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# Energy intensity and global warming potential of corn grain ethanol production in Wisconsin (USA)

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## Abstract

Increasing demand for renewable alternative fuels, such as ethanol, is driven by decreasing availability of fossil resources and increasing attention to climate change. Life cycle assessment (LCA) is the tool used to evaluate environmental impacts, such as energy intensity (EI) and global warming potential (GWP), from ethanol production, but the application of this tool varies greatly. The goals of this study were to enumerate the life cycle EI, net energy value (NEV), and GWP of corn grain ethanol production in Wisconsin, to explore ethanol production scenarios which differ at the treatment of the whole stillage (WS) coproduct, and to evaluate the various solutions to the multifunctionality problem which arises in LCA. In Scenario 1, all suggested solutions to the multifunctionality problem are considered by transforming WS into the animal feed dried distillers grains with solubles (DDGS). Scenario 2 avoids allocation using an integrated system which recycles the WS with an anaerobic biodigester and a combined heat and power (CHP) plant to provide electricity and steam to the ethanol refinery and returns the residue to the land as fertilizer. Based on the Scenario 1 analysis, we recommend the use of the subdivision (SD) solution to the multifunctionality problem because it enables clear comparisons between different ethanol production systems, it distinguishes between the environmental impacts from ethanol production and coproduct processing and it reduces the number of assumptions in the LCA calculations. From the comparison of both scenarios, we find that recycling the WS into electricity, heat, and fertilizer is the most environmentally beneficial coproduct use because it results in a 54% lower EI and a 67% lower GWP than the processing of WS into DDGS.

## Introduction

Scarcity of resources and concerns about climate change spur a steadily increasing worldwide demand for renewable transportation fuel. Biomass is seen as a possible sustainable and renewable energy source and also as a way to reduce the global warming potential (GWP) of transportation fuels (Murey and Dey 2006). A renewable fuel's sustainability, however, must be thoroughly examined throughout its life cycle before the fuel can receive credit for environmental benefits. A large number of researchers have recognized the conundrum of possible ecological drawbacks and benefits of biofuel production (Blottnitz and Curran 2007).

Ethanol made from corn grain is the predominant biofuel in the United States and uses over 30% of the annual corn crop (ERS (United States Department of Agriculture Economic Research Service) (2010). The ethanol production from corn starch was increasing by 25% between the years 2003 and 2007 (Halford 2012). h Ethanol is produced by the fermentation of sugars derived from starch found in corn grain. Fermentation produces alcohol, which can then be blended with gasoline or used as a pure fuel in certain engines. Dry milling is the prevailing technology for producing corn ethanol in the Unites States. About 10 to 15 L of whole stillage (WS) are produced as a coproduct of the production of one liter of alcohol (Pieper 1983). The WS is nearly free of starch and consists mainly of protein, fat, minerals, and fiber (Pieper 1983). Between 74 and 95% of the dry matter in WS is organic (Braun 1982). The use of yeast during the fermentation adds additional protein and vitamins to the WS. The WS can be used as fertilizer, animal feed, and as a feedstock for the production of biogas. A major coproduct produced from the WS is distillers grains (DG). The DG can be used wet or dry. In Wisconsin, most of the DG is used as animal feed in the form of dried distillers grains with solubles (DDGS). Alternatively, the DG can be fed to animals in wet form, but the limited shelf-life of the product makes it less attractive as an animal feed. The influence of the use of the coproduct WS on the quantification of the environmental impact of ethanol production is discussed with in this study. Carbon dioxide released during the fermentation step of the ethanol production process can also be considered as a coproduct of corn ethanol production, but it is generally not captured. Instead, it is vented to the atmosphere as the cost of purifying and transporting it to an end user often outweighs any economic gains from selling it (Kwiatkowski et al. 2006). This study does not include the carbon dioxide as valuable coproduct of ethanol production.

The focus of this study is the calculation of some environmental impact categories associated with corn ethanol production energy intensity (EI), net energy value (NEV), and GWP. The EI is expressed as the ratio of the energy inputs (EIP) per amount of produced ethanol. The GWP is defined as the ratio of the generated greenhouse gas (GHG) emissions per amount of produced ethanol. Some studies in literature have shown net gains in EI, NEV, and GWP while others have reported net losses in these environmental impact indicators for corn grain ethanol compared with gasoline (Wang 1999; Shapouri et al. 2004; Farrell et al. 2006; Hill et al. 2006; Patzek 2004). These disparate results arise not only from differences in data sources, assumptions, and geographical system boundaries, but also from different solutions to the multifunctionality of the process (Plevin 2010). In this context different methods for dealing with the multifunctionality problem encountered in the corn grain ethanol LCA due to the coproduction of WS and DG are dealt with in this study. It is discussed which method used for solving the multifunctionality problem is to recommend for suitable comparisons of the environmental impact of ethanol production of corn grain to different production processes, for example, with equal feedstock's, but also with different plants as sugarcane and other biofuels as biodiesel.

Patzek (2004, 2006) and Kube (2008) recommend neglecting any credits for using the DDGS. They recommend that the WS be returned to the soil to replace nutrients removed from the soil by corn production. Patzek (2004, 2006) stated that the high energy credits, given by some researchers to the DDGS, are unrealistic because the production of livestock feed from ethanol is uneconomical given the high costs of fossil energy plus the costs of soil depletion to the farmer. Other studies acknowledge the coproduct DDGS as a high-quality livestock feed and give energy and GHG emissions credits to the environmental impact of the ethanol production (Kim and Dale 2002; Liska et al. 2009; Bremer et al. 2010). Many researchers give energy and GHG credits to corn ethanol for the use of DG as animal feed because they argue that it displaces other feeds (such as corn grain, soybean meal, and urea) in the animal diet (Klopfenstein et al. 2008; Hsu et al. 2010). The calculation of these credits, however, hinges on the type of animal consuming the DG, the proportional displacement of other feeds in the diet and any effects on the quality or quantity of the animal product being produced.

Life cycle assessment (LCA) is the preferred method for quantifying the environmental impacts and sustainability of biofuels. The evaluation of the environmental impacts of ethanol production is strongly influenced by the methodology used to account for the coproducts of the process (Curran 2007; Reap et al. 2008; Kaufman et al. 2010). There are several methods described in LCA standards for solving multifunctionality problems (ISO 14044 2006). The method chosen to solve the multifunctionality problem will influence the assessment of the environmental impacts of ethanol production. Allocation, however, has the distinction of being called one of the most controversial issues in LCA because the selection and application of allocation methods in an LCA can dramatically alter the results of the analysis (Reap et al. 2008). The choice of the most appropriate method depends upon different factors such as the goal of the study, available data, and the characteristics of the multifunctional process (European Commission 2010).

Especially the coproduct use influences the environmental impact of the ethanol process as well. Therefore, to highlight the influence on the environmental impact of the ethanol production, two different coproduct use scenarios are discussed. Scenario 1 includes the processing of WS into DDGS. Scenario 2 considers the integration of biogas production from WS and the generation of electricity and heat from this biogas for use in the ethanol refinery.

The goals of this study were as follows:

- To investigate the environmental impact of ethanol production of corn grain ethanol produced in Wisconsin using the environmental indicators EI, NEV, and GWP.

 

- To demonstrate the influence of two different production systems and coproduct handling on the sustainability of the ethanol production.
- To highlight recommendations for the methodological approach used for the assessment of the sustainability of biofuel production.
- To show possibilities to reduce the EI and GWP of ethanol production.

## Methods

### Scope and functional unit

In this study, a corn grain ethanol production system is used for the calculation of the environmental impacts EI, NEV, and GWP, based on recent developments of ethanol production in Wisconsin. The calculations are done using the examples of two defined scenarios of the production process to show the influence of the handling of coproducts within the process. A selection of characteristics of the ethanol production system is presented in Table 1.

According to Bossel 2003 a meaningful analysis of the environmental impact of fuel production and consumption which involves different chemical energy carriers must be based on the true energy content or the higher heating value (HHV) of all fuels considered. With regard to choosing the lower heating value (LHV) or HHV in calculations, a thorough discussion has been provided by Bossel (2003) about the use of HHV, who established conclusively that only the HHV values can be used to compare different fuels, especially those with different oxygen contents (Patzek 2010).

This study uses 2005 Wisconsin corn production data and the calculated EI (Kraatz et al. 2009) and the GWP for producing corn grain in Wisconsin. The data for the biorefinery industrial processes were sourced from an ethanol plant survey conducted in Wisconsin (Sinistore 2008). The calculations presented here are based on an average value.

The system boundaries of the two ethanol production scenarios are defined from “cradle to gate.” These boundaries include corn grain production at the farm, transportation of the corn to the ethanol plant, and the industrial processes at the ethanol plant (Fig. 1). The geographical boundary of this study is the state of Wisconsin in the United States.

The two scenarios differ in how the coproduct WS is processed and used. Therefore, the production system diverges at the WS processing step (Fig. 1). The first scenario includes the production of DDGS and contains the centrifuging and drying of the WS.

The use of WS for biogas production (Scenario 2) 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 Scenario 2 (Fig. 1).

### Data sources and assumptions

The EI of biofuel production includes both direct and indirect EIP. Direct energy is considered in form of transportation fuel, electricity, and natural gas. Indirect energy includes the EIP for manufacturing machinery and technical equipment (e.g., fertilizer, seed, pesticide, and machinery). The cumulative energy calculation includes the EIP, valued as primary energy, which arise from the production, use and disposal of an economic good. The EI of ethanol production is calculated as sum of the EIP to corn grain production and the biorefinery. A NEV is calculated by subtracting the HHV of the ethanol from the EI of the ethanol production process.

The generation of GHG emissions is related to energy use among others. Direct and indirect GHG emissions are defined in the same way as direct and indirect energy use

**Table 1.** Ethanol plant structure and basic assumptions of the ethanol production system.

| Inputs/Characteristics | Values used in this study | References |
|---|---|---|
| Location | Wisconsin, United States | |
| Ethanol production | 147,730,000 kg ethanol refinery$^{-1}$ year$^{-1}$ | Sinistore and Bland (2010) |
| Ethanol/gasoline mixture | 95%/5% | |
| Corn grain yield | 9398 kg ha$^{-1}$ | USDA (2009) |
| Higher heating value | 29.6 MJ kg$^{-1}$ ethanol | Patzek (2004) |
| Density | 0.79 g cm$^{-3}$ ethanol | US NIST (2010) |
| Ethanol plant | Dry milling system | |
| Conversion rate | 3.25 kg corn kg$^{-1}$ ethanol | According to Sinistore (2008) |

 

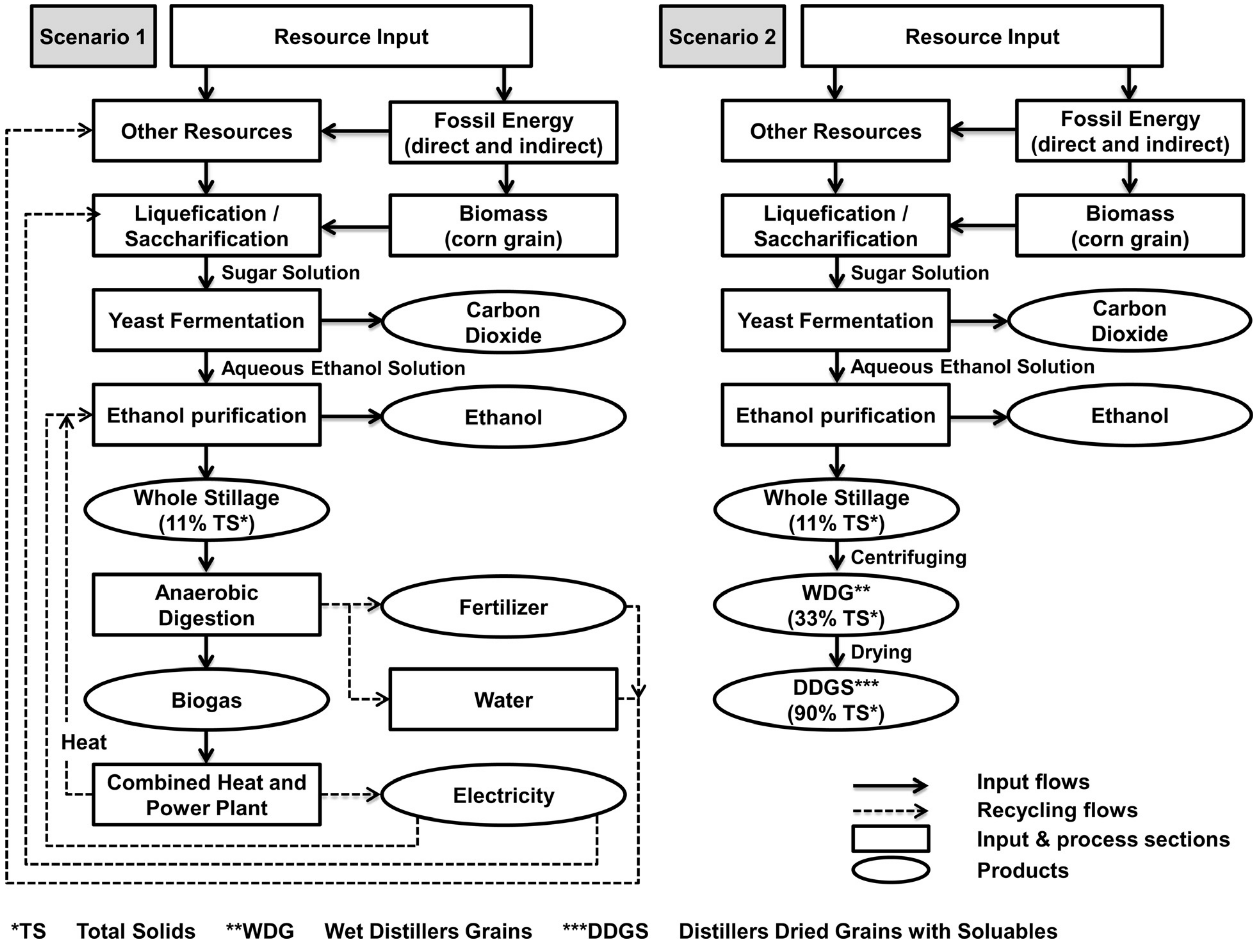


**Figure 1.** Process plan for ethanol production from corn grain and coproduct processing: system boundaries of Scenario 1 ethanol production with the production of dried distillers grains with solubles (DDGS) and Scenario 2 ethanol production with the production of biogas.

and are calculated according to the EIP of the ethanol production process. The calculation of the GWP includes the emissions of carbon dioxide ($CO_2$) and nitrous oxide ($N_2O$). The GHG emissions are aggregated on a $CO_2$ equivalent basis ($CO_{2\text{-eq}}$), using the 100-year GWP factors recommended by the international panel on climate change (IPCC 2006). These values are one equivalent for $CO_2$, and 298 equivalents for $N_2O$. The $N_2O$ emission is calculated using the IPCC coefficient of 0.0125 kg $N_2O$ emission for 1 kg fertilizer N (IPCC 2006).

Table 2 shows the basic data used for the EI and GWP calculations. The specific electricity grid used in Wisconsin is included in the calculation.

## Ethanol production scenarios

According to the system boundaries and the production processes included in this study, WS is produced as a coproduct of corn ethanol. It has been suggested that the WS could be used as a soil amendment on agricultural fields because it has many qualities which are beneficial to soil (Jenny 1980). This coproduct, however, also has a high energetic and nutritional value and these qualities provide an economic incentive to process the WS into DG and sell it as animal feed. Therefore, the direct use of WS to increase soil fertility is acknowledged as one potential use of the coproduct, but it is not explored further in this study.

In the final step of ethanol production, ethanol is separated from the WS (water and solid materials) in a distillation process. After the distillation process, the WS has a very high moisture content (8–15% dry matter). Solids are further separated from the liquid portion using a centrifuge to produce the wet DG with moisture content of 67%. The liquid contains unfermented sugars, protein, fat, minerals, and fiber. The liquids are commonly put through an evaporation process to produce syrup. This syrup is added back to the DG to produce DGS or distillers grains with solubles. The DGS may then be dried further to a dry matter content of 90% to become the

 

**Table 2.** Basic values for calculations of energy intensity and global warming potential.

| 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 | – | – | 0.00,193 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 2004, 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 (Global Emission Model for Integrated Systems) (2006) |
| Diesel fuel use | 45.6 MJ $L^{-1}$ | Staffell 2011 | 3.57 kg $CO_{2\text{-eq}}$ $L^{-1}$ | GEMIS (Global Emission Model for Integrated Systems) (2006) |
| Nitrogen fertilizer | 35.3 MJ $kg^{-1}$ | Appl 1997 | 1.46 kg $CO_{2\text{-eq}}$ $kg^{-1}$ | GEMIS (Global Emission Model for Integrated Systems) (2006) |
| Phosphate fertilizer | 36.2 MJ $kg^{-1}$ | Kaltschmitt and Reinhardt 1997 | 0.39 kg $CO_{2\text{-eq}}$ $kg^{-1}$ | GEMIS (Global Emission Model for Integrated Systems) (2006) |
| Potassium fertilizer | 11.2 MJ $kg^{-1}$ | Hülsbergen 2003 | 0.533 kg $CO_{2\text{-eq}}$ $kg^{-1}$ | GEMIS (Global Emission Model for Integrated Systems) (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 (Global Emission Model for Integrated Systems) (2006) |
| Pesticides production | 196 MJ $L^{-1}$ | Hülsbergen 2003 | 24.5 kg $CO_{2\text{-eq}}$ $L^{-1}$ | GEMIS (Global Emission Model for Integrated Systems) (2006) |
| Sewage effluent | 4 kWh[1] | 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 | |

[1]Required to process 1 kg biological oxygen demand (BOD), 20 kg BOD/1000 L ethanol produced (Kuby et al. 1984).

DDGS. An alternative to drying the WS is to use it in an anaerobic biodigester to produce biogas which can be burned for process heat and power. This heat and power is then used in the ethanol production process to reduce fossil EIP. Furthermore, this use of the WS avoids the energy intense drying of the DG for the animal feed entirely. Additionally, the postdigestion solids from the biodigestion become available for use as fertilizer in the field for corn production and this supports the reduction of artificial fertilizer inputs to the agricultural process.

## Scenario 1: Ethanol production with DDGS as coproduct

Considering the DDGS as coproduct of the ethanol production process leads to the question how the multifunctionality should be solved to reach a comparable and fair evaluation of the environmental impact of the ethanol. Therefore, different solutions are discussed in the following which are developed according the guidance on LCA allocation decisions given in ISO 14041 (1998) and ISO 14044 (2006).

The mentioned ISO guidelines achieve as first goal that an allocation between different products of a process should be avoided if possible. Including the use of DG as a valuable animal feed does not achieve this goal. When the DG is used as animal feed, it crosses the ethanol production system boundary. It is at this point that system expansion (SE), SD, or allocation by physical or economic relationships must be applied to capture the value or apportion the environmental burdens of the DG coproduct. The EI and GWP of ethanol production are discussed using six different methodological solutions for solving the multifunctionality which avoid allocation (Variant 1–3) and three methods of using allocation (Variant 4–6).

### *Variant 1. Without allocation (WA)*

Ethanol receives the whole environmental burden of its production process, regardless of a defined value of the coproduct DDGS. The allocation is avoided by disregarding the allotment of environmental burdens to the coproduct DDGS.

### *Variant 2. Avoiding allocation by using subdivision (SD)*

Partial SD is the first option to avoid the need for allocation in a multifunctional process like ethanol production, and should be done if it is not possible to split the black box process entirely. The SD methodology in ethanol production refers to the collection of data individually for the monofunctional process of DDGS drying. Here, the actual required process of drying is cut free from the ethanol production process which solves the multifunctionality problem.

### *Variant 3. Avoiding allocation by including SE*

The SE is the state of art for assigning credit for coproduced distillers' grains (DGs) (Plevin 2010). The quantity of other feed products displaced by the DGs has to be determined and the environmental burdens associated with these displaced products have to be subtracted from the ethanol life cycle. This involves the expansion of the system boundary to include the substitution of animal feed with DDGS. In this example, the substituted animal feed is corn grain. Substitution entails subtracting the inventory of another separate system from the analyzed system (Fig. 2). Therefore, the environmental impacts of corn grain production are displaced on a mass basis with DDGS.

It is assumed that the DDGS replaces corn grain feed in dairy cattle diets. The use of DDGS as cattle feed is assumed because DDGS has been shown to have better nutritional performance in cattle diets than in other livestock diets (Firkins et al. 1985; Ham et al. 1994; and Al-Suwaiegh et al. 2002). The dairy diet is considered because dairy cows make up the majority of the cattle kept in Wisconsin (USDA 2005).

Table 3 gives an overview of the nutritional value of the DDGS as feed. Each feed in a dairy diet has a specific conversion efficiency for the production of body mass in growing the animals and a specific conversion efficiency for milk production. The concept of net energy lactation (NEL) is used by dairy nutritionist to account for the specific quality of the feed. Changes in the dairy diet are required to substitute DDGS for corn grain feed. In this study the first-order effects of displacing corn grain were considered.

It is assumed that the production of corn grain for animal feed employs the same cultivation practices and site conditions as the corn grain produced for ethanol production. EIP and GHG emissions avoided using DDGS instead of corn grain in the dairy diet were calculated

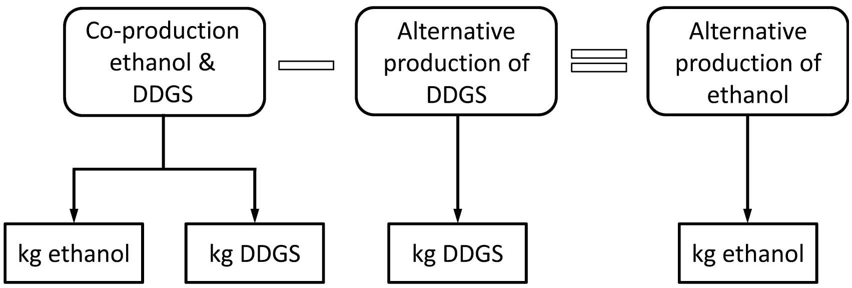


**Figure 2.** Solving the multifunctionality problem by substitution of the use of the coproduct dried distillers grains with solubles (DDGS) in animal feeding.

**Table 3.** Nutritional value of DDGS and corn grain as dairy cattle feed (Kirchgeßner 2004).

| | Unit | DDGS | Corn grain | Comparison corn grain to DDGS (%) |
|---|---|---|---|---|
| DM (dry matter) | g/kg | 900 | 880 | 97.78 |
| XP (crude protein) | g/kg DM | 297 | 100 | 33.67 |
| XL (crude lipids) | g/kg DM | 82 | 40 | 48.78 |
| XF (crude fiber) | g/kg DM | 104 | 59 | 56.73 |
| nXP (convertible crude protein) | g/kg DM | 242 | 161 | 66.53 |
| RNB (ruminant nitrogen balance) | g/kg DM | 9 | −9 | −100.00 |
| ME (metabolic energy) | MJ/kg DM | 12.68 | 13.29 | 104.81 |
| NEL (net energy lactation) | MJ/kg DM | 7.75 | 8.4 | 108.39 |
| VQ (organic mass) | % | 79 | 87 | 110.13 |
| NfE (nitrogen free extractive) | g/kg DM | 466 | 784 | 168.24 |
| Starch | g/kg DM | 92 | 613 | 666.30 |
| Sugar | g/kg DM | 16 | 0 | 100.00 |

assuming that 1.1 kg of DDGS substitutes 1 kg of corn grain based on the NEL of the feed (Table 3). Other literature sources suggest different substitution ratios, but these ratios are based on the entire balanced dairy diet (Kaiser 2008), which is not considered here. The 1.1 to 1 ratio considered in this study results in a substitution of an EI of 1.77 MJ per kg DDGS and of a GWP of 0.14 kg $CO_{2\text{-eq}}$ per kg DDGS.

#### *Variant 4. Mass allocation (AMASS)*

The mass allocation ratio of the refinery products ethanol and DDGS is based on the outgoing mass of the process. Mass inputs in this process are 3.3 kg corn grain and 3.4 L water for the production of 1 kg ethanol, 1.03 kg DDGS, and 1 kg $CO_2$. The mass allocation ratio of the environmental burdens on the ethanol and DDGS is therefore 49%:51%.

#### *Variant 5. Energy allocation (AENER)*

The allocation based on the energy outputs of the ethanol process relates to the heating values of the products. The HHV of ethanol is 29.6 MJ $kg^{-1}$ (Patzek, 2004) and the LHV for DDGS is 20.4 MJ $kg^{-1}$ (Morey et al. 2009). The LHV of DDGS was used because no information about its HHV was available. These values result in an energy allocation ratio of 57%:43% for ethanol and DDGS.

#### *Variant 6. Economic allocation (AECON)*

In life cycle studies, the multifunctionality of production processes is often solved using an economic allocation. The economic allocation is recommended if no better relationship between the production process and the produced products can be explained separately or if no detailed data about the process are available.

The economic allocation is based on the market value of ethanol and its coproduct DDGS (USDA 2011) with a ratio of 64%:36%. The prices are set with 290$ $ton^{-1}$ DDGS and 2.6 $ $gal^{-1}$ ethanol according to USDA (2012). The market value of the DDGS, however, is strongly affected by its fat and protein content. Belyea et al. (2004) describe a higher sale price of $5–$20 per ton for DDGS with a high fat (12.6%) and high protein (33.3%) content compared to DDGS with lower fat (10.9%) and lower protein (28.0%) content and this would affect the result.

### Scenario 2. Ethanol production with integrated biogas production (BG)

The use of the WS as biomass for bioenergy generation is explored by including a biodigester in the system boundary of the ethanol plant (Fig. 1). In order to use the generated energy of the coproduct biogas at the ethanol plant, it is necessary to transform the biogas into electricity and/or heat. Therefore, a CHP plant is included in the calculations as well. Basic data for the biodigester and CHP plant are shown in Table 4. According to Gleixner (2004), the ethanol plant can produce about 90% of its required energy using the WS for energy generation. The heat produced by the CHP plant can be used as steam in the ethanol refinery.

This analysis is based on 1,771,778 Mg of WS produced on average in Wisconsin ethanol plants per year. This amount of WS was calculated from the data presented in a Wisconsin ethanol plant survey done by Sinistore and Bland (2010). This gives an average production of 3.68 kg WS $kg^{-1}$ corn processed. The WS from alcohol production has a total solids (TS) content of 30–120 g $l^{-1}$ (Braun 1982). For this study a TS content of 11% is defined according to Gleixner (2004).

Biogas production ranges from 17 to 30 $m^3$ $m^{-3}$ WS with a methane content of 55–75% (Braun 1982), depending on the feedstock and process control. In this study, an average biogas methane content of 60% is used and it is assumed that the WS is the only feed in the biodigester. We also assumed that 26.25% of the thin stillage is sent back to the ethanol fermentation tank according to Kwiatkowski et al. (2006), which is in agreement with Alkan-Ozkaynak (2011).

We assumed that the biogas will be used in a CHP plant with 38% electrical conversion efficiency and thermal efficiency of 48%, or a total energy conversion efficiency of 86% (FNR 2005).

The biodigester and CHP plant both require electricity as an input. According to FNR (2005), 10–40% of the produced energy from the CHP plant is used for its own processes. Therefore, an average of 25% of the energy generated from the biogas is subtracted from the energy production of the system and the calculations in Scenario

**Table 4.** Basic values for ethanol and biogas production.

| Material properties | Unit | | Reference |
|---|---|---|---|
| Density biogas | $kg/m^3$ | 1.2 | FNR (2006) |
| 1 $m^3$ biogas | $kWh_{el}$ | 1.5–3 | FNR (2006) |
| 1 $m^3$ methane | kWh | 9.97 | FNR (2006) |
| Mass of whole stillage used in biodigester | % | 74 | Mei et al. (2005) |
| Dry matter content WS | % | 11 | Gleixner (2004) |
| Organic dry matter substance | % | 89.5 | Gleixner (2004) |
| Quality of biogas | % $CH_4$ | 60 | According to Braun (1982) |
| Efficiency of CHP $\eta$electr. | % | 38 | FNR (2005) |
| Efficiency of CHP $\eta$therm. | % | 48 | FNR (2005) |

2 do not include credits for the substitution of energy from fossil fuels.

## Results

### EI and GWP of ethanol production and coproduction of the animal feed DDGS – Scenario 1

The EI of Wisconsin corn grain ethanol production is 25.1 MJ $kg^{-1}$ ethanol calculated according to Scenario 1 WA. The main contributor to the EI of the industrial process at the ethanol plant is the electricity with 30% (Table 5). The supply of corn grain and its transportation to the ethanol plant makes up 23% of the EI of ethanol production. The addition of gasoline to ethanol contributes 12% to the EI of the ethanol production process. The drying of the WS to DDGS accounts for one quarter of the EI of ethanol production if natural gas is used for the drying.

The GWP is 2.35 kg $CO_{2\text{-eq}}$ $kg^{-1}$ ethanol. More than half of the total GWP can be attributed to electricity generation. Corn production comprises the second largest share of the GWP of ethanol production (Table 5).

### Influence of the multifunctionality solution on corn grain ethanol environmental impact assessment

The multifunctionality solution methods for the ethanol production process that we investigated progress along the hierarchal chain identified in the international LCA standard methodology (ISO 14041 1998). The various nonallocation solutions to the multifunctionality problem influence all of the environmental impact results with differing intensity. The allocation solutions, AENER and AECON, however, produce the same trends for GWP and EI and give a majority of the GWP to the ethanol while AMASS gives it to the DDGS (Table 6). The NEV ranges from 4.54 to 17.28 MJ $kg^{-1}$ ethanol, nearly a fourfold difference. In contrast, the GWP varies from 1.16 to 2.35 kg $CO_{2\text{-eq}}$ $kg^{-1}$ ethanol or a 50% difference across solutions.

**Table 5.** Scenario 1 WA: Contributions to the EI and GWP of corn grain ethanol production from individual processes for 1 kg ethanol including the production of the coproduct DDGS.

| Input | Energy intensity MJ $kg^{-1}$ ethanol | Global warming potential kg $CO_{2\text{-eq}}$ $kg^{-1}$ ethanol |
|---|---|---|
| Electricity | 7.6 | 1.57 |
| Natural gas | 1.9 | 0.02 |
| Sewage effluent | 0.3 | 0.08 |
| Chemicals enzymes and additives | 0.2 | – |
| Building | 0.2 | – |
| Gasoline | 3.0 | 0.03 |
| Farming of corn grain | 5.1 | 0.55 |
| Corn grain transport | 0.7 | 0.05 |
| Drying DDGS | 6.1 | 0.05 |
| Sum | 25.1 | 2.35 |

### Scenario 2 – EI and GWP of ethanol production using WS as biodigester feedstock

The integration of a biodigester and CHP plant results in an EI of 11.6 MJ $kg^{-1}$ ethanol and a GWP of 0.78 kg $CO_{2\text{-eq}}$ $kg^{-1}$ ethanol and the nutrients from the digester effluent also have considerable value (Table 7).

Nearly 50% of the EIP stems from corn production and corn transportation to the ethanol plant (Table 8). 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 Scenario 2 is dominated by the emissions from corn grain.

## Discussion

This study includes the same basic procedures for ethanol processing in both scenarios. Our investigation shows that the coproduct use has a strong influence on the environmental impacts of ethanol production. It also shows that altering the WS processing leads to different results for the environmental impact of ethanol production.

In Scenario 2 the WS is recycled completely within the system. Therefore, the only product which leaves the system cycle is the ethanol. The recycling of the WS into electricity, heat, and fertilizer results in a 39% lower EI and a 66% lower GWP than the ethanol production in Scenario 1 in which the SD method is used. The EI and GWP, of 54 and 67%, respectively, become even more beneficial to the integrated system if the multifunctionality is completely neglected in Scenario 1 variant WA.

In order to compare different ethanol production procedures and other procedures for renewable energy production, it is necessary to define an equivalent method for solving the multifunctionality problem within the process. Based on our study, we recommend the SD method because it leads to an ethanol production analysis which is not burdened with environmental impacts caused by the processing of coproducts which are not recycled within the production process itself. On the other hand, the ethanol production will also not benefit from eventual environmental impact reductions from the coproduct use.

 

**Table 6.** Scenario 1. Energy Intensity and Global Warming Potential of ethanol production with the coproduct DDGS accounted for by different multifunctionality solutions.

| | Ethanol | | DDGS | | Net energy value |
|---|---|---|---|---|---|
| Multifunctionality solution | Energy Intensity (MJ $kg^{-1}$ Ethanol) | GWP kg $CO_{2\text{-eq}}$ $kg^{-1}$ Ethanol (g $CO_{2\text{-eq}}$ $MJ^{-1}$ ethanol) | Energy intensity (MJ $kg^{-1}$ Ethanol) | GWP (kg $CO_{2\text{-eq}}$ $kg^{-1}$ Ethanol) | MJ $MJ^{-1}$ ethanol |
| WA – neglecting coproducts | 25.06 | 2.35 (79) | – | – | 0.85 |
| SD – subdivision | 18.94 | 2.30 (78) | 6.12 | 0.05 | 0.64 |
| SE – system expansion | 23.24[1] | 2.18[2] (74) | – | – | 0.79 |
| AMASS – mass allocation | 12.32 | 1.16 (40) | 12.74 | 1.19 | 0.42 |
| AENER – energy allocation | 14.83[3] | 1.39[3] (47) | 10.22[4] | 0.96[4] | 0.50 |
| AECON – economic allocation[5] | 15.96 | 1.50 (51) | 9.01 | 0.85 | 0.54 |

[1]Including displacement credit 1.77 MJ $kg^{-1}$ ethanol.
[2]Including displacement credit 0.14 kg $CO_{2\text{-eq}}$ $kg^{-1}$ ethanol.
[3]Higher heating value 29.6 MJ $kg^{-1}$ ethanol.
[4]Lower heating value 20.4 MJ $kg^{-1}$ DDGS (Morey et al. 2009).
[5]Prices from Wisconsin August 2012 (USDA 2012).

**Table 7.** Power and heat produced by use of WS for biogas production.

| Item | Unit | Amount produced by biodigester and combined heat and power plant | Amount available for ethanol production process |
|---|---|---|---|
| Whole stillage | t $year^{-1}$ | 1,766,343 | |
| Production period | days $year^{-1}$ | 350 | |
| Biogas | m³ $year^{-1}$ | 57,499,000 | |
| Primary energy in biogas | $kWh_{prim}$ $year^{-1}$ | 3,43,959,016 | |
| Electricity[1] | $kWh_{elec}$ $year^{-1}$ | 1,30,704,426 | 98,028,320 |
| Heat[2] | $kWh_{therm}$ $year^{-1}$ | 1,65,100,328 | 99,060,197 |
| Fertilizer[3] | | | |
| N | kg dry matter $year^{-1}$ | | 1,669,798 |
| $P_2O_5$ | kg dry matter $year^{-1}$ | | 1,233,841 |
| $K_2O$ | kg dry matter $year^{-1}$ | | 1,028,201 |

[1]total 25% of the produced electricity is subtracted as the amount of electricity used to operate the biodigester and the CHP plant according to FNR 2005.
[2]It is assumed that 60% of the producible heat will be used in the ethanol production process.
[3]total1.6 kg fertilizer $kg^{-1}$ ethanol produced (Kube 2008).

These benefits, however, would be inextricably linked to an increasing number of assumptions in the LCA, which can decrease the confidence in the results. Two major benefits of the SD method are that a clear division between the DDGS coproduct processing and the ethanol production is made and the data for WS processing into DDGS are readily available. The clear division between the ethanol process and the DDGS process makes it easier to evaluate different steps of ethanol production and identify areas for improvement. Breaking the coproduct production out of the ethanol production LCA also allows the more direct comparison of the environmental impacts of ethanol production from many feedstocks.

**Table 8.** Scenario 2: EI and GWP of the production of 1 kg ethanol by integrating of biogas production into the ethanol production process.

| Input | Energy intensity MJ $kg^{-1}$ ethanol | Global warming potential kg $CO_{2\text{-eq}}$ $kg^{-1}$ ethanol |
|---|---|---|
| Electricity | 0.3 | 0.07 |
| Natural gas | 2.6 | 0.02 |
| Sewage effluent | 0.3 | 0.08 |
| Chemicals enzymes and additives | 0.2 | – |
| Building | 0.2 | – |
| Gasoline | 3.0 | 0.03 |
| Farming of corn grain | 4.4 | 0.53 |
| Corn grain transport | 0.7 | 0.05 |
| Sum | 11.6 | 0.78 |

In the literature, SE is the most recommended method of solving the multifunctionality of ethanol production (Wang 2001; Graboski 2002; Kim and Dale 2005; Farrell et al. 2006; Kaufman et al. 2010). We find problems with this recommendation because the use of SE in the corn ethanol analysis increases the number of assumptions included in the coproduct DDGS credit assessment. The SE method does not allow the environmental impacts of various ethanol production systems to be compared easily. For example, a SE of DDGS as animal feed from corn grain ethanol is not comparable to a SE for lignocellulosic ethanol production with lignin coproducts such as carbon fibers because the uses of animal feed and carbon fibers differ greatly. Careful considerations of system boundary compatibility between various ethanol production methods must be made when SE is used to solve the multifunctionality problem. These considerations are obviated when the SD method is used.

The calculations in Scenario 1 show that the three allocation variants (mass, energy content, and economic value of the products) result in the lowest EI and GWP from ethanol production (Table 6). The three allocation variants are based on static allocation ratios. The use of static allocation ratios produces mirror image results in the EI and GWP measures; whereas, the other multifunctionality solutions give more disparate results for the same measures. Static methods do not reflect the dynamic differences between the different environmental impacts EI and GHG emissions encountered under real conditions.

Economic allocation is widely practiced in LCA studies because it does not require an understanding of the physical processes involved with ethanol production and economic data are readily available. Of the allocation strategies, however, economic allocation is recognized as the least accurate and desirable (ISO 14041 1998) Dramatic fluctuations and unpredictability in the price of inputs to the corn grain and ethanol production systems and the economic value of coproducts make economic allocation undesirable.

On average, our results show a positive NEV for Wisconsin corn grain ethanol production. Also, the average GWP of this ethanol production is higher than that of gasoline production and use. Exceptions to this finding occur in Scenario 1 variants AMASS and in Scenario 2 BG. No credits have been given to the ethanol for the avoided use of gasoline. The U.S. Energy Information Administration stated that the U.S. consumption of liquid fuels will continue to grow through the year 2035. The total U.S. consumption of liquid fuels will rise from about 18.8 million barrels per day in 2009 to 21.9 million barrels per day in 2035 (EIA 2011). Therefore, ethanol will not displace the use of gasoline, but rather it will supply more transportation fuel to the growing US demand for fuel. In the long term it is to recommend to further improve the efficient resource use in biofuel production but especially to enforce the reduction of fuel use.

## Conclusions

It is to conclude that only minor energy gain is reached within the life cycle of ethanol production from corn grain in Wisconsin. A positive NEV for Wisconsin corn grain ethanol production is calculated. The average GWP of this ethanol production is higher than that of gasoline production and use.

The method chosen for solving the multifunctionality problem in an LCA has a strong influence on the environmental assessment of the process. This is abundantly evident in the case of corn grain ethanol production. We recommend avoiding allocation of environmental burdens to coproducts by applying the SD solution to the corn grain ethanol production process for several reasons.

First, it draws a clear system boundary of analysis around the primary product, which in this case is ethanol. Additionally, if all biomass fuel LCAs used the SD method to deal with coproducts, then all biomass fuel LCAs would be more directly comparable. This is not the case when SE or allocation methods are used in the LCA of many different types of biomass fuels because of the wide range of coproducts and their uses outside of the system boundaries. Furthermore, the SD method reduces the overall number of assumptions in the LCA calculations as compared to the SE method. Finally, when compared to the allocation method, the SD method shows dynamic differences between the EI and GWP results. Given all of these reasons, we aver that the SD method gives the most equitable and representative results for the various environmental impacts of biofuel production.

The use of the SD method to deal with the coproduct WS illustrates all of the aforementioned benefits of the method. We were able to compare the environmental impacts of two different ethanol production scenarios with different uses of the WS because we used the SD method.

We showed that the most environmentally beneficial use of the WS coproduct is to biodigest it to produce methane and burn that methane in a CHP plant to displace natural gas and electricity use in the refinery. These benefits are enhanced when the biodigester residue is used as fertilizer to displace conventional fertilizer in corn production. This scenario (Scenario 2) resulted in a significantly lower EI and GWP than Scenario 1 which used SD. While we agree with previous studies which found that the most environmentally preferable treatment of the WS was to avoid drying it to produce DDGS, to improve the sustainability of ethanol production, we recommend avoiding DG production entirely and recycling the WS into the ethanol production process.

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## Conflict of Interest

None declared.

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