Agronomy Research **11** (1), 189–196, 2013

Environmental Impact of Corn Grain Ethanol Production focussed on Energy Intensity and Global Warming Potential

S. Kraatz

Leibniz-Institute for Agricultural Engineering Potsdam-Bornim, Department Technology-Assessment and Substance Cycles, Max-Eyth-Allee 100, 14469 Potsdam, Germany; e-mail: sikraatz@atb-potsdam.de

Abstract. The need of fossil fuels and renewable energy is steadily increasing. The evaluation of the sustainability of the bio-fuel production needs to be considered in detail and under a holitistic point of view.

The goals of this study are to enumerate the life cycle Energy Intensity (EI) and Global Warming Potential (GWP) of corn grain ethanol production, and to explore ethanol production scenarios which differ at the treatment of the Whole Stillage (WS) co-product, the starch content of the corn kernels and the corn production process at farm scale.

A case study of ethanol production in Wisconsin, United States is done. The system boundaries of the investigation are from 'cradle to plant gate'. In this study statistic data are used for real conditions of corn grain production in Wisconsin. The data for energy use at the biorefinery industrial processes are sourced from an ethanol plant survey.

From the comparison of co-product use scenarios, we find that recycling the WS into electricity, heat and fertilizer is the most environmentally beneficial co-product use because it results in a 54% lower EI and a 49% lower GWP than the processing of WS into Distillers Dried Grains with Soluables (DDGS). An increasing starch content of the corn kernels shows a strong decrease of the EI and GWP of the ethanol production up to 20%.

Key words ethanol, Life Cycle Assessment, corn, biofuel.

INTRODUCTION

The U.S. Renewable Fuels Standard enacted in The Energy Independence and Security Act of 2007 requires the use of biofuels starting in 2009. Therefore a rapid year over year biofuel production is required to produce up to 21 billion gallons by 2022, which relates on a compounded annual growth rate in excess of 30%.

The idea of becoming self-sufficient regarding the use of fossil and renewable resources is to discuss because its production affects the earth system with the outcomes of climate change and resource scarcity. A global point of view is necessary to develop mitigation strategies of GHG emissions and to reduce resource use for the exposure of natural goods for food and energy. Biofuels are promoted in an effort to address energy security concerns and the reduction of greenhouse gas emissions of transportation fuels.

The United States government has instructed a maximum production of 15 billion gal of corn ethanol by 2015 (EISA, 2007). The Energy Independence and Security Act also requires a 20% reduction in lifecycle greenhouse gas emissions of corn ethanol in comparison to baseline lifecycle greenhouse gas emissions of gasoline. Corn ethanol is the predominant biofuel in the United States, and is already using over 30% of the corn produced currently. In Wisconsin is corn grain the typical used plant material for ethanol production.

The investigations assess the influence of ethanol production from corn grain (*Zea mays ssp. Mays*) on the environment.

The goals of this study are

- To investigate the energy intensity and the generation of greenhouse gas emissions of corn grain ethanol production.
- To show the influence of the corn grain production process at farm scale on the environmental impact of ethanol production.
- To discuss the influence of corn grain quality on ethanol production.
- To demonstrate the influence of co-product use on the resource efficiency of biofuel production.

METHODS

Scope and Functional Unit

In this study the environmental impacts EI and GWP are calculated based on recent developments of ethanol production in Wisconsin. The calculations are done from cradle to ethanol plant gate. This study focusses on the agricultural process of corn grain production and on the industrial process of Ethanol production.The examples of two defined scenarios of the ethanol production process are used to show the influence on the resource use of the handling the co-product whole stillage (WS) within the process (Kraatz et al., 2011). The results of this study are reported for 1 kg of ethanol denatured with gasoline (95% ethanol, 5% gasoline). The energy value of ethanol was assumed to be its higher heating value (HHV) 29.6 MJ kg^{-1} (Patzek, 2004). The density of the ethanol was assumed to be 0.79 g cm^{-3} (US NIST, 2010). According to the real data of the investigated ethanol plants in Sinistore and Bland (2010) the corn use is defined with 3.25 kg corn grain kg^{-1} ethanol.

Data Sources and Assumptions

This study uses 2005 Wisconsin corn production data and the estimated energy intensity and GWP for producing corn grain in Wisconsin. The investigations are done based on the methodical approach of Kraatz et al. (2009) but extended with various cultivation scenarios of the corn grain.

The energy use data for the biorefinery industrial processes were sourced from an ethanol plant survey conducted in Wisconsin (Sinistore, 2008). The average production of ethanol from these data is 147,730,000 kg from one plant in a year. The calculations presented here are based on this average value. The basic data used for the calculation of energy intensity and GWP are presented in table 1.

The Energy Intensity (EI) of ethanol includes both direct (EIP_{direct}) and indirect energy input ($EIP_{indirect}$). Direct energy is considered in form of fuel oil, electricity and natural gas. Indirect energy includes the energy input for resources, manufacturing machinery and technical equipment (e.g. fertilizer, seed, pesticide and machinery). The cumulative energy calculation includes the energy inputs, valued as primary energy, which arise in connection with the production, use and disposal of an economic good.

The EI of ethanol production is calculated as sum of the energy inputs of corn grain production and energy use at the biorefinery.

Table 1. Basic values for the energy input and greenhouse gas emissions of the inputs of the corn grain production and the processing at the ethanol plant

Item	Energy Inputs	References	GHG emissions	References
Gasoline	46.9 MJ kg^{-1}	Staffell, 2011	0.065 kg $CO_{2\text{-eq}}$ MJ^{-1}	NREL, 2008
Gasoline combusted	–	–	2.344 kg $CO_{2\text{-eq}}$ L^{-1}	NREL, 2008
LP gas	50.0 MJ kg^{-1}	Staffell, 2011	0.749 kg $CO_{2\text{-eq}}$ MJ^{-1}	NREL, 2008
LP gas combusted	–	–	1.534 kg $CO_{2\text{-eq}}$ L^{-1}	NREL, 2008
Natural gas (NG)	50.8 MJ kg^{-1}	Staffell, 2011	0.063 kg $CO_{2\text{-eq}}$ MJ^{-1}	NREL, 2008
NG combusted	–	–	0.00193 kg $CO_{2\text{-eq}}$ L^{-1}	NREL, 2008
Electricity	10.97 MJ kWh^{-1}	Passos Fonseca, 2010	0.207 kg $CO_{2\text{-eq}}$ MJ^{-1}	Passos Fonseca, 2010
Hybrid corn seeds	104 MJ kg^{-1}	Patzek, 2006	6.20 kg $CO_{2\text{-eq}}$ kg^{-1}	Own calculations
Machinery manufacture	109 MJ kg^{-1}	Kalk and Hülsbergen, 1996	0.4 kg $CO_{2\text{-eq}}$ kg^{-1}	GEMIS, 2006
Diesel fuel use	45.6 MJ l^{-1}	Staffell, 2011	3.57 kg $CO_{2\text{-eq}}$ L^{-1}	GEMIS, 2006
Nitrogen fertilizer	35.3 MJ kg^{-1}	Appl, 1997	1.46 kg $CO_{2\text{-eq}}$ kg^{-1}	GEMIS, 2006
Phosphate fertilizer	36.2 MJ kg^{-1}	Kaltschmitt and Reinhardt, 1997	0.39 kg $CO_{2\text{-eq}}$ kg^{-1}	GEMIS, 2006
Potassium fertilizer	11.2 MJ kg^{-1}	Hülsbergen, 2003	0.533 kg $CO_{2\text{-eq}}$ kg^{-1}	GEMIS, 2006
Lime			0.44 kg $CO_{2\text{-eq}}$ kg^{-1}	Farrell et al., 2006
Herbicides production	288 MJ l^{-1}	Green, 1987	24.5 kg $CO_{2\text{-eq}}$ L^{-1}	GEMIS, 2006
Pesticides production	196 MJ l^{-1}	Hülsbergen, 2003	24.5 kg $CO_{2\text{-eq}}$ L^{-1}	GEMIS, 2006
Sewage effluent	4 kWh°	Blais et al., 1995	0.207 kg $CO_{2\text{-eq}}$ MJ^{-1}	NREL, 2008
Construction	0.067–0.332 MJ kg^{-1} Ethanol	Calculated from Bernesson, 2004	No data available	
Enzymes and additives	0.07 MJ kg^{-1} Ethanol	Bentsen et al., 2009	No data available	

° required to process 1 kg Biological Oxygen Demand (BOD), 20 kg BOD/1,000 L ethanol produced (Kuby et al., 1984)

The generation of greenhouse gas emissions is directly connected to the energy input. Direct and indirect GHG emissions are defined in the same way as direct and indirect energy use and are calculated according to the energy inputs of the ethanol production process. The calculations of the Global Warming Potential (GWP) include carbon dioxide (CO_2) and nitrous oxide (N_2O). The GHG emissions are aggregated on a carbon dioxide-equivalent basis ($CO_{2\text{-eq}}$), using the 100-year GWP factor for N_2O recommended by the International Panel on Climate Change (IPCC, 2006) These values are 1 for CO_2, 298 for N_2O with an emission factor of 0.0125 kg kg^{-1}N (IPCC, 2006).

Scenario corn grain production at farm scale

The environmental impact of ethanol production from corn grain is influenced by the agricultural processes of the corn grain supply. Therefore four different scenarios are defined to determine the sustainability of the production of corn grain ethanol. The first scenario describes the real conditions of corn production in Wisconsin including the use of artificial fertilizer. The second scenario is similar to scenario 1 but includes additionally the drying of the corn grain. Scenario 3 and 4 do also base on the real conditions of corn grain production in Wisconsin but include the use of manure instead of artificial fertilizer. Within scenario three it is assumed that no energy demand is given for the nutrients within the manure itself, but the spreading of the manure is included as an energy input for its use. The fourth scenario is similar to scenario 3 but includes the accounting for the environmental burdens for the cattle manure. The used equivalent values per ton of dairy cattle manure is calculated to be 27 MJ and 2.2 kg $CO_{2\text{-eq}}$, respectively.

Scenario quality of corn grain

The quality of corn grain varies by year and location. The corn quality influences the ethanol yield and the environmental impacts of the ethanol production. The composition of the corn used in this calculation bases on different assumptions related to its quality. The theoretical ethanol yield from corn grain is 0.51 kg ethanol per 1 kg starch excluding conversion losses which might appear during the production process.

Data from literature are used to show the influence of the starch content of the corn grain on the results of the environmental impact of ethanol production. Scenarios are shown with varying starch contents from 60 % to 76 % per kg of corn grain. Ranges of the data of the starch content are built related to studies from literature (Patzek, 2006, Oberforster et al., 2010; Sinistore, 2009 and Kim & Dale, 2002).

Scenario using whole stillage as biodigester feedstock

This scenario differs to the standard scenario in how the co-product WS is processed and used. Therefore, the production system diverges at the WS processing step. The standard scenario includes the production of Distillers Dried Grains with Soluables (DDGS) and contains the centrifuging and drying of the WS.

The use of WS for biogas production not only omits the drying and centrifuging of WS, but it also provides an opportunity to integrate the generated energy from the WS into the process cycle of the ethanol plant. Biodigestion, however, requires the addition of a biodigester to the system. The use of the biogas from biodigestion requires the addition of a Combined Heat and Power plant (CHP). The integration of a biodigester and a CHP plant is considered within the system boundary of this scenario.

RESULTS AND DISCUSSION

The environmental impact of ethanol production from corn grain is calculated by using Wisconsin specific conditions and results in an EI of 25.1 MJ kg^{-1} ethanol and a GWP of 3.33 kg $CO_{2\text{-eq}}$ kg^{-1} ethanol (table 2).

The influence of the discussed scenarios on the environmental impact of corn grain ethanol production is shown in table 2 as well.

Strongest influence on the efficient use of energy and the generation of greenhouse gas emissions has the use of the co-product. Already using the separation of the resource input for the production of the ethanol and its co-product DDGS leads to a differing result. The EI is 18.94 MJ kg^{-1} ethanol and the GWP is 3.28 kg $CO_{2\text{-eq}}$ kg^{-1} ethanol. The environmental impact allocated to the processing of the WS for producing the co-product DDGS results in an EI of 6.12 MJ kg^{-1} ethanol and a GWP 0.05 kg $CO_{2\text{-eq}}$ kg^{-1} ethanol, respectively. The main contributor to the EI of the industrial process at the ethanol plant is the electricity with 30%. The supply of corn grain and its transportation to the ethanol plant makes up 23% of the EI of ethanol production. Half of the total GWP can be attributed to electricity generation and about one third can be attributed to biotic carbon emitted during the fermentation. Corn production comprises the third largest share of the GWP of ethanol production.

Table 2. Influence of the different scenarios on the environmental impact of ethanol production from corn grain

Scenario	Energy Intensity (EI) MJ kg^{-1} ethanol	EI ratio to standard scenario %	Global Warming Potential (GWP) kg $CO_{2\text{-}eq}$ kg^{-1} ethanol	GWP ratio to standard scenario %
Standard*	25.1	100	3.33	100
Co-product use				
Standard with DDGS	18.9	75	3.28	98
Integrated system	11.6	46	1.70	51
Corn grain production				
2-standard plus drying of corn grain	25.9	103	3.37	101
3-using manure	23.2	92	3.27	98
4-manure and allocated value for its supply	24.6	98	3.28	98
Starch content				
66.2%[$]	22.8	91	3.03	91
72.3%[§]	20.9	83	2.78	83
73.6%[§]	20.5	82	2.73	82
75.7%[§]	20.1	80	2.67	80

*based on real conditions of corn grain production in Wisconsin (USA) (Kraatz et al., 2009), starch content: 60.3% (Sinistore, 2010; Kim and Dale, 2002); co-product processing included (Drying DDGS) with no use of allocation; [$] Patzek, 2006; [§] Oberforster et al., 2010

The integration of a biodigester and CHP plant results in an EI of 11.6 MJ kg^{-1} ethanol and a GWP of 1.7 kg $CO_{2\text{-}eq}$ kg^{-1} ethanol and the nutrients from the digester effluent also have considerable value. Nearly 50% of the energy input stems from corn production and corn transportation to the ethanol plant. The waste water treatment and the addition of gasoline to the ethanol each make up 20% of the EI of ethanol production, respectively. The ethanol production GWP in this scenario is dominated by the emissions from corn grain production and the release of biotic carbon during the fermentation.

The second highest influence on the EI and the GWP of the ethanol production has within the compared scenarios the starch content of the corn kernels. The investigation show that with increasing starch content the EI and the GWP are decreasing up to 20% in the examples discussed within this study (table 3).

The share of the corn production on the energy intensity of the ethanol production is 20%. The discussed scenarios of corn grain production at farm scale show the lowest influence on the environmental impact of the ethanol production compared to the other considered scenarios (table 2).

Table 3. Environmental impact of four varying corn grain production scenarios

Resource input	Corn grain production scenario							
	Standard		2 – standard plus drying of corn grain		3 – manure		4 – manure (allocation used)	
per ha	MJ	kg $CO_{2\text{-eq}}$	MJ	kg $CO_{2\text{-eq}}$	MJ	kg $CO_{2\text{-eq}}$	MJ	kg $CO_{2\text{-eq}}$
Fertilizer	6512	314	6512	314	883	99	4820 *	124
Pesticide	907	77	907	77	907	77	907	77
Seed	2059	123	2059	123	2059	123	2059	123
Machinery	1461	47	1461	47	1461	47	1461	47
Diesel	3840	584	3840	584	4113	625	4113	625
Gasoline			650	40				
LPG			812	32				
Natural gas			510	4				
Electricity			549	37				
N_2O		448		448		448		448
per kg corn	MJ	kg $CO_{2\text{-eq}}$	MJ	kg $CO_{2\text{-eq}}$	MJ	kg $CO_{2\text{-eq}}$	MJ	kg $CO_{2\text{-eq}}$
	1.57	0.17	1.84	0.18	1.00	0.15	1.42	0.15

The decreasing use of artificial fertilizer substituted by manure shows a marginal decrease of the EI. Detached from the ethanol production scenario the corn grain production shows stronger differences in energy use and generation of GHG emissions regarding the discussed scenarios (table 3). The use of manure as fertilizer leads to a lower input of fossil energy ressources even with consideration of fossil energy used through allocation of the energy inputs of the manure as co-product from dairy farming. Dependent on the weather conditions the drying of the corn grain might be necessary. The drying leads to an increase of 17% of fossil energy use compared to standard scenario. The GWP of corn grain production is marginally varying within the described corn grain production scenarios. It shows the use of manure instead of artificial fertilizer leads to decreasing GHG emissions.

CONCLUSIONS AND OUTLOOK

It is to conclude that the use of the co-product of ethanol production has strong influence on its environmental impact. It is shown that the most environmentally beneficial use of the WS co-product is to biodigest it to produce methane. These benefits are enhanced when the biodigester residue is used as fertilizer to displace conventional fertilizer in corn production. The use of allocation has a crucial influence on the environmental impact assessment. The starch content of corn used for ethanol production shows an effective opportunity to improve its sustainability. Even with a low impact of the corn grain production on the environmental impact of ethanol production it is to conclude that the on-farm production of the corn grain needs to be considered carefully. Using artificial fertilizer causes higher fossil energy use than the use of manure. Finally it is to highlight that only minor energy gain is reached within the life cycle of ethanol production from corn grain in Wisconsin.

ACKNOWLEDGMENTS. The authors gratefully acknowledge support provided by the German Research Foundation (DFG).

REFERENCES

Appl, M. 1997. Modern production technologies: A review. Nitrogen. *Nitrogen – The J. of the World Nitrogen and Methanol Inds*. 4–56.

Bernesson, S. 2004. 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.

Bentsen, N.S., Thorsen, B.J., Felby, C. 2009. Energy, feed and land-use balances of refining winter wheat to ethanol. *Biofuels, Bioproducts and Biorefining*. **3**(5), 521–533.

Blais, J.F., Mamouny, K., Nlombi, K., Sasseville, J.L., Letourneau, M. 1995. Les measures deficacite energetique dans le secteur de leau. In: Sassville, J.L., Balis, J.F. (Eds.), Les Mesures deficacite Energetique pour Lepuration des eaux Usees Municipales. Scientific Report 405, vol 3. INRS-Eau, Quebec.

EISA. 2007. Energy Independence and Security Act of 2007. Washington, D.C.: Public Law 110–140, pp.121: 110th Congress.

Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O´Hare, M., Kammen, D.M. 2006. Ethanol can contribute to energy and environmental goals. *Science*. **311**, 506–508.

GEMIS (Global Emission Model for Integrated Systems), 2006. Version 4.3. Öko-Institut Freiburg i.Br. (Institut für angewandte Ökologie e. V.). Available at: http://www.oeko.de/service/gemis. (accessed April 2011).

Green, M.B. 1987. Energy in pesticide manufacture, distribution and use. In Energy in *Plant Nutrition and Pest Control*, ed. Helsel, Z. R., 165–177. Amsterdam: Elsevier Scientific Pub.

Hülsbergen, K.-J. 2003. Entwicklung und Anwendung eines Bilanzierungsmodells zur Bewertung der Nachhaltigkeit landwirtschaftlicher Systeme (Development and use of a balancing model for the assessment of the sustainability of agricultural systems). Berichte aus der Agrarwissenschaft. Aachen: Shaker.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4. Agriculture, Forestry and other Land Use. Intergovernmental Panel on Climate Change.

Kalk, W.D., Hülsbergen, K.J. 1996. Methodik zur Einbeziehung des indirekten Energieverbrauchs mit Investitionsgutern in Energiebilanzen von Landwirtschaftsbetrieben. (Method for considering the materialized energy (indirect energy consumption) in capital goods on energy balance sheets of farms). *Kuhn-Arch.* **90** (1), 41–56.

Kaltschmitt, M., Reinhardt, A. 1997. Nachwachsende Energietrager. Grundlagen, Verfahren, okologische Bilanzierung (Renewable source of energy. Base, procedure and ecological balancing). Vieweg Verlag. Braunschweig Wiesbaden.

Kraatz, S., Sinistore, J.C., Reinemann, D.J. 2011. Methods for Solving the Multifunctionality Problem in the Life Cycle Assessment of Ethanol Production from Corn Grain. ASABE Annual International Meeting 2011. 7–10 August, Louisville, Kentucky. ASABE Paper-no.1110828. St. Joseph, MI: ASABE.

Kuby, W.R., Markoja, R., Nackford, S. 1984. Testing and Evaluation of On-Farm Alcohol Production Facilities. Acures Corporation. Industrial Environmental Research Laboratory, Office of Research and Development,U.S. Environmental Protection Agency, Cincinnati, OH.

Kwiatkowski, J.R., McAloon, A.J., Taylor, F., Johnston, D.B. 2006. Modeling the process and costs of fuel ethanol production by the corn dry-grind process. *Industrial Crops and Products.* **23**(3), 288–296.

NREL. 2008. Life Cycle Inventory Database. Available at: http://www.nrel.gov/lci/database/. (accessed June 21 2011).

Oberforster, M., Flamm, C., Prieler, W., Felder, H., Lipp, M., Hammerl, S., Kinastberger, A., Schulmeister, K., and Zechner, E. 2010. Eignung von Getreide- und Maissorten sowie optimierte Anbaustrategien zur Erzeugung von Rohstoffen für Bioethanol und verwertbare Nebenprodukte (GEMBEOL) (suitability of grain and corn species as well as optimized cultivation strategies for the production of commodities for bioethanol and usable by-products). Research project # 100197. Österreichische Agentur für Gesundheit und Ernährungssicherheit GmbH (AGES) Verein zur Förderung von Mohn- und Getreidezüchtung.

Passos Fonseca, T.H. 2010. Net energy intensity and greenhouse gas emissions of integrated dairy and bio-fuels systems in Wisconsin. MS thesis. Madison, Wisconsin: University of Wisconsin/Madison, Department of Biological Systems Engineering.

Patzek, T.W. 2004. Thermodynamics of the Corn-Ethanol Biofuel Cycle. Critical Reviews in Plant Sci. 23(6): 519–567 (2004). Periodically updated web-vers. Available at: http://www.hubbertpeak.com/patzek/ThermodynamicsCornEthanol.pdf. (accessed June 2 2011).

Patzek, T.W. 2006. A statistical approach of the theoretical yield of ethanol from corn starch. *Natural Resources research*. **15**(3), 205–212.

Sinistore, J.C. 2008. Corn ethanol production in the Wisconsin agricultural context : energy efficiency, greenhouse gas neutrality and soil and water implications. MS thesis. Madison, Wisconsin: University of Wisconsin/Madison, Department Biological Systems Engineering.

Sinistore, J.C., Bland, W.L. 2010. Life-Cycle Analysis of Corn Ethanol Production in the Wisconsin Context. *Biological Engineering*. **2** (3), 147–163.

Staffell, I. 2011. The energy and fuel data sheet. University of Birmingham, UK, http://www.claverton-energy.com/wp-content/uploads/2012/08/the_energy_and_fuel_data_sheet.pdf. (accessed January 2013)

US NIST. 2010. Conversion factors for energy equivalents. Gaithersburg, M.D.: United States National Institute of Standards and Technology. Available at: http://physics.nist.gov./cuu/Constants/energy.html. (accessed July 30 2010).