailey 2003; Rosenberger 2001) hence the differences in energy input. Differences in soil conditions, precipitation, agricultural practice and year to year variation may also affect the results. There seems to be a tendency, but not a significant correlation, between energy input and harvested yield (figure 18).

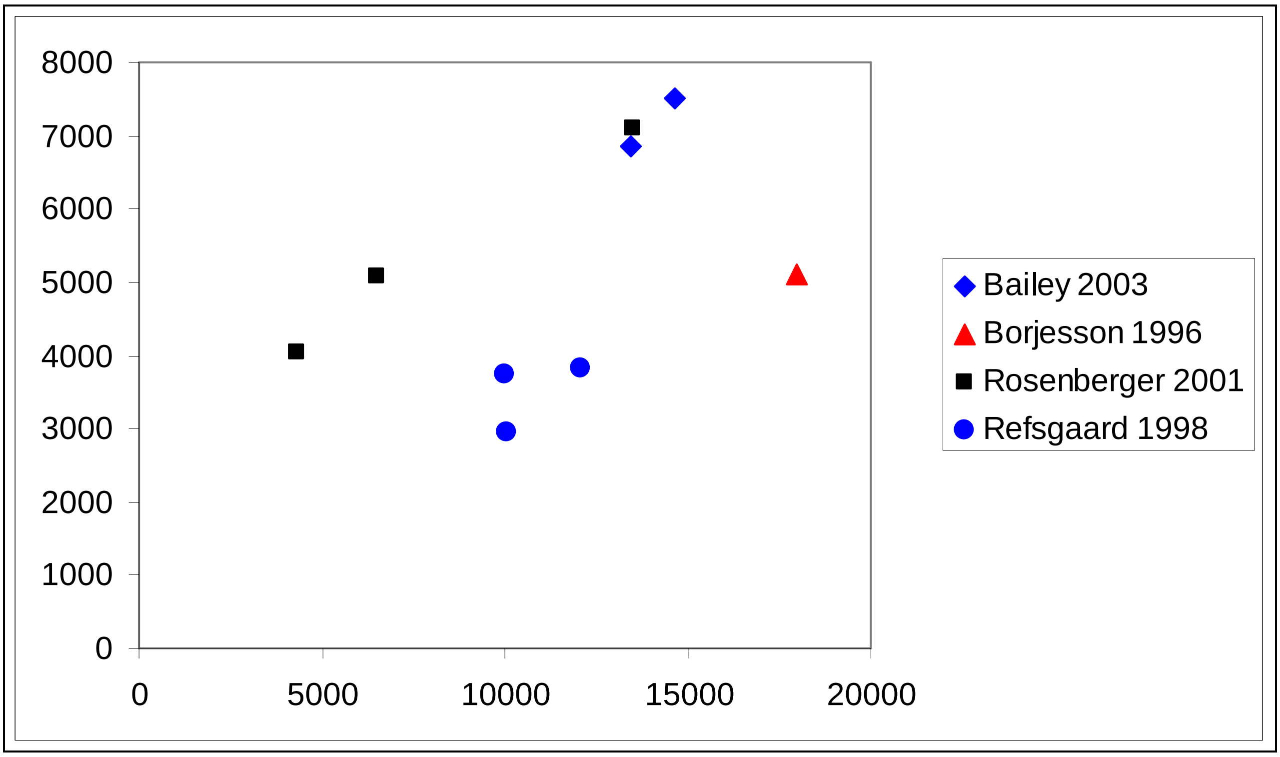


Figure18. Correlation between energy input and kernel output in different European studies on energy effectivenes in agricultural production.

Finally studies like these are very susceptible to definition and delimitation of the production systems studied (Dalgaard et al., 2001).
The referenced studies used in this screening are all considered of high quality with thorough description of model assumptions and methods, and we do not aim at evaluating or comparing them individually. We consider all reported energy input as equally valid estimates of the energy needed to produce a cereal crop under different, mainly European, conditions. We have chosen to neglect the possible influence from methodological differences.

In the models presented in this study most parameters vary independently of each other. We have not been able to study interdependencies of parameters, but obviously there is a certain level of interdependency between several of the parameters.
This being a static overview we evaluate that this shortcut has only limited impact on the conclusions from this study. It will not affect the ranges of energy consumption and content shown in the paper, but it may affect the shape of the EC distributions shown.

Sustainability
The subject of long term sustainability of the agricultural production system has not been thoroughly analysed in this study. Patzek (2005) deems industrial agriculture (corn for ethanol) as not sustainable due to loss of soil organic matter and loss of topsoil caused by erosion.
Christensen (2005) show that removal of both kernels and straw from the field in cereal production reduces the carbon content in the topsoil more than just removing kernels and leaving the straw.
Removing both kernels and straw is normal agricultural practice. In 2003 in Denmark only on

257.700 ha of the 651.700 ha grown with wheat the straw was left (Danmarks Statistik, 2004). This being a common practice does not make it a sustainable practice, but it is considered a stable production system by the agricultural community. This can be explained by that, even with removal of the straw 30-40 % of the biomass is left in the field as roots, stubs, leaves etc. However, on a long-term basis the current agricultural practice for wheat may be modified or alternatively other crops should be used as biomass source for energy purposes.
In the IBUS system a major part of the nutrients are returned to the eco-system, and it can therefore be part of a sustainable agricultural production..
Long-term sustainability (e.g. more than 50 years under Danish conditions) of an agricultural production for ethanol may be achieved by suitable crop rotation or by growing crops at certain intervals that can sequester nitrogen, add carbon and ameliorate the soil. The energy consumption for growing intercrops, if these were to be non marketable, should then be allocated to the energy crop.

Outlook on technological development
The current study is based on the technology in the IBUS process as it is today. The same count for the agricultural practice of today that is focused on producing food, not energy. Future improvements, which will reduce the energy consumption and energy output, are expected. Some of the possible improvements are listed below. All are known technologies and methods that can be combined and built in to the current processes.

- The use of CO_2 from the fermentation process combined with electricity from windmills or biomass to produce e.g. DME as diesel substitute or methanol for fuel cells, i.e. Elsam´s REtrol vision (VEnzin vision (Elsam 2005b)).
- New dedicated energy crops improving the output of desired biomass fractions (e.g. more carbohydrates and lignin and less protein) at reduced energy input for agricultural production.
- New agricultural practice with reduced energy input and improved long term sustainability.
- General process improvements.

The level of improvement with regard to reduced energy input and higher energy output on the basis of technological development, is not estimated or included in this report. However, if the use of biomass for production of transport fuels is implemented, it is very likely that the overall efficiency of the process will be significantly improved. As an example in the period from 1980 to 2000 the traditional corn to ethanol process shows a 40% improvement for energy input/output (source xx), a development which is still ongoing. The same development is likely to take place for a straw/whole crop process.

Outlook on agricultural development
In this study winter wheat is used as the baseline scenario. The reasons are that winter wheat has a reasonably high biomass production, and it is already available in quantities necessary for a full-scale ethanol process. Wheat kernels are well suited for traditional ethanol processing and the current system for collection and storage of wheat straw is well developed and can be directly transferred to an energy system based on the IBUS process. As shown in this study there are several indications that, on a long-term basis, winter wheat is probably not the best-suited crop for a sustainable production of biomass feedstock.
With the development of biomass conversion technologies a much wider range of crops and crop types will be available for bioethanol production. Both grasses and tubers may be used but given the

current knowledge whole crop corn shows a large potential. Not only can the biomass production pr. area be doubled or more compared to wheat, but the energy input will also be smaller. The use of new biomass feedstock can therefore markedly increase the production potential and energy input/output ratio.

Conclusion

This study has shown that the production of ethanol based on whole crop winter wheat using the IBUS process has a good energy output-input ratio as the output energy is 2.03 times higher than the input energy. An equivalent production based on green field generation of steam delivers only 1.53 times the energy input.

The overall energy balance of the whole production system shows for 1 ha of winter wheat that the total energy input for agriculture, processing and transport is 66,000 MJ.
For the agricultural production 14,500 MJ is needed mainly for diesel and fertilizers. The refining of wheat feedstock to ethanol, feed and solid fuels requires for the IBUS process 50,300 MJ mainly in the form of steam and electricity, whereas an equivalent green field plant will require 71,900 MJ.

A whole crop winter wheat to ethanol production system is multifunctional and delivers a range of bi-products together with ethanol. Based on 1 ha the production system delivers in average 2,987 kg ethanol, 2,510 kg protein fodder (DDGS) for ruminants or pigs, 561 kg C5 molasses also for fodder, 1,674 kg lignin rich biomass for combustion and 2,897 kg pure CO_2 with multiple appliances.

A maximum of 125,400 ha of average wheat land would be needed in order to meet the 2010 obligation of Directive 2003/30/EC of basing 5.75 % of the energy consumption for Danish road transport on biomass.

Within the IBUS process the nutrients in straw and kernels are recycled to the eco-system in order to obtain maximum sustainability. This will not give the maximum energy output of the process, but the recycling of nutrients for eco-system stability is a pre-requisite for large scale implementation of ethanol as transportation fuel.

With the recent development of biomass conversion technologies a much wider range of crops and crop types are now available for bioethanol production, and winter wheat should only be included as feedstock in the short term. The use of other biomass feedstocks will markedly increase energy input/output ratio as well as multiply the production potential.

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References

Armstrong, A. P., Baro, J., Dartoy, J., Groves, A. P., Nikkonen, J., Rickeard, D. J., 2002: Energy and greenhouse gas balance of biofuels for Europe – An update.

CONCAWE Report No. 2/02.

Bailey, A. P., Basford, W. D., Penlington, N., Park, J. R., Keatinge, J. D. H., Rehman, T., Tranter, R. B., Yates, C. M., 2003: A comparison of energy use in conventional and integrated arable farming systems in the UK.
Agriculture, Ecosystems and Environment 97 (2003) 241-253.

Bernesson, S., 2004: Life cycle assessment of rape seed oil, rape methyl ester and ethanol as fuels – a comparison between large- and smallscale production.
Statens energimyndighet, Sverige.

Börjesson, P. I. I., 1996: energy analysis of biomass production and transportation.
Biomass and Bioenergy Vol. 11, No. 4, 305-318.

Börjesson, P., Gustavsson, L., 1996: Regional production and utilization of biomass in Sweden.
Energy Vol. 21, No. 9, 747-764.

Börjesson, P., 2004: energianalys av drivmedel från spannmål og vall.
Rapport nr. 54, Lunds Tekniska Högskola.

Clements, D. R., Weise, S. F., Brown, R., Stonehouse, D. P., Hume, D. J., Swanton, C. J., 1995: energy analysis of tillage and herbicide inputs in alternative weed management systems.
Agriculture, Ecosystems and Environment 52 (1995) 199-128.

Council of the European Union, 2002: Council Decision of 25 April 2002 concerning the approval, on behalf of the European Community, of the Kyoto Protocol to the United Nations Framework Convention on Climate Change and the joint fulfilment of
commitments there under (2002/358/CE), OJ L 130, 15.5.2002, p. 1

Dalgaard, T., Halberg, N., Fenger, J., 2000: Simulering af fossilt energiforbrug og emission af drivhusgasser.
FØJO-rapport nr. 5/2000
Forskningscenter for Økologisk Jordbrug.

Dalgaard, T., Halberg, N., Porter, J. R., 2001: A model for fossil energy use in Danish agriculture used to compare organic and conventional farming.
Agriculture, Ecosystems and Environment 87 (2001) 51-65.

Dalgaard, T., Halberg, N., Jørgensen, M. H., 2002: Status for energiinput og –output i økologisk jordbrug samt muligheder for energibesparelser. In Jørgensen et al. (eds.), Energi i økologisk jordbrug.
Forskningscenter for Økologisk Jordbrug.

Danish Energy Authority, 2005: Technology Data for Heat and Electricity Generating Plants.

Danmarks JordbrugsForskning, 2005: Normtal 2005.
www.agrsci.dk

Danmarks Statistik, 2004: Landbrug 2003 [Agricultural Statistics 2003].

Danmarks Statistik, 2005: Salg af pesticider efter måleenhed, pesticidgruppe og tid. www.statstikbanken.dk/PEST1.

Dansk Landbrugsrådgivning, 2003: Vinterhvede
Dyrkningsvejledning.

Dansk Landbrugsrådgivning, 2004: Oversigt over Landsforsøgene 2004.
Landscentret, Planteavl.

EFMA: Harvesting Energy with Fertilizers.
European Fertilizer Manufacturers Association.

Elsam, Energi E2, Elkraft System, Eltra, 2000: Life Cycle Assessment of Production of Electricity and Co-generated heat In Denmark. Main Report (in Danish).

Elsam, 2004: Integrated Biomass Utilisation for production of Biofuels. WP4 – 24 months feasibility study. EU contract no. ENK6-CT-2002-00650

Elsam, 2005: Comparative study on possible advantages of establishing bioethanol production adjacent to major power plants. Elsam Engineering, report no. 199316 (in Danish, the report contains proprietary information and is therefore not available to the general public)

Elsam, 2005: Essential thinking.
http://www.elsam.dk/multimedia/essential_thinking_enkeltsider.pdf

Energistyrelsen, 2004: Energistatistik 2003 [Danish Energy Statistics 2003].

Energistyrelsen, 2005: Basic data 2003, www.ens.dk.

Energistyrelsen, 2005: Sammenfattende baggrundsrapport for energistrategi 2025.

European Parliament, 2001: Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market.
Official Journal of the European Communities L 283/33

European Parliament, 2003: Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport.
Official Journal of the European Union 17.5.2003

Feldvoss, C., Kann, M., Rosing, L., Leth, K. D., Mundt, P., Pedersen, H., Skovsby, K., Nielsen, A. M., 2002: Oversigt over miljøpåvirkninger fra rundstykker.
LCA- Food.dk.

Fulton, L., Eads, G, 2004: IEA/SMP Model Documentation and Reference Case Projection.
International Energy Agency and

World Business Council for Sustainable Development.

Iversen, F., Elsam Engineering, 2005: Personal communication

Keeney, D. R., DeLuca, T. H., 1992: Biomass as an energy source for the Midwestern U.S.
American Journal of Alternative Agriculture, Vol. 7, 137-143.

Kuesters, J., Lammel, J., 1999: Investigations of the energy efficiency of the production of winter wheat and sugar beet in Europe.
European Journal of Agronomy 11 (1999) 35-43.

Landbrugets Rådgivningscenter, 2002: Kalkningsvejledning.

Larsen, M.G., 2000: Brændselsdata
Videnblad nr. 155.
Videncenter for Halm og Flisfyring.

Lorenz, D., Morris, D., 1995: How Much energy Does It Take to Make a Gallon of Ethanol?
Institute of Local-Self-Reliance.

Macedo, I. dC., 1998: Greenhouse gas emissions and energy balances in bio-ethanol production and utilization in Brazil (1996).
Biomassans Bioenergy Vol. 14, No. 1, 77-81.

Marland, G., Turhollow, 1992: CO_2 Emissions from the Production and Combustion of Fuel Ethanol from Corn.
Oak Ridge National Lab.
U.S. Department of Energy.

McLaughlin, S. B., Walsh, M. E., 1998: Evaluating environmental consequences of producing herbaceous crops for bioenergy.
Biomass and Bioenergy Vol. 14, No. 4, 317-324.

Miljø & Energi ministeriet, 2000: Reformopfølgning Aftale mellem regeringen, Venstre, Det Konservative Folkeparti, Socialistisk Folkeparti, Centrum-Demokraterne og Kristligt Folkeparti.

Miljøstyrelsen, 2005: Bekæmpelsesmiddelstatistik 2004.
Orientering fra Miljøstyrelsen nr. 6 2005.
Miljøstyrelsen.

Ministeriet for Fødevarer, Landbrug og Fiskeri, 2005: Bekendtgørelse om jordbrugets anvendelse af gødning og om plantedække i planperioden 2005/2006.
Bekendtgørelse nr. 744 af 19/07/2005.

Ministerio de Minas e Energia 2005: Balanco Energetico National 2004.

Morris, D., Ahmed, I., 1992: How much Energy Does it take to Make a Gallon of Ethanol?
Institute of Self Reliance.

Møller, J, Thøgersen, R., Helleshøj, M. E., Weisbjerg, M. R., Søegaard, K., Hvelplund, T., 2005: Fodermiddelbabel 2005.
Dansk Kvæg.

Nielsen, P.H., Wenzel, H., 2005: 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.

Oak Ridge National Laboratory, 2006: Bioenergy Conversion Factors
http://bioenergy.ornl.gov.

Patzek, T.W., 2005: Thermodynamics of the Corn-Ethanol Biofuel Cycle.
Department of Civil and Environmental Engineering.
University of California, Berkeley.

Pimentel, D., Patzek, T. W., 2005: Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower.
Natural Resources Research, Vol. 14, No. 1, 65-76.

Pimentel, D., 2003: Ethanol fuels: Energy balance, economics, and environmental impacts are negative.
Natural Resources and Research Vol. 12, No. 2, 127-134.

Pimentel, D., 2001: The Limits of Biomass Energy.
Encyclopedia of Physical Sciences and Technology.

Pimentel, D., 1991: Ethanol Fuels: Energy Security, Economics, and the Environment.
Journal of Agricultural and Environmental Ethics, Vol. 4, 1-13.

Plantedirektoratet, 2004: Vejledning og skemaer 2004/05.
Ministeriet for Fødevarer, Landbrug og Fiskeri.

Prakash, R., Henham, A., Bhat, I. K., 1998: Net energy and gross pollution from bioethanol production in India.
Fuel Vol. 77, No. 14, 1629-1633.

Punter, G. et al., 2004: Well-to Wheel Evaluation for production of Ethanol from Wheat.
Low Carbn Vehicle Partnership.
United Kingdom.

Refsgaard, K., Halberg, N., Kristensen, E.S., 1998: Energy Utilization in Crop and Dairy Production in Organic and Conventional Livestock Production Systems.
Agricultural Systems Vol. 57, No. 4.

Regeringen, 1993: Aftale om øget anvendelse af biomasse i energiforsyningen og til industrielle formål.

Regeringen, 1997: Tillægsaftale til biomasseaftalen af 14. juni 1993.

Rosenberger, A., Kaul, H. –P., Senn, T., Aufhammer, W., 2001: Improving the energy balance of bioethanol production from winter cereals: the effect of crop production intensity.
Applied Energy 68 (2001) 51-67.

Shapouri, H., Duffield, J. A., Wang, M., 2002: The energy Balance of Corn Ethanol: An Update.
United States Department of Agriculture.
Agricultural Economic Report No. 814.
July 2002.

Shapouri, H., Duffield, J. A., Graboski, M. S., 1995: Estimating the Net Energy Balance of Corn Ethanol.
United States Department of Agriculture.
Agricultural Economic Report No. 721.
July 1995.

Sønderjysk Landboforening, 2004: Etablering af bioethanolfabrik I Sønderjylland.

Sørensen, C.A.G., 2005: Personal communication.

Transport- og Energiministeriet, 2005: Europaparlamentet og Rådets direktiv 2003/30/EF af 8. maj 2003 om fremme af anvendelse af biobrændstoffer og andre fornyelige brændstoffer til transport.
Notat af 14. november 2005.

Ulgiati, S., 2001: A Comprehensive Energy and Economic Assessment of Biofuels: When "Green" Is Not Enough.
Critical Reviews in Plant Sciences, 20 (1): 71-106.

U.S. Department of Energy, 2005: Annual Energy Review 2004.
Report No. DOE/EIA-0384 (2004).

Venendaal, R., Jørgensen, U., Foster, C. A., 1997: European energy crops: A synthesis.
Biomass and Bioenergy Vol. 13, No. 3, 147-185.

Venturi, P., Venturi, G., 2003: analysis for energy comparison for crops in European agricultural systems.
Biomass and Bioenergy 25 (2003) 235-255.

Wang, M., Saricks, C., Santini, D., 1999: Effects fo Fuel Ethanol Use on Fuel-Cycle energy and Greenhouse Gas Emissions.
U.S. Department of Energy.
Argonne National Laboratory.

Wang, M. et al., 1997: Fuel-cycle fossil energy use and greenhouse gas emissions of fuel ethanol produced from U.S. Midwest corn.
Argonne National Laboratory, Centre for Transportation Research.