LCA Case Studies

Allocation Procedure in Ethanol Production System from Corn Grain

I. System Expansion

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Abstract. We investigated the system expansion approach to net energy analysis for ethanol production from domestic corn grain. Production systems included in this study are ethanol production from corn dry milling and corn wet milling, corn grain production (the agricultural system), soybean products from soybean milling (i.e. soybean oil and soybean meal) and urea production to determine the net energy associated with ethanol derived from corn grain. These five product systems are mutually interdependent. That is, all these systems generate products which compete with or displace all other comparable products in the market place. The displacement ratios between products compare the equivalence of their marketplace functions. The net energy, including transportation to consumers, is 0.56 MJ_{net}/MJ of ethanol from corn grain regardless of the ethanol production technology employed. Using ethanol as a liquid transportation fuel could reduce domestic use of fossil fuels, particularly petroleum. Sensitivity analyses show that the choice of allocation procedures has the greatest impact on fuel ethanol net energy. Process energy associated with wet milling, dry milling and the corn agricultural process also significantly influences the net energy due to the wide ranges of available process energy values. The system expansion approach can completely eliminate allocation procedures in the foreground system of ethanol production from corn grain.

Keywords: Allocation; corn; ethanol; life cycle assessment; net energy; sensitivity analysis; system expansion

Introduction

The allocation procedure in a multi-input/output process is one of the most critical issues in life cycle assessment. The coproduct allocation procedure allows one to partition the environmental burdens associated with a multi-output process to its product and coproducts.

According to ISO 14041 [1], 'the allocation should be avoided by dividing the unit process to be allocated into two or more subprocesses or expanding the product system to include the additional functions related to coproducts.' Furthermore, ISO 14041 also states, 'where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way which reflects the underlying physical relationships or other relationships between them." The sub-division approach and the system expansion approach are preferable to other procedures. We describe here a system expansion approach, not fully attempted previously, to estimate environmental burdens in producing fuel ethanol from corn grain (corn ethanol).

Various allocation approaches for multi–input/output process have been reported [2–6]. Azapagic and Clift [2] have done the allocation in a multi-input/output process by marginal changes, which reflect the partial derivatives at the point of operation. Frischknecht [3] proposed an allocation approach with a combination of economic and environmental evaluation of multi-input/out process. Huppes [4] divided a process into a separated sub-process, a combined sub-process, and a fully joint sub-process by using a cost allocation approach. Kim and Overcash [5] estimated the environmental burdens associated with ammonia in an ammonia plant using the sub-division procedure in order to minimize the allocation, but did not completely avoid allocation procedures. Weidema [6] demonstrated how the system expansion approach was performed.

This study investigates the allocation procedure, especially the system expansion approach, in the corn ethanol production system. Ethanol from crops is widely used in oxygenated fuels in the United States. Corn is the major feedstock for producing fuel ethanol in the United States. Other potential plant feedstocks for ethanol are corn stover, alfalfa, switchgrass or other cellulosic biomass crops.

There are two primary methods used for producing corn ethanol: dry milling and wet milling. The dry milling process produces ethanol and distillers' dried grains and solubles (DDGS), which is a high quality livestock feed. DDGS contains protein, fats and carbohydrates. In the wet milling process, ethanol, corn oil, corn gluten meal (CGM) and corn gluten feed (CGF) are produced. Corn gluten meal and corn gluten feed are used as animal feed as well. Consequently, these two corn refining approaches are multi-output processes, and a proper allocation approach is necessary to determine the environmental burdens associated with the product and coproducts.

Wang [7] estimated energy consumption and air emissions associated with ethanol derived from corn grain. Shapouri et. al. [8] calculated the net energy balance for ethanol produced

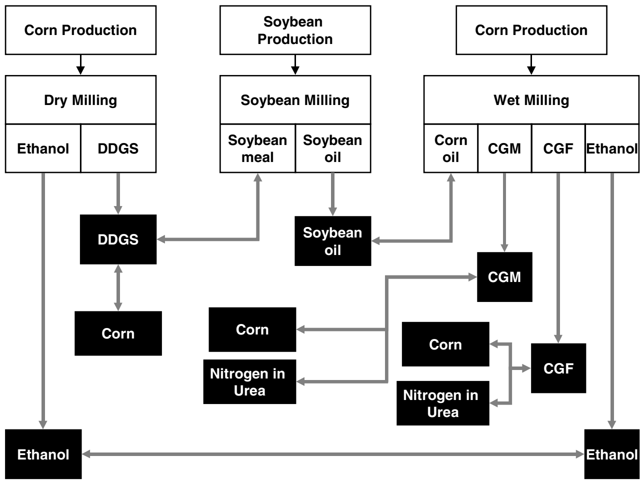

Fig. 1: System boundary in ethanol production from corn grain

from corn grain and applied various allocation approaches. Both studies used the system expansion approach, called a replacement method (or a displacement method) to minimize the allocation procedure. However, they failed to avoid the allocation procedures completely in the foreground system.

The systems under consideration in this study include the ethanol production system from dry milling and wet milling, the agricultural corn production system, the soybean products system from soybean milling (i.e. soybean oil and soybean meal) and the urea production system for animal feed. It is assumed that these five product systems are mutually dependent. In other words, one product system influences other product systems in the market (**Fig. 1**). The black boxes indicate the equivalent product systems.

1 System Expansion Approach in the Ethanol Production System from Corn Grain

The underlying assumption in the system expansion approach is that product systems with an equivalent function have the same environmental burdens [9]. Hence, the environmental burdens associated with ethanol from dry milling are assumed to be equivalent to those associated with ethanol from wet milling. The system expansion approach starts with the dry milling process. Environmental burdens associated with dry milling can be expressed by Equation (1).

$$E_{\text{corn dry mill}} = a^{d}_{\text{ethanol}} \cdot E_{\text{ethanol}} + a_{\text{DDGS}} \cdot E_{\text{DDGS}} \tag{1}$$

where

$E_{\text{corn dry mill}}$: Environmental burdens associated with the dry milling process

E_{ethanol}: Environmental burdens associated with producing one kg of ethanol

E_{DDGS}: Environmental burdens associated with producing one kg of DDGS

a^{d}_{ethanol} : Amount of ethanol produced in dry milling

a_{DDGS} : Amount of DDGS produced in dry milling

Since DDGS is a coproduct in the dry milling process, a product system equivalent to the function of DDGS is required to estimate the environmental burdens of ethanol production. Wang [7] indicated that DDGS could replace both soybean meal from the soybean milling process and corn in the market, but the quantity of alternative product replaced is not equal to the quantity of DDGS used. Therefore, a correlation factor for each alternative product system is required to make the function of DDGS equivalent to the function of soybean meal or corn. The correlation factor is referred to as displacement ratio. Wang [7] also estimated the displacement ratios for coproducts in dry milling and wet milling. The displacement ratio indicates that one kg (bone-dry) of DDGS could replace 0.823 kg (bone-dry) of soybean meal and 1.077 kg (bone-dry) of corn in the market (Equation 2). (Note that the displacement ratio weights are based on bone-dry compositions, i.e., containing no moisture.)

$$E_{\text{DDGS}} = b_{\text{DDGS/soybean meal}} \cdot E_{\text{soybean meal}} + b_{\text{DDGS/corn}} \cdot E_{\text{corn}} \tag{2}$$

where

$E_{\text{soybean meal}}$: Environmental burdens associated with producing one kg of soybean meal

E_{corn}: Environmental burdens associated with producing one kg of corn grain

$b_{\text{DDGS/soybean meal}}$: Displacement ratio between DDGS and soybean meal (Value is in mass of DDGS per mass of soybean meal, which is equal to 0.823 [7])

$b_{\text{DDGS/corn}}$: Displacement ratio between DDGS and corn (Value is in mass of DDGS per mass of corn, which is 1.077 [7])

Soybean meal is a coproduct of the soybean milling process. The environmental burdens associated with the soybean milling process, $E_{\text{soybean milling}}$, become

$$E_{\text{soybean milling}} = a_{\text{soybean oil}} \cdot E_{\text{soybean oil}} + a_{\text{soybean meal}} \cdot E_{\text{soybean meal}} \tag{3}$$

where

$E_{\text{soybean oil}}$: Environmental burdens associated with producing one kg of soybean oil

$a_{\text{soybean oil}}$: Amount of soybean oil produced in the soybean milling process

$a_{\text{soybean meal}}$: Amount of soybean meal produced in the soybean milling process

To complete the system expansion approach for the dry milling process, a product system whose function is equivalent to the function of soybean oil is required as well. Corn oil is assumed to replace soybean oil in the market with the same quantity [7] (Equation 4).

$$E_{\text{soybean oil}} = b_{\text{soybean oil/corn oil}} \cdot E_{\text{corn oil}} \tag{4}$$

where

$E_{\text{corn oil}}$: Environmental burdens associated with producing one kg of corn oil

$b_{\text{soybean oil/corn oil}}$: Displacement ratio between corn oil and soybean oil(Value is in mass of soybean oil per mass of corn oil, which is equal to one [7])

Corn oil is a coproduct in the wet milling process, in which ethanol, corn gluten meal and corn gluten feed are produced as well. Estimating the environmental burdens associated with corn oil requires the environmental burdens of the wet milling process, which are expressed as Equation (5).

$$E_{\text{corn wet mill}} = a^{w}_{\text{ethanol}} \cdot E_{\text{ethanol}} + a_{\text{corn oil}} \cdot E_{\text{corn oil}} + a_{CGM} \cdot E_{CGM} + a_{CGF} \cdot E_{CGF} \quad (5)$$

where

$E_{\text{corn wet milling}}$: Environmental burdens associated with the wet milling process
E_{CGM}: Environmental burdens associated with producing one kg of corn gluten meal
E_{CGF}: Environmental burdens associated with producing one kg of corn gluten feed
a^{w}_{ethanol} : Amount of ethanol produced by wet milling
$a_{\text{corn oil}}$: Amount of corn oil produced by wet milling
a_{CGM}: Amount of corn gluten meal produced by wet milling
a_{CGF}: Amount of corn gluten feed produced by wet milling

It is assumed that corn gluten meal could replace both corn and nitrogen in urea in the market, and corn gluten feed could replace corn and nitrogen in urea, which is used for animal feed as well [7] (Equation 6,7).

$$E_{CGM} = b_{CGM/\text{corn}} \cdot E_{\text{corn}} + b_{CGM/\text{N in urea}} \cdot E_{\text{urea}} \quad (6)$$

$$E_{CGF} = b_{CGF/\text{corn}} \cdot E_{\text{corn}} + b_{CGF/\text{N in urea}} \cdot E_{\text{urea}} \quad (7)$$

E_{urea}: Environmental burdens associated with urea production
$b_{CGM/\text{corn}}$: Displacement ratio between CGM and corn (Value is in mass of CGM per mass of corn, which equals 1.529 [7])
$b_{CGM/\text{N in urea}}$: Displacement ratio between CGM and nitrogen in urea (Value is in mass of CGM per mass of nitrogen in urea, which equals 0.023 [7])
$b_{CGF/\text{corn}}$: Displacement ratio between CGF and corn (Value is in mass of CGF per mass of corn, which equals 1.0 [7])
$b_{CGF/\text{N in urea}}$: Displacement ratio between CGF and nitrogen in urea (Value is in mass of CGF per mass of nitrogen in urea, which equals 0.015 [7])

Overall there are nine linear equations derived from the system boundary presented in Fig. 1, including the environmental burdens associated with producing corn grain and with producing urea.

2 Results

The net energy is cumulative energy, defined as energy consumed in the fuel life cycle including the heat content of fuel so that the energy quality is implicitly taken into account. For instance, one MJ of electricity might be different from one MJ from coal or another fossil fuel in terms of the energy used because electricity requires more energy to generate than it delivers at the end use. For example, the net energy for electricity in the United States is 2.1 MJ_{net}/MJ of electricity [10]. This value indicates that 2.1 MJ of energy is required to generate one MJ of electricity. Therefore, the net energy is cradle-to-use energy, which is typically shown in life cycle inventories.

Kim and Dale [10] estimated the net energy for producing corn grain and soybean, which included transportation of these crops to a 'biorefinery', a crop processing facility. Wang [7] estimated the process energy for dry milling, wet milling and soybean milling as well as the energy consumed by producing corn grain and soybean. Shapouri et. al. [8] also reported the net energy for producing ethanol from dry milling and wet milling. Sheehan et. al. [11] collected inventory data for a biodiesel system, which included the soybean milling process. The net energy (based on the low heat value) for each process used in this study is shown in **Table 1**. There are two values for producing corn grain and soybean in the first column of Table 1. In case A, the net energy for the nitrogen fertilizer used to grow crops is estimated assuming that carbon dioxide in the ammonia plant is a coproduct [12], and that the coproduct allocation is done by the subdivision approach [5]. For case B the carbon dioxide in the ammonia plant is treated as an emission. The values in black-shaded cells in Table 1 are used in the base scenario, and others are used in the sensitivity analysis. The net energy values for producing corn grain and soybeans presented in Table 1 are based on the dry weight of the crop. The net energy values for the dry milling process, the wet milling process and the transportation of ethanol are based on one kg of ethanol, and the values for the soybean milling process are also based on one kg of soybean oil. The net energy value for urea production is based on one kg of urea and includes the upstream processes.

The ethanol yield in the base scenario is assumed to be 0.307 kg ethanol/kg corn grain for the dry milling process, which is

Table 1: Net energy for each process (based on low heat content)

Net energy [MJ_{net}/kg]	Kim [10]		Wang [7]		Shapouri [8]	Sheehan [11]
	Case A	Case B				
Corn grain	1.78E+00	2.34E+00	2.50E+00		2.42 E+00	
Soybean	1.79E+00	1.84E+00	3.04E+00			3.04E+00
			Future	Current		
Dry milling			1.37E+01	1.63E+01	1.62E+01	
Wet milling			1.23E+01	1.46E+01	1.99E+01	
Soybean milling			1.80E+01			1.94E+01
Urea production	2.04E+01					
Transportation of ethanol			7.06E–01			

Table 2: Product and coproducts [7]

[kg]	Dry milling	Wet milling	Soybean milling
Ethanol	1.00	1.00	
DDGS	0.92		
Corn oil		0.13	
Corn gluten meal		0.16	
Corn gluten feed		0.68	
Soybean oil			1.00
Soybean meal			3.81

equal to 2.6 gallon/bushel (1 bushel of corn grain = 25.4 kg of corn grain), 0.295 kg of ethanol/kg of corn grain for the wet milling process, and the yield of soybean oil is 0.175 kg of soybean oil/kg of soybean [7]. **Table 2** shows the quantity of product and coproducts in the dry milling, the wet milling and the soybean milling processes. (Weights in Table 2 all on a bone-dry basis.) It is assumed that corn grain contains 15% moisture. The unallocated cradle-to-gate net energy is 19.5 MJ_{net} in the dry milling process, 18.4 MJ_{net} in the wet milling process, and 28.1 MJ_{net} in the soybean milling process for the product and coproduct amounts shown in Table 2.

Solving the linear equations with the base scenario, the net energy for producing ethanol from corn grain becomes 14.3 MJ_{net}/kg, or 73% of the total net energy for the dry milling process. The net energy for DDGS is 5.6 MJ_{net}/kg. The net energy associated with ethanol in the wet milling process is 78% of the total net energy. The net energy associated with corn oil is 12.5 MJ_{net}/kg of corn oil, which is equal to that for soybean oil because corn oil is assumed to replace soybean oil by the exact equivalent amount in the market. The net energy associated with corn gluten feed represents 10 percent of the total net energy associated with the wet milling process. The net energy for corn gluten meal is 4.2 MJ_{net}/kg. Fifty six percent of the net energy associated with the soybean milling process is assigned to soybean meal. The net energy associated with all products is shown in **Fig. 2**.

With the data in Table 1, the best-case scenario and the worst-case scenario with respect to corn-derived ethanol can be estimated. The best-case scenario occurs with the lowest energy use data in the net energy for processes related to ethanol production systems and the highest energy use data for processes related to soybean products. The worst-case scenario is the reverse. The net energy associated with producing ethanol varies between 13.6 MJ_{net}/kg in the best-case scenario and 20.8 MJ_{net}/kg in the worst-case scenario. It is also important to determine the sensitivity of net energy toward each parameter. Sensitivity analysis indicates which parameters most affect net energy in the ethanol production system. The parameters affecting the final results are as follows:

- Net energy for producing corn grain
- Net energy for dry milling
- Net energy for wet milling
- Net energy for producing soybean
- Net energy for soybean milling
- Yield of ethanol
- Displacement ratios
- Different allocation procedures

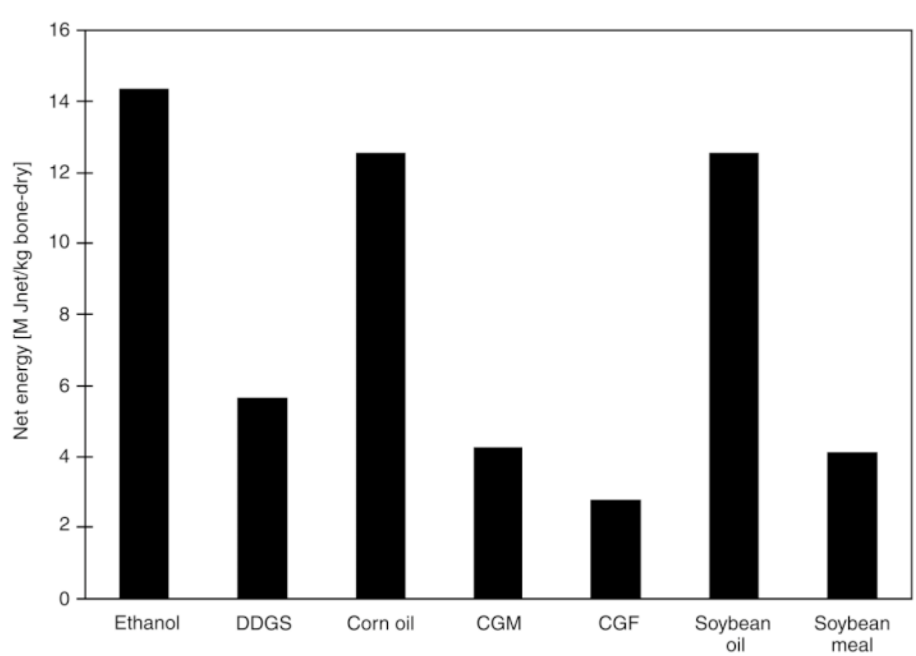

Fig. 2: Net energy associated with all products

The last parameter is directly related to the methodology. Increasing the net energy associated with producing corn grain, the dry milling process and the wet milling process increases the net energy for ethanol. This is illustrated in **Fig. 3**, where corn production and soybean production represent the agricultural production processes. With the exception of methodological parameters, the process energy for the wet milling process has the greatest impact on the net energy associated with ethanol production for the data given in Table 1. The worst-case data for the wet milling process increase the net energy for ethanol by 28.6 percent of the base value. The worst-case process net energy data for the dry milling process also increase the net energy for ethanol by 7.0 percent. The worst-case net energy associated with the agricultural process for producing corn grain increases the net energy for ethanol by 11.2%.

It is interesting that higher energy values related to processes in the soybean system such as producing soybean and the soybean milling process decrease the net energy for the ethanol. This is because the soybean product system is an alternative product system for DDGS and corn oil. Increasing the net energy for soybean product processes gives rise to partitioning the environmental burdens associated with dry milling or wet milling more to DDGS and corn oil, respectively. The sensitivity analysis shows that the processes associated with soybean system are less sensitive than the other processes – corn grain production, dry milling and wet milling – to changes in the net energy associated with ethanol production.

This sensitivity analysis determines the relative priority of improvement options as well. Slopes in Fig. 3 indicate the relative priorities; a steep slope shows that a small change in process energy leads to a large ethanol net energy change. For instance, a 10 percent reduction in the process net energy in the wet milling process lowers the net energy for ethanol by 5.3 %, and a 10 percent reduction in the process net energy in the dry milling process leads to 3.7% decrease in the net energy for ethanol. In contrast to wet milling or dry milling, a 10 % increase in the ethanol yield reduces ethanol net energy by 3.8%. The slopes show that wet milling process energy, dry milling process energy and yield of ethanol should be the first focus areas for overall environmental improvement. Note that the soybean product systems have a negative effect. For example, a 10% reduction of the process net energy in the soybean milling process increases the net energy for ethanol by 1%. However, it is clear that worsening the environmental performance of the soybean product systems is not a realistic improvement option.

Table 3 illustrates the effect of the displacement ratios on the ethanol net energy. Since there are no statistical data available for the displacement ratios, each displacement ratio is increased or decreased arbitrarily assuming each displacement ratio is independent. The displacement ratio between corn gluten meal and nitrogen in urea has less impact than other displacement ratios because the displacement ratio between corn gluten meal and nitrogen in urea is relatively small, and the corn gluten meal contribution to the total net energy associated with dry milling process is also small. The most important displacement ratio affecting the net energy for ethanol occurs in the DDGS-soybean meal, the corn oil-soybean oil, the CGF-corn and the DDGS-corn displacements. However, the effect of the displacement ratio on the net energy for ethanol is smaller than the effect of other parameters, specifically the wet milling process energy, the dry milling process energy and the agricultural energy for corn production. Increasing the displacement ratio reduces the net energy associated with ethanol. In other words, more

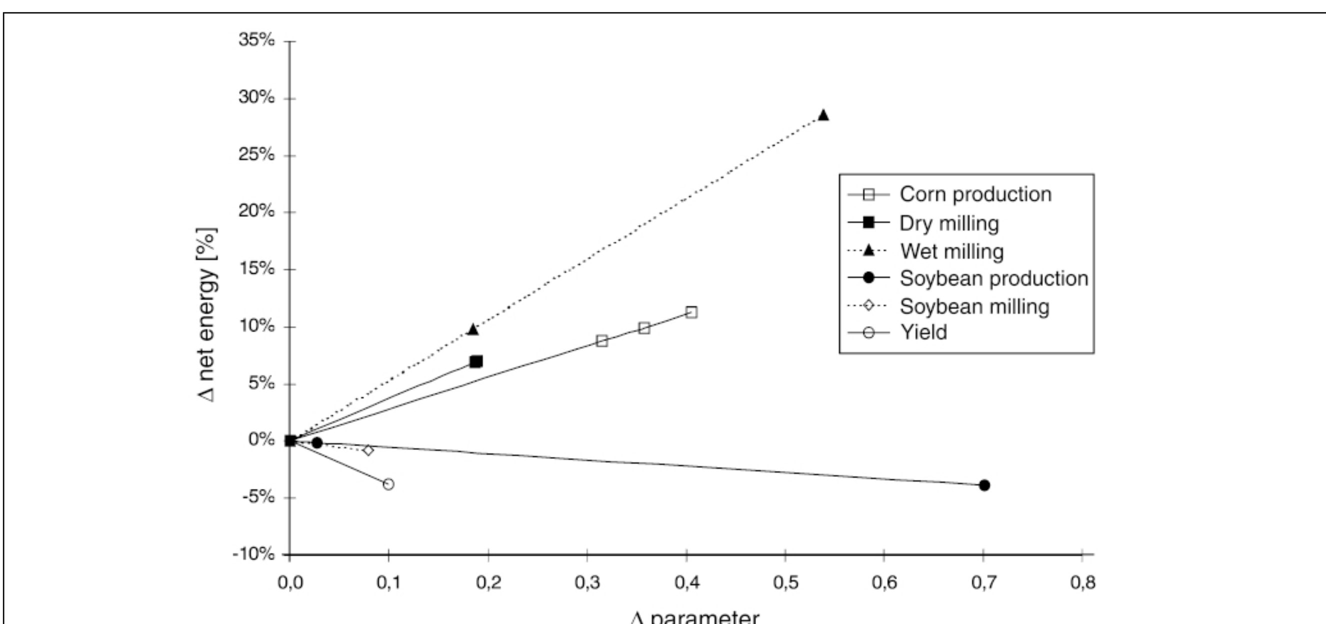

Fig. 3: Sensitivity of net energy to contributing parameters for ethanol production

$$\Delta_{\text{net energy}} = \frac{\text{Net energy} - \text{Net energy}_{\text{basescenario}}}{\text{Net energy}_{\text{basescenario}}},\ \Delta_{\text{parameter}} = \frac{\text{Parameter} - \text{Parameter}_{\text{basescenario}}}{\text{Parameter}_{\text{basescenario}}}$$

Table 3: Effect of the displacement ratio on the net energy for ethanol

Displacement Ratio	Displacement system						
	DDGS: soybean meal	DDGS:corn	soybean oil:corn oil	CGM:corn	CGF:corn	CGM:N in urea	CGF:N in urea
	Net energy change [(Net energy – Net energy$_{base\ scenario}$)/Net energy$_{base\ scenario}$]						
0.5·b*	6.1%	2.8%	4.2%	1.1%	3.1%	0.3%	1.0%
0.6·b	4.5%	2.3%	3.2%	0.9%	2.4%	0.3%	0.8%
0.7·b	3.1%	1.7%	2.3%	0.6%	1.8%	0.2%	0.6%
0.8·b	1.9%	1.1%	1.5%	0.4%	1.2%	0.1%	0.4%
0.9·b	0.9%	0.6%	0.7%	0.2%	0.6%	0.1%	0.2%
1.0·b	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1.1·b	–0.8%	–0.6%	–0.6%	–0.2%	–0.6%	–0.1%	–0.2%
1.2·b	–1.5%	–1.1%	–1.3%	–0.4%	–1.2%	–0.1%	–0.4%
1.3·b	–2.1%	–1.7%	–1.8%	–0.6%	–1.8%	–0.2%	–0.6%
1.4·b	–2.7%	–2.3%	–2.3%	–0.9%	–2.4%	–0.3%	–0.8%
1.5·b	–3.2%	–2.8%	–2.8%	–1.1%	–3.1%	–0.3%	–1.0%

* b: Displacement ratio

alternative products are replaced by a coproduct so that the environmental credit associated with the coproduct increases.

The effect of different allocation approaches on the ethanol net energy is illustrated in **Fig. 4**. Wang [7] and Shapouri et. al. [8] presented allocation factors for ethanol in the dry milling and the wet milling systems for various allocation approaches: market value, energy content of outputs, mass, sub-division and system expansion. Results in Fig. 4 are estimated as the net energy for producing ethanol using their allocation factors for each allocation method.

The allocation by market value, using 10-year average market values of ethanol and its coproducts, results in a 76-percent of the total net energy allocated to ethanol in the dry milling system and a 70-percent in the wet milling case [8]. In the allocation based on energy content, which uses the energy contents of ethanol and its coproducts, the dry milling system gets a 39-percent coproduct net energy credit, and wet milling has a 43-percent coproduct credit. The disadvantage of this method is that the calories of coproducts, a measurement of food nutritional value, are not a good measurement of energy in a fuel context [8]. The output mass allocation results in about 49 percent (48 percent) of the net energy used in the dry milling (wet milling) system assigned to ethanol.

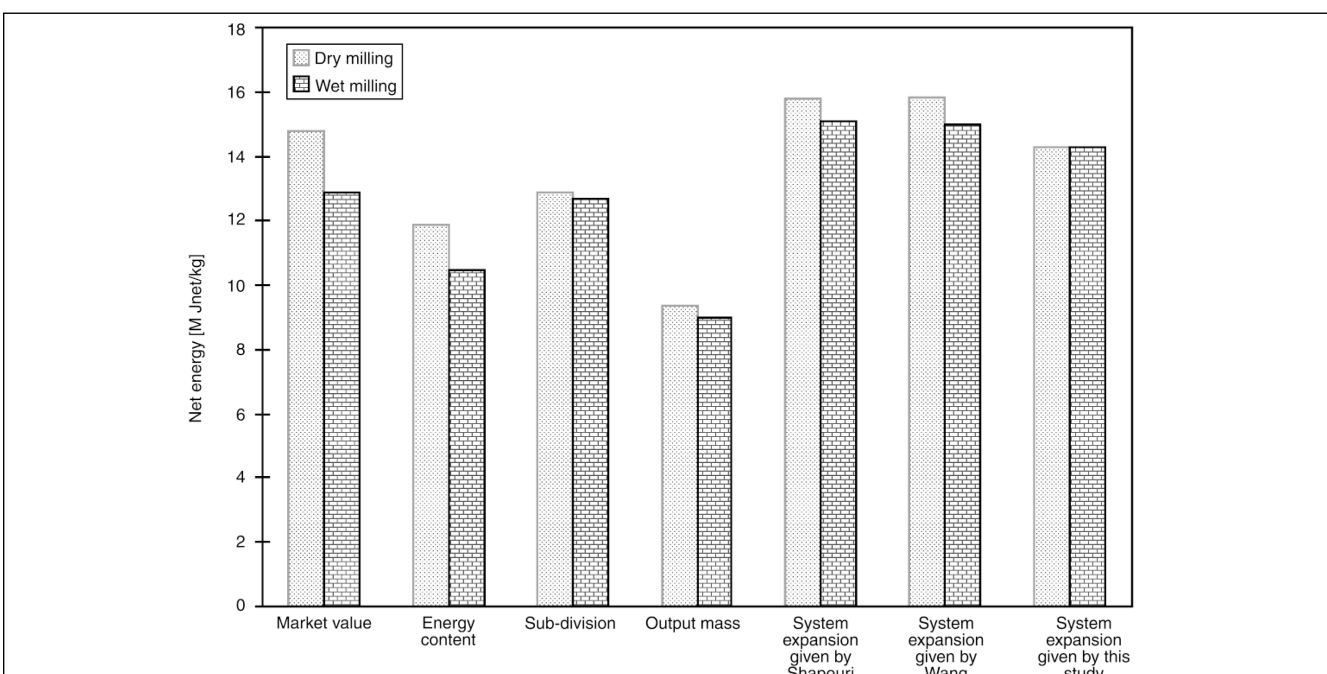

Fig. 4: Effect of the choice of allocation procedures on the net energy for ethanol in the base scenario

Wang [7] and Shapouri et. al. [8] also calculated the environmental burdens associated with ethanol using the system expansion approach. The system boundaries used in their studies are dry milling, corn production, and soybean milling for the ethanol production system in the dry milling and wet milling, corn production, urea production, and soybean milling for the ethanol production system in the wet milling system. About 80 percent of the net energy used in both dry milling and wet milling is allocated to ethanol. However, their methodologies under the system expansion method fail to avoid the allocation procedures completely in the foreground system. Their allocations in the alternative product systems were done by economic value and physical properties.

The net energy value allocated to ethanol by output mass is lowest, and the net energy value associated with ethanol done by the system expansion is highest. The choice of allocation approach influences the final results more significantly than other any parameter investigated. Therefore, the allocation procedure is a critical part of determining the environmental burdens associated with ethanol production from corn grain.

3 Conclusions

Although this study focused only on the net energy, the system expansion approach might be easily applied to other environmental burdens. The system expansion approach can completely avoid the allocation procedure in the foreground system of ethanol production from corn grain. The primary existing production processes for fuel ethanol are corn dry milling and wet milling. The dry milling process produces ethanol and DDGS that is equivalent to corn and soybean meal. The wet milling process produces ethanol, corn oil, corn gluten meal and corn gluten feed. Corn oil replaces soybean oil in the market. Corn and nitrogen in urea are displaced by corn gluten meal and corn gluten feed. The alternative product systems are the corn production system, the urea production system and the soybean milling system, in which soybean oil and soybean meal are produced. Therefore, five product systems are required to determine ethanol environmental burdens in the system expansion approach, and to completely avoid the allocation procedures in the foreground system.

The system expansion approach is equivalent to assuming that the environmental burdens associated with ethanol from dry milling are equal to those associated with ethanol from wet milling. The allocation procedures required by this approach are eliminated in the foreground system due to this assumption. This approach could be used to compare the environmental burdens associated with ethanol to those associated with petroleum-based fuel (e.g. gasoline) as well. However, this approach would not work for an LCA study in which the goal of a study is to compare the environmental burdens between different ethanol production technologies. A possible system expansion approach, that could meet the goal of such an LCA study, would be to allocate the environmental burdens to either soybean meal or soybean oil in the soybean milling system based on physical properties or economic values even though the allocation procedures would not be phased out.

Sensitivity analyses show that the allocation approach chosen influences the final results more than any other parameter investigated. The difference in the net ethanol energy varies by up to 37% between the various allocation approaches. Except for their sensitivity to the allocation approach, the final results are most sensitive to 1) the process energy for the wet milling process, 2) the dry milling process energy and 3) the corn production energy. Hence, it is recommended that more accurate data in these three areas be developed. Improvements in the wet milling and the dry milling processes could also significantly reduce the environmental burdens associated with the ethanol production system.

The net energy associated with ethanol in the system expansion approach is 0.56 MJ_{net}/MJ of ethanol in the base scenario, including ethanol transportation to consumers. Therefore, the available energy from ethanol is much higher than the input energy for producing ethanol. In other words, using ethanol as a liquid transportation fuel would significantly reduce domestic use of petroleum even in the worst-case scenario.

References

[1] ISO 14041 (1998): Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis

[2] Azapagic A, Clift R (1998): Linear Programming as a Tool in Life Cycle Assessment. Int J LCA 3 (6) 305–316

[3] Frischknecht R (1998): Life Cycle Inventory Analysis for Decision-Making. Ph.D. thesis, Swiss Federal Institute of Technology, Switzerland

[4] Huppes G (1994): A General Method for Allocation in LCA. Proceedings of Allocation in LCA. SETAC-Europe, p74

[5] Kim S, Overcash M (2000): Allocation Procedure in Multi-Output Process – An Illustration of ISO 14041. Int J LCA 5 (4) 221–228

[6] Weidema B (2001): Avoiding Co-Product Allocation in Life-Cycle Assessment. Journal of Industrial Ecology 4 (3) 11–33

[7] Wang M (2000): Greet 1.5 – Transportation Fuel-Cycle Model. Argonne National Laboratory, Illinois, USA (http://greet.anl.gov/publications.html)

[8] Shapouri H, Duffield JA, Graboski MS (1995): Estimating the Net energy Balance of Corn Ethanol. Agricultural Economic Report 721, US Department of Agriculture. Washington, DC, USA

[9] Tillman A, Ekvall T, Baumann H, Rydberg T (1994): Choice of System Boundaries in Life Cycle Assessment. Journal of Cleaner Production 2 (1) 21–29

[10] Kim S, Dale BE (2001): Net Energy and Global Warming Impact Associated with Producing Biomass for Biobased Industrial Products. Submitted to Journal of Industrial Ecology

[11] Sheehan J, Camobreco V, Duffield J, Graboski M, Shapouri H (1998): Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus. NREL/SR-580-24089, National Renewable Energy Laboratory, Colorado, USA

[12] McKetta JJ, Cunningham WA (1976): Encyclopedia of Chemical Processing and Design, Vol 6, Marcel Dekker, Inc., New York, USA

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