Supporting Information

Assessing Resource Intensity and Renewability of Cellulosic Ethanol Technologies using Eco-LCA

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The supporting information is organized as follows. Section S1 provides raw data and assumptions based on which economic inputs required for producing 3.79E+06 liters (1E+06 gallons) of cellulosic ethanol for each feedstock were calculated. The input tables provided in Section 2 contains 1997 costs for each input purchased from the economy. These costs were entered into Eco-LCA software (http://resilience.osu.edu/ecolca/) to calculate resource consumption. Section 2 contains direct inputs from nature for crop farming (corn stover, yellow poplar and switchgrass). Results for corn ethanol which are used as reference in this study were derived from raw input data published in an Ecological Modelling paper by Baral et al. (2010). The resource consumption data were combined with any direct inputs from nature, such as sunlight for crop farming, to obtain the total life cycle resource consumption of individual ecosystem goods and services. This constitutes a hybrid approach. For the detailed description of the hybrid Eco-LCA approach, please refer to Baral and Bakshi, 2010. The life cycle resource consumption was aggregated using energy, ICEC, and ECEC to calculate various metrics such as return on energy investment and renewability. Section 3 deals with energy credit calculations and allocation methods. Section 4 provides theoretical estimates of cellulosic ethanol production from various feedstocks. Section 5 provides conversion units to calculate resource consumption in various units (mass, exergy, ECEC, energy). Section 6 provides energy contents and transformities of data used in this study. A list of resources considered in Eco-LCA and classification are included Section 7. Some of the results of the study are provided in Section 8 in the form of data and charts.

Section S1: Background data and assumptions

Table S1. Farm inputs for corn stover and switchgrass

Input	Corn stover	Unit	Switchgrass	Unit
Nitrogen (N)	7.50E+00	kg/ MT biomass	7.50E+00	kg/ MT biomass
Posphorous (P)	3.00E+00	kg/ MT biomass	2.10E+00	kg/ MT biomass
Potash (K)	1.25E+01	kg/ MT biomass	8.60E+00	kg/ MT biomass
Herbicide			4.15E+00	kg/ MT biomass
Seeds			8.30E+00	kg/ ha
Diesel (tractor)	2.54E+00	MJ/L ethanol	3.11E+00	MJ/L ethanol
Diesel for biomass transport (truck)	5.00E-01	MJ/L ethanol	5.20E-01	MJ/L ethanol

Note: For corn stover-2 scenario, seed used was not allocated to corn stover. Biomass refers to dry biomass.

Source: Spatari et al., 2005

Table S2. Farm input data for yellow poplar (total for 23 years)

Inputs	Quantity	Unit	
Steel (Implement)	1.48E+02	kg/ ha	
Nitrogen fertilizer	1.00E+02	kg N/ha	as ammonium sulphate
Weed control	2.24E+00	kg AI/ha	simazine
Herbicide	3.36E+00	kg AI/ha	simazine and oxyflourfen
Herbicide	2.50E+00	kg AI/ha	glyophoshate
Diesel used	8.60E+03	MJ/ha	

Note: Assumed field operation data for yellow poplar to be the same as for willow cropping system, Heller et al. 2002.

Table S3. Steel used in yellow poplar farming

Tractor weight (kg / ha)	Operating time (hr./ha)	Unit	Allocated tractor weight (kg/ha)	Allocated implement weight (kg/ha)	Unit
7.66E+02	1.63E+01		1.04E+00	1.81E+00	kg/ha
Total steel used	2.85	kg/ha			

Source: Heller et al., 2002

Table S4. Steel and cement used for ethanol production from switchgrass

Inputs		Unit
Machinery for reseeding and establishment	1.90E+01	g/gal of ethanol based on yield of 619 gal per ha
Farm machinery	9.00E+00	g/gal of ethanol based on yield of 619 gal per ha
Truck for transport	1.00E+00	g/gal based on 9.9 tons/ha
Machinery (steel) for ethanol production	1.20E+00	g/gal
Steel building	2.13E+00	g/gal
Cement	3.00E+00	g/gal

Source: Felix et al., 2006

Table S5. Energy for transportation of chemicals

Chemicals	Total BTU/ ton
Ammonium nitrate	2.90E+05
Sulfuric acid	2.90E+05
For all other chemicals	2.90E+05
Biomass (woody and herbaceous)	1.42E+05

Source: Argonne National Laboratory, 2008 (GREET)

Table S6. Chemical composition of various feedstocks (% dry basis)

Yellow poplar[a]		Corn stover[b]		Newsprint[c]		Switchgrass[d]		MSW[e]	
Cellulose	42.67	Cellulose	37.4	Cellulose	63.77	Cellulose	40	Cellulose	63.77
Xylan	19.05	Hemicellulose	27.5	Xylan	5.26	Hemicellulose	22	Hemicellulose	11.44
Arabinan	0.79	*Xylan*	21.1	Arabinan	0.61	Lignin	17	Xylan	5.26
Mannan	3.93	*Arabinan*	2.9	Mannan	4.96			Arabinan	0.61
Galactan	0.24	*Mannan*	1.6	Galactan	0.61			Mannan	4.96
Acetate	4.64	*Galactan*	1.9	Acetate	0			Galacatan	0.61
Lignin	27.68	Lignin	18	Lignin	21.26			Lignin	21.26
Ash	1.00	Ash	5.2	Ash	3.54			Ash	3.54
		Acetate	2.9						
		Protein	3.1						
		Extractives	4.7						
		Other	1.1						

[a] Aden et al., 2002
[b] Wooley et al., 1999
[c] Kemppainen and Shonnard, 2005
[d] Spatari et al., 2005
[e] SRI consulting

Table S7. Moisture contents of feedstocks

Yellow poplar	47.90
Corn stover	15
Newsprint	5.0
Switchgrass	15

Table S8. Estimation of cellulosic ethanol yields

Feedstock	Cellulose conversion	Hemicellulose conversion	Total carbohydrate conversion	Yield (liters/dry MT)	Yield (gallons/ dry MT)
Corn stover	3.20E-01	2.10E-01	5.30E-01	3.40E+02	8.98E+01
Switchgrass	3.42E-01	1.68E-01	5.10E-01	3.27E+02	8.65E+01
Poplar	3.65E-01	1.84E-01	5.49E-01	3.52E+02	9.29E+01
Newsprint	5.45E-01	8.64E-02	6.32E-01	4.05E+02	1.07E+02
MSW	3.35E-01	6.50E-02	4.00E-01	2.57E+02	6.78E+01

Note: Yields of switchgrass, poplar, newsprint and MSW are calculated in reference to the yield of corn stover considering cellulose and hemicellulose contents. Also it was assumed that 90% of cellulose and hemicellulose are converted to sugars. Glucose sugar and pentose sugars conversion rates are 95% and 85% respectively.

Table S9. Feedstocks yield per hectare

Feedstock	Worst case	Best case	Unit	References	Average	Unit
Corn stover	8.00E+00	1.00E+01	wet MT per ha	Based on 2002-2006 corn yields per ha, USDA	7.65E+00	dry MT/ha
Poplar	1.00E+01	1.39E+01	dry MT per ha	Heller et al., 2002	1.31E+01	dry MT/ha
Switchgrass	3.81E+00	9.24E+00	dry MT per acre	Perlack et al., 2005	1.60E+01	dry MT/ha

Table S10. Total lignin from energy consumed in ethanol production

Feedstock	Amount of lignin used (kg)	Energy content (MJ/kg)	Total energy (J)
Switchgrass	1.97E+06	21.27	4.18E+13
Yellow poplar	2.98E+06	21.27	7.61E+13
Corn Stover	2.00E+06	21.27	5.12E+13
Newsprint	1.99E+06	21.27	4.23E+13
MSW	-	-	-

Note: For MSW, it was assumed that lignin is not used in ethanol production.

Section S2: Input data for Hybrid Eco-LCA

Table S 11. Inputs for cellulosic ethanol production from yellow poplar (3.79E+06 liters)

Inputs	Quantity	Unit	Sources	Cost/unit	Year	Costs	1997 costs
Yellow poplar farming							
Herbicide	2.90E+02	AI kg	Heller et al., 2003	1.05E+01	1997	3.04E+03	3.04E+03
Ammonium nitrate	2.35E+05	kg	Heller et al., 2003	2.50E-01	1997	5.88E+04	5.88E+04
Diesel for planting and harvesting	2.23E+03	gal	Heller et al., 2003	5.75E-01	1997	1.28E+03	1.28E+03
Diesel for biomass transport	2.49E+04	gal	GREET	5.75E-01	1997	1.43E+04	1.43E+04
Steel (farming machinery)	2.35E+03	kg	Heller et al., 2003	2.90E-01	1997	6.80E+02	6.80E+02
Steel (truck for transport)	1.29E+03	kg	Felix, 2006	2.90E-01	1997	3.74E+02	3.74E+02
Irrigation water (nursery)	4.25E+05	gal	Heller et al., 2003	1.00E-03	2000	4.25E+00	4.32E+02
Cellulosic ethanol production							
Cement	3.00E+03	kg	Felix, 2006	8.40E-02	2004	2.52E+02	2.17E+02
Steel (ethanol production)	1.20E+03	kg	Felix, 2006	2.90E-01	1997	3.48E+02	3.48E+02
Steel (building)	2.13E+03	kg	Felix, 2006	2.90E-01	1997	6.18E+02	6.18E+02
Sulfuric acid	3.66E+05	kg	Aden et al.,2002	2.73E-02	2001	9.98E+03	9.08E+03
Lime	2.67E+05	kg	Aden et al.,2002	7.66E-02	2001	2.04E+04	1.86E+04
Diammonium phosphate	2.18E+04	kg	Aden et al.,2002	1.55E-01	2001	3.38E+03	3.08E+03
Corn steep liquor	1.74E+05	kg	Aden et al.,2002	1.77E-01	1998	3.09E+04	3.02E+04
Clarifier polymer	3.74E+03	kg	Aden et al.,2002	2.75E+00	2000	1.03E+04	9.67E+03
Purchased cellulase	1.01E+06	kg	Aden et al.,2002	1.24E-01	2000	1.24E+05	1.17E+05
LPG	2.05E+03	gal	Aden et al.,2002	3.70E-01	1997	7.60E+02	7.60E+02
Make-up Water	6.59E+06	gal	Aden et al.,2002	1.00E-03	2000	6.59E+03	6.29E+03
Cooling water chemicals	6.71E+01	kg	Aden et al.,2002	2.24E+00	2000	1.50E+02	1.41E+02
BFW chemicals	3.53E+01	kg	Aden et al.,2002	2.97E+00	2000	1.05E+02	9.85E+01
WWT chemicals	1.19E+04	kg	Aden et al.,2002	3.47E-01	2000	4.12E+03	3.87E+03
Diesel for transport of chemicals	4.54E+03	gal		5.75E-01	1997	2.61E+03	2.61E+03
Pipeline transport (Diesel+LPG)	4.24E+04	gal		2.30E-02	2006	9.76E+02	7.81E+02
Ethanol Transport							
Diesel	8.73E+03	gal	GREET	5.75E-01	1997	5.02E+03	5.02E+03

Note: 1 gallon= 3.79 liters. 1997 prices represent producer prices.

Table S 12. Inputs for cellulosic ethanol production from corn stover (3.79E+06 liters) for scenario corn stover-1

Inputs	Quantity	Unit	Sources	Cost/unit	year	Costs	1997 costs
Corn stover farming							
Ammonium nitrate	2.81E+05	kg	Spatari et al., 2005	2.50E-01	1997	7.02E+04	7.02E+04
Trisuperphosphate	2.00E+05	kg	Spatari et al., 2005	2.83E-01	1997	5.66E+04	5.66E+04
KCl	3.27E+05	kg	Spatari et al., 2005	1.67E-01	1997	5.47E+04	5.47E+04
Diesel (tractor)	6.98E+04	gal	Spatari et al., 2005	5.75E-01	1997	4.02E+04	4.02E+04
Diesel (truck)	1.37E+04	gal	Spatari et al., 2005	5.75E-01	1997	7.90E+03	7.90E+03
Steel (truck for transport)	8.19E+02	kg	Felix, 2006	2.90E-01	1997	2.37E+02	2.37E+02
Nitrogen(NH4NO3)	9.77E+05	kg	Hill et al., 2006	2.50E-01	1997	2.44E+05	2.44E+05
Potash(KCl)	2.56E+05	kg	Hill et al., 2006	1.67E-01	1997	4.27E+04	4.27E+04
Trisuperphosphate	2.76E+05	kg	Hill et al., 2006	2.80E-01	1997	7.73E+04	7.73E+04
Lime(CaO)	6.03E+05	kg	NREL	6.09E-02	2000	3.67E+04	3.45E+04
Diesel	7.10E+04	gal	Liska et al., 2009	5.70E-01	1997	4.05E+04	4.05E+04
Gasoline	9.83E+03	gal	Liska et al., 2009	6.03E-01	1997	5.93E+03	5.93E+03
LPG(Propane)	2.70E+04	gal	Liska et al., 2009	3.70E-01	1997	9.98E+03	9.98E+03
Electricity	2.49E+06	kWh	Liska et al., 2009	4.53E-02	1997	1.13E+05	1.13E+05
Natural Gas(methane)	6.15E+07	SCF	Liska et al., 2009	3.59E-03	1997	2.21E+05	2.21E+05
Herbicide	5.22E+03	kg	Hill et al., 2006	1.05E+01	1997	5.48E+04	5.48E+04
Insecticide	1.87E+02	kg	Hill et al., 2006	1.38E+01	1997	2.58E+03	2.58E+03
Corn seeds	6.36E+04	kg	Estimated	3.27E+00	1997	2.08E+05	2.08E+05
Water (corn production)	1.70E+08	gal	NREL	1.00E-03	1997	1.70E+05	1.70E+05
Water (ethanol Production)	2.69E+07	gal	Wu et al., 2009	1.00E-03	1997	2.69E+04	2.69E+04
Cellulosic ethanol production							
Cement	3.00E+03	kg	Felix, 2006	8.40E-02	2004	2.52E+02	2.24E+02

Steel (ethanol production)	1.20E+03	kg	Felix, 2006	2.90E-01	1997	3.48E+02	3.48E+02
Steel (building)	2.13E+03	kg	Felix, 2006	2.90E-01	1997	6.18E+02	6.18E+02
Sulfuric Acid	4.39E+05	kg	Aden et al., 2002	2.73E-02	2001	1.20E+04	1.28E+04
Lime	3.20E+05	kg	Aden et al., 2002	7.66E-02	2001	2.45E+04	2.35E+04
Diammonium phosphate	2.18E+04	kg	Aden et al., 2002	1.55E-01	2001	3.38E+03	3.60E+03
Corn steep liquor	1.74E+05	kg	Aden et al., 2002	1.77E-01	1998	3.09E+04	3.18E+04
Clarifier polymer	3.74E+03	kg	Aden et al., 2002	2.75E+00	2000	1.03E+04	1.05E+04
Purchased cellulase	9.12E+05	kg	Aden et al., 2002	1.24E-01	2000	1.13E+05	9.60E+04
LPG	1.30E+03	gal	Aden et al., 2002	3.70E-01	1997	4.82E+02	4.82E+02
Make-up Water	6.59E+06	gal	Aden et al., 2002	1.00E-03	2000	6.59E+03	6.29E+03
Cooling water chemicals	6.71E+01	kg	Aden et al., 2002	2.24E+00	2000	1.50E+02	1.40E+02
BFW chemicals	3.53E+01	kg	Aden et al., 2002	2.97E+00	2000	1.05E+02	9.76E+01
WWT chemicals	1.19E+04	kg	Aden et al., 2002	3.47E-01	2000	4.12E+03	3.84E+03
Diesel for transport of chemicals	4.62E+03	gal		5.75E-01	1997	2.66E+03	2.66E+03
Pipeline transport (Diesel+LPG)	9.82E+04	gal		2.30E-02	2006	2.26E+03	1.92E+03
Ethanol Transport							
Diesel	8.73E+03	gal	GREET	5.75E-01	1997	5.02E+03	5.02E+03

Note: 1 gallon= 3.79 liters

Table S 13. Inputs for cellulosic ethanol production from corn stover (3.79E+06 liters) for scenario corn stover-2

Inputs	Quantity	Unit	Sources	Cost/unit	Year	Costs	1997 costs
Corn stover farming							
Ammonium nitrate	2.81E+05	kg	Spatari et al., 2005	2.50E-01	1997	7.02E+04	7.02E+04
Trisuperphosphate	2.00E+05	kg	Spatari et al., 2005	2.83E-01	1997	5.66E+04	5.66E+04
Potassium chloride (KCl)	3.27E+05	kg	Spatari et al., 2005	1.67E-01	1997	5.47E+04	5.47E+04
Diesel (tractor)	6.98E+04	gal	Spatari et al., 2005	5.75E-01	1997	4.02E+04	4.02E+04
Diesel (truck)	1.37E+04	gal	Spatari et al., 2005	5.75E-01	1997	7.90E+03	7.90E+03
Steel (truck for transport)	8.19E+02	kg	Felix, 2006	2.90E-01	1997	2.37E+02	2.37E+02
Cellulosic ethanol production							
Cement	3.00E+03	kg	Felix, 2006	8.40E-02	2004	2.52E+02	2.24E+02
Steel (ethanol production)	1.20E+03	kg	Felix, 2006	2.90E-01	1997	3.48E+02	3.48E+02
Steel (building)	2.13E+03	kg	Felix, 2006	2.90E-01	1997	6.18E+02	6.18E+02
Sulfuric acid	4.39E+05	kg	Aden et al., 2002	2.73E-02	2001	1.20E+04	1.28E+04
Lime	3.20E+05	kg	Aden et al., 2002	7.66E-02	2001	2.45E+04	2.35E+04
Diammonium phosphate	2.18E+04	kg	Aden et al., 2002	1.55E-01	2001	3.38E+03	3.60E+03
Corn steep liquor	1.74E+05	kg	Aden et al., 2002	1.77E-01	1998	3.09E+04	3.18E+04
Clarifier polymer	3.74E+03	kg	Aden et al., 2002	2.75E+00	2000	1.03E+04	1.05E+04
Purchased cellulase	9.12E+05	kg	Aden et al., 2002	1.24E-01	2000	1.13E+05	9.60E+04
LPG	1.30E+03	gal	Aden et al., 2002	3.70E-01	1997	4.82E+02	4.82E+02
Make-up water	6.59E+06	gal	Aden et al., 2002	1.00E-03	2000	6.59E+03	6.29E+03
Cooling water chemicals	6.71E+01	kg	Aden et al., 2002	2.24E+00	2000	1.50E+02	1.40E+02
BFW chemicals	3.53E+01	kg	Aden et al., 2002	2.97E+00	2000	1.05E+02	9.76E+01
WWT chemicals	1.19E+04	kg	Aden et al., 2002	3.47E-01	2000	4.12E+03	3.84E+03
Diesel for transport of chemicals	4.62E+03	gal		5.75E-01	1997	2.66E+03	2.66E+03
Pipeline transport (Diesel+LPG)	9.82E+04	gal		2.30E-02	2006	2.26E+03	1.92E+03
Ethanol Transport							
Diesel	8.73E+03	gal	GREET	5.75E-01	1997	5.02E+03	5.02E+03

Note: 1 gallon= 3.79 liters

Table S14. Inputs for cellulosic ethanol production from switchgrass (3.79E+06 liters)

Inputs	Quantity	Unit	Sources	Cost/unit	Year	Costs	1997 costs
Switchgrass production							
Ammonium nitrate	2.92E+05	kg	Spatari et al., 2005	2.50E-01	1997	7.29E+04	7.29E+04
Trisuperphosphate	1.45E+05	kg	Spatari et al., 2005	2.83E-01	1997	4.12E+04	4.12E+04
Potassium chloride	2.35E+05	kg	Spatari et al., 2005	1.67E-01	1997	3.92E+04	3.92E+04
Herbicide	2.99E+03	kg	Spatari et al., 2005	1.05E+01	1997	3.14E+04	3.14E+04
Seeds	5.44E+02	kg	Spatari et al., 2005	8.80E+00	2001	4.79E+03	4.36E+03
Diesel (tractor)	8.55E+04	gal	Spatari et al., 2005	5.75E-01	1997	4.92E+04	4.92E+04
Diesel (truck)	1.43E+04	gal	Spatari et al., 2005	5.75E-01	1997	8.22E+03	8.22E+03
Steel (farming machinery)	1.25E+04	kg	Felix, 2006	2.90E-01	1997	3.63E+03	3.63E+03
Steel (truck for feedstock transport)	8.50E+02	kg	Felix, 2006	2.90E-01	1997	2.47E+02	2.47E+02
Cellulosic ethanol production							
Cement	3.00E+03	kg	Felix, 2006	8.40E-02	2004	2.52E+02	2.24E+02
Steel (ethanol production)	1.20E+03	kg	Felix, 2006	2.90E-01	1997	3.48E+02	3.48E+02
Steel (building)	2.13E+03	kg	Felix, 2006	2.90E-01	1997	6.18E+02	6.18E+02
Sulfuric acid	3.65E+05	kg	Aden et al., 2002	2.73E-02	2001	9.95E+03	1.06E+04
Lime	2.66E+05	kg	Aden et al., 2002	7.66E-02	2001	2.03E+04	1.95E+04
Diammonium phosphate	2.18E+04	kg	Aden et al., 2002	1.55E-01	2001	3.38E+03	3.60E+03
Corn steep liquor	1.74E+05	kg	Aden et al., 2002	1.77E-01	1998	3.09E+04	3.18E+04
Clarifier polymer	3.74E+03	kg	Aden et al., 2002	2.75E+00	2000	1.03E+04	1.05E+04
Purchased cellulase	1.01E+06	kg	Aden et al., 2002	1.24E-01	2000	1.25E+05	1.07E+05
LPG	1.26E+03	gal	Aden et al., 2002	3.70E-01	1997	4.66E+02	4.66E+02
Make-up Water	6.59E+06	gal	Aden et al., 2002	1.00E-03	2000	6.59E+03	6.29E+03
Cooling water chemicals	6.71E+01	kg	Aden et al., 2002	2.24E+00	2000	1.50E+02	1.40E+02
BFW chemicals	3.53E+01	kg	Aden et al., 2002	2.97E+00	2000	1.05E+02	9.76E+01
WWT chemicals	1.19E+04	kg	Aden et al., 2002	3.47E-01	2000	4.12E+03	3.84E+03
Diesel for transport of chemicals	4.55E+03	gal		5.75E-01	1997	2.62E+03	2.62E+03
Pipeline transportation	1.14E+05	gal		2.30E-02	2006	2.63E+03	2.24E+03
Ethanol transport							
Diesel	8.73E+03	gal	GREET	5.75E-01	1997	5.02E+03	5.02E+03

Table S 15. Inputs for cellulosic ethanol production from newsprint (3.79E+06 liters)

Inputs	Quantity	Unit	Sources	Price per unit	year	costs	1997 costs
Diesel (newsprint transport)	1.19E+04	gal	GREET	5.75E-01	**1997**	6.82E+03	6.82E+03
Steel (truck for newsprint transport)	6.15E+02	kg	Felix, 2006	2.90E-01	1997	1.78E+02	1.78E+02
Ammonia	7.15E+04	kg	Kemppainen and Shonnard, 2005	0.1925	1998	1.38E+04	1.40E+04
Ammonium sulfate	1.89E+04	kg	Kemppainen and Shonnard, 2005	0.0495	1998	9.38E+02	9.57E+02
Antifoam	3.99E+04	kg	Kemppainen and Shonnard, 2005	0.5478	1998	2.19E+04	2.25E+04
Calcium phosphate	1.89E+04	kg	Kemppainen and Shonnard, 2005	0.2728	1991	5.17E+03	5.32E+03
Gasoline	3.93E+04	gal	Kemppainen and Shonnard, 2005	6.04E-01	1997	2.37E+04	2.37E+04
Lime	6.39E+04	kg	Kemppainen and Shonnard, 2005	0.07656	2001	4.89E+03	4.69E+03
Purchased cellulase	1.30E+06	kg	Aden et al., 2002	0.12364	2000	1.61E+05	1.37E+05
Sulphuric acid	1.88E+05	kg	Kemppainen and Shonnard, 2005	0.02728	2001	5.14E+03	5.47E+03
Diesel for transport of chemicals	4.19E+03	gal	Kemppainen and Shonnard, 2005	5.75E-01	1997	2.41E+03	2.41E+03
Pipeline transport (Diesel+Gasoline)	6.41E+04	gal		0.023	2006	1.47E+03	1.25E+03
Makeup water	3.02E+06	gal	Wooley et al., 1999	0.001	2000	3.02E+03	2.89E+03
Cement	3.00E+03	kg	Felix, 2006	8.40E-02	2004	2.52E+02	2.24E+02
Steel (ethanol production)	1.20E+03	kg	Felix, 2006	2.90E-01	1997	3.48E+02	3.48E+02
Steel (building)	2.13E+03	kg	Felix, 2006	2.90E-01	1997	6.18E+02	6.18E+02
Ethanol transport							
Diesel	8.73E+03	gal	GREET	5.75E-01	1997	5.02E+03	5.02E+03

Note: 1 gallon= 3.79 liters

Table S 16. Inputs for cellulosic ethanol production from MSW (3.79E+06 liters)

Inputs	Quantity	Unit	Sources	Cost/unit	Year	Costs	1997 costs
Steel (truck transport)	1.04E+03	kg	Felix, 2006	2.90E-01	1997	3.00E+02	3.00E+02
Diesel (MSW collection and hauling)	2.01E+04	gal	Kalogo et al., 2007	5.75E-01	1997	1.16E+04	1.16E+04
Electricity (MSW classification)	1.16E+06	kWh	Kalogo et al., 2007	4.53E-02	1997	5.27E+04	5.27E+04
Electricity (pretreatment)	1.11E+05	kWh	Kalogo et al., 2007	4.53E-02	1997	5.05E+03	5.05E+03
Hydrolysis							
Input-H2SO4	3.10E+05	kg	Kalogo et al., 2007	2.73E-02	2001	8.46E+03	9.00E+03
Input-Ca(OH)2	5.15E+05	kg	Kalogo et al., 2007	6.96E-02	2001	3.58E+04	3.44E+04
Electricity	1.30E+05	kWh	Kalogo et al., 2007	4.53E-02	1997	5.89E+03	5.89E+03
Natural gas for steam	4.76E+06	SCF	Kalogo et al., 2007	3.59E-03	1997	1.71E+04	1.71E+04
Flash distillation for furfural removal							
Electricity	5.23E+02	kWh	Kalogo et al., 2007	4.53E-02	1997	2.37E+01	2.37E+01
Natural gas for steam	1.25E+06	SCF	Kalogo et al., 2007	3.59E-03	1997	4.48E+03	4.48E+03
Fermentation							
Electricity	2.08E+04	kWh	Kalogo et al., 2007	4.53E-02	1997	9.41E+02	9.41E+02
Distillation of ethanol						0.00E+00	0.00E+00
Electricity	1.28E+04	kWh	Kalogo et al., 2007	4.53E-02	1997	5.78E+02	5.78E+02
Natural gas for steam	4.22E+06	SCF	Kalogo et al., 2007	3.59E-03	1997	1.52E+04	1.52E+04
Miscellaneous							
Process water make-up	8.68E+05	gal	Kalogo et al., 2007	1.00E-03	2000	8.68E+02	8.29E+02
Electricity for CO2 compression	5.76E+04	kWh	Kalogo et al., 2007	4.53E-02	1997	2.61E+03	2.61E+03
Electricity for waste water treatment	6.34E+03	kWh	Kalogo et al., 2007	4.53E-02	1997	2.87E+02	2.87E+02
Natural gas for sludge drying	2.08E+05	SCF	Kalogo et al., 2007	3.59E-03	1997	7.45E+02	7.45E+02
Total electricity for plastic recovery	2.30E+05	kWh	Kalogo et al., 2007	4.53E-02	1997	1.04E+04	1.04E+04
Diesel for chemical transport	2.02E+03	gal		5.75E-01	1997	1.16E+03	1.16E+03
Pipeline transport	3.08E+04	gal		2.30E-02	2006	7.09E+02	6.03E+02
Cement	3.00E+03	kg	Felix, 2006	8.40E-02	2004	2.52E+02	2.24E+02
Steel (ethanol production)	1.20E+03	kg	Felix, 2006	2.90E-01	1997	3.48E+02	3.48E+02
Steel (building)	2.13E+03	kg	Felix, 2006	2.90E-01	1997	6.18E+02	6.18E+02
Ethanol transport							
Diesel	8.73E+03	gal	GREET	5.75E-01	1997	5.02E+03	5.02E+03

Note: 1 gallon= 3.79 liters

Table S 17. Inputs for gasoline production (3.67E+07 liters)

Inputs	Quantity	Units	Source	Cost	per unit	Year	Cost (Dollars)	1997 costs
Crude oil	2.25E+07	gal	EIA	4.91E-01	gal	1997	1.11E+07	1.11E+07
Liquefied petroleum gases	1.69E+04	gal	EIA	3.70E-01	gal	1997	6.27E+03	6.27E+03
Natural gas	6.60E+07	SCF	EIA	3.59E-03	SCF	1997	2.37E+05	2.37E+05
Residual fuel oil	8.95E+03	gal	EIA	4.00E-01	gal	1997	3.58E+03	3.58E+03
Still gas	9.67E+05	gal	EIA	2.89E-01	gal	2000	2.80E+05	2.08E+05
Petroleum coke	3.64E+05	gal	EIA	1.50E-01	gal	2005	5.47E+04	2.21E+04
Diesel	3.06E+03	gal	EIA	5.70E-01	gal	1997	1.75E+03	1.75E+03
Coal	2.91E+05	kg	EIA	2.60E-02	kg	2005	7.56E+03	6.23E+03
Electricity	3.53E+06	kWh	EIA	4.53E-02	kWh	1997	1.60E+05	3.23E+04
Water in refining	3.38E+07	gal	Wu et al., 2009	1.00E-03	gal	2000	3.38E+04	1.60E+05
Steel (refinery)	2.82E+04	kg		2.90E-01	kg	1997	8.19E+03	8.19E+03
Pipeline transportation (crude oil)	2.25E+07	gal		1.40E-02	gal	2006	3.16E+05	2.24E+05
Electricity (wastewater treatment)	2.08E+05	kWh	Sheehan et al., 1998	4.53E-02	kWh	1997	9.44E+03	9.44E+03
Rail transport (coal)	2.91E+05	kg		1.10E-02	kg	2000	3.20E+03	3.13E+03
Pipeline transportation (gasoline)	9.70E+06	gal		0.023	gal	2006	2.23E+05	1.78E+05

Note: 1 gallon= 3.79 liters

Table S18. Natural resource inputs in yellow poplar farming

Direct Inputs	Amount	Unit	ECEC (sej)
Sunlight	4.87E+16	J	4.87E+16
Soil (erosion)	3[a]	MT/ha	5.90E+16
Nitrogen from mineralization	6.47[b]	MT	5.00E+16
Phosphorous from mineralization	4.30[b]	MT	1.29E+17
Nitrogen from atmospheric deposition	4.30[b]	MT	3.33E+16
Evapotranspiration (rainfall)	8.97E+13[c]	J	1.38E+18
Atm. CO_2 removal (photosynthesis)	3.90E+03[b]	MT	4.06E+17
Detrital matter	1.18E+03[b]	MT	4.46E+17
Pastureland	822.7	ha	

MT= Metric ton

[a] Calculated based on soil erosion data provided Tolbert et al., 1998

[b] Calculated from Ayres and Ayres, 1998

[c] Energy of evapotranspiration is 6.49E+10 J per ha, Brandt-Williams, 2002

Table S19. Natural resources/services used in corn stover farming after allocating equally between corn stover and corn.

Direct Inputs	Quantity	Unit	(ECEC (sej)
Solar (photosynthesis)[a]	3.48E+16	J	3.48E+16
Soil Erosion	6.12	MT	2.43E+17
	9.22[b]	MT	
Nitrogen from mineralization			7.13E+16
	6.14[b]	MT	
Phosphorous from mineralization			1.84E+17
	6.14[b]	MT	
Nitrogen from atmosphere			4.74E+16
Evapotranspiration	7.10E+13[c]	J	5.66E+17
Atm. CO_2 removal (photosynthesis)	5.57E+03[b]	MT	5.79E+17
Detrital matter	1.69E+03[b]	MT	6.37E+17
Cropland	1119.69	ha	
Total			

[a] Considers six months corn growing season

[b] Calculated from Ayres and Ayres, 1998

[c] Energy of evapotranspiration is 6.05E+10 J per ha, Brandt-Williams, 2002

Table S20. Natural resources/services used in switchgrass farming

Direct Inputs	Amount	Unit	ECEC (sej)
Sunlight	4.27E+16	J	4.27E+16
Soil Erosion	0.2[a]	MT/ha	3.45E+15
Nitrogen	5.67[b]	MT	4.38E+16
Phosphorous	3.77[b]	MT	1.13E+17
Nitrogen from atmosphere	3.77[b]	MT	2.92E+16
Evapotranspiration (rainfall)	8.30E+13[c]	J	2.15E+18
Atm. CO_2 removal (photosynthesis)	3.42E+03[b]	MT	3.56E+17
Detrital matter	1.04E+03[b]	MT	3.92E+17
Pastureland	721.48	ha	

[a] Calculated based on soil erosion data provided by Tolbert et al., 1998

[b] Calculated from Ayres and Ayres, 1998

[c] Energy of evapotranspiration is 1.15E+11 J per ha, Brandt-Williams, 2002

Section S3: Allocation and Energy Credits

1. Allocation

Market-based allocation

Price of electricity = 7.2 cents/kWh

Price of ethanol = $ 2.24/gal

Table S21. Inputs for market-based allocation

Feedstock	Electricity credit due to excess electricity (kWh/gal)	Total electricity credit (kWh) per million gallons	Total energy credit (J)[a]	Total price for excess electricity or avoided landfilling ($)	Total price for ethanol ($)	% ethanol market share
Yellow poplar	2.2	2.2E+06	1.90E+13	1.58E+05	2.24E+06	93.4
Switchgrass	1.4	1.4E+06	1.25E+13	1.04E+05	2.24E+06	95.6
Corn stover	1.5	1.5E+06	1.27E+13	1.06E+05	2.24E+06	95.5
Newsprint	0.4	4.0E+05	3.87E+12[b]	2.74E+04[c]	2.24E+06	98.6
MSW			1.01E+12[d]	1.71E+04[e]	2.24E+06	99.2

gal = gallon (1 gallon = 3.79 liters).

[a] energy credit is subtracted from process energy to calculate return on energy investment.

[b] includes energy credit due to avoided energy use in landfilling .

[c] includes price of fuel (electricity, diesel, gasoline) avoided due to avoided land filling (see Table S22)

[d] only energy credit due to avoided energy use in landfilling.

[e] price of fuel (electricity, diesel, gasoline) avoided due to avoided land filling (see Table S22)

Displacement Method

The price of energy avoided or displaced as shown in Table S22 was used to calculate resources avoided using Eco-LCA and was subtracted from total resource consumption.

Table S22. Energy savings due to avoided land filling

Feedstock	Unleaded fuel ($)	Diesel ($)	Electricity ($)	Total energy ($)
Newsprint	3.03E+02	5.59E+03	3.75E+03	9.64E+03
MSW	9.90E+03	5.37E+02	6.64E+03	1.71E+04

Source: Solid Waste Authority of Central Ohio

2. **Energy credit calculations**

Energy Credit calculations:

Energy credits were calculated for market-based allocation and displacement method. Formulae for calculating energy credits are provided below.

1) Market value-based allocation

If a process produces co-products A (e.g., ethanol) and B (electricity) with corresponding market values of x and y, then

Energy credit for co-product electricity = Total process energy consumption * $y/(x+y)$

For MSW which has no co-product electricity, y represents the price of avoided energy.

2) Displacement method

If a process produces co-products A (e.g., ethanol) and B (electricity) and electricity displaces the grid electricity, then energy credit is equivalent to the primary energy of the displaced electricity in the grid. In this study, we assumed the US average electricity mix in 1997 (69% from fossil fuels (coal, natural gas, petroleum), 20% from nuclear, and 11% from renewable).

For nuclear and renewable electricity (hydropower, wind, solar, geothermal), 1 joule of electricity from lignin displaces 1 joule of primary energy, whereas for electricity from fossil fuels, on average, it displaces 3 J of primary energy considering efficiency of 33%. Therefore, on aggregate, 1 joule of co-product electricity displaces 2.4 J of primary energy.

Hence energy credit for co-product electricity = Co-product electricity (J)*2.4

In the case of newsprint and MSW, diversion of feedstock from a landfill to ethanol production avoids gasoline, diesel and electricity use. Hence, the energy credit equivalent to the amount of energy avoided is also added.

Note: For the displacement method, the amounts of other resources avoided were calculated using the price of electricity produced and energy avoided in Eco-LCA.

Section 4: Estimation of potential cellulosic ethanol production from various feedstocks

Table S23: Potential cellulosic ethanol production from various feedstocks

Feedstock	Potential supplies (dry MT)	Reference	Potential ethanol production (actual gallons)	Comments
MSW	1.38E+08	US EPA (20)	9.35E+09	
Newsprint	7.72E+07	US EPA (20)	8.26E+09	
Corn stover	6.80E+07	Perlack et al., 2005	6.11E+09	
Yellow Poplar	2.92E+08	Perlack et al., 2005, Heller et al, 2002	2.71E+10	Yield 13.1 MT per ha (Heller et al, 2002) and poplar is grown in 55 million acres (Perlack et al., 2005) which include idle cropland, cropland pasture and cropland
Switchgrass	3.42E+08	Perlack et al., 2005	2.95E+10	

MT = metric ton

As a reference, the volumes of ethanol produced and gasoline consumed in the US in 2009 were 10.6 billion gallons (http://www.ethanolrfa.org/pages/statistics) and 138 billion gallons, respectively (http://www.eia.doe.gov/ask/gasoline_faqs.asp).

Section S5: Conversion units

Table S24: Conversion units used in Eco-LCA

Natural resources	Exergy	Unit (per energy or mass)	Transformity	Unit
Crude oil	1	J/J	90720	sej/J
Natural gas	1	J/J	80640	sej/J
Coal	1.406402	J/J	1680000000	sej/g
Nuclear	1	J/g	336000	sej/g
Iron ore	111	/g Fe2O3	1680000000	sej/g
Copper ore	4713.333	/g three copper ores	1680000000	sej/g
Lead ore (as galena)	3100	J/g galena	1680000000	sej/g
Zinc ore (as sphalerite)	7670	J/g sphalerite	1680000000	sej/g
Gold ore	259.5434	J/g [=(J/mol) / (g/mol)]	1680000000	sej/g
Argenite (as silver ore)	2850	J/g acanthite	1680000000	sej/g
Molybdenum ore (as molybdenite)	10480	J/g Molybdenite	1680000000	sej/g
Titanium ore (as rutile TiO2)	264	J/g rutile	1680000000	sej/g
Alumina	197.6667	J/g three ores	1680000000	sej/g
Chromite (Fe3Cr2O3)	744	J/g Fe3Cr2O3 chromite	1680000000	sej/g
crushed stone	102.6667	J/g three ores considered as rock	1680000000	sej/g
Sand	102.6667	J/g three ores considered as rock	1680000000	sej/g
Apatite	26	J/g florapatite	1680000000	sej/g
Clay	57	J/g kaolinite Al2Si2O5	1680000000	sej/g
Feldspar (aluminosilicates of potassium, sodium, and calcium)	102.6667	J/g three ores considered as rock	1680000000	sej/g
Gypsum	149	J/g	1680000000	sej/g Ca
Garnet	279.62	J/g five ores	1680000000	sej/g
Potash (K2O)	4385.35	J/g	1680000000	sej/g

Contd.

Natural resources	Exergy	Unit	Transformity	Unit
Salt (NaCl)	248	J/g halite, rock salt	1680000000	sej/g
Barite (BaO)	128	J/g	1680000000	sej/g
Soda ash (sodium carbonate)	391.5094	J/g	1680000000	sej/g
Diatomite (a light soil consisting of siliceous diatom remains)	102.6667	J/g three ores considered as rock	1680000000	sej/g Silicon
Pumice (a porous or spongy form of volcanic glass)	102.6667	J/g three ores considered as rock	1680000000	sej/g
Talc and pyrophyllite	56.5	J/g talc	1680000000	sej/g Silicon
Quick lime (CaO)	186	J/g calcite CaCO3	1680000000	sej/g Ca
Tripoli	102.6667	J/g three ores considered as rock	1680000000	sej/g
Perlite (volcanic glass for insulation)	102.6667	J/g three ores considered as rock	1680000000	sej/g
Mica (scrap)	102.6667	J/g three ores considered as rock	1680000000	sej/g
Other Non-metallic minerals	102.6667	J/g three ores considered as rock	1680000000	sej/g
Nitrogen from mineralization	387.0533	J/g	1460869565	sej/g
Phosphorous from mineralization	495	J/g	7052830189	sej/g
Nitrogen deposition from atmosphere	387.0533	J/g	1460869565	sej/g
Detrital matter	20260.24	J/g	376723765	sej/g
Wood(dry)	15906.8	J/g	293957664	sej/g
Grass	15906.8	J/g dry grass	195888000	sej/g
Fish and related species	10032.75	J/g	90497913188	sej/g
Water	4.94	J/g	202540	sej/g
CO2 (Photosynthetic)	0	J/g	103992000	sej/g
Sunlight	1	J/J	1	sej/J
Hydroelectricity	1	J/J	46643	sej/J
Geothermal	1	J/J	10172	sej/J
Wind	1	J/J	2513	sej/J

Section S6: Energy contents and transformities

Table S25. Energy contents and transformities of fuels

Fuels	Energy content (LHV) (MJ)	Unit	Transformity	Unit
LPG	47.3	kg	1.11E+05	sej/J
Gasoline	44.8	kg	1.11E+05	sej/J
Diesel	43.3	kg	1.11E+05	sej/J
Still gas	35.8	liter	1.11E+05	sej/J
Petroleum coke	38.1	liter	1.11E+05	sej/J
Coal	20.6	kg	1.68E+09	sej/g
Residual fuel oil	39.1	liter	1.11E+05	sej/j
Crude oil	43.4	kg	9.07E+04	sej/J
Natural gas	55.1	kg	8.06E+04	sej/J
Hydroelectricity	1	MJ	4.66E+04	sej/J
Wind	1	MJ	2.51E+03	sej/J
Geothermal	1	MJ	1.02E+04	sej/J
Ethanol	26.8	kg		

Energy content and transformities of feedstocks

Municipal solid waste (MSW): energy content = 10 MJ/kg, transformity = 6.89E+04 sej/g

Newsprint: energy content = 16 MJ/kg, transformity = 6.89E+04 sej/g

Section S7: List of natural resources considered and classification

Table S26: List of natural resources considered used in Eco-LCA and classification

1) Ecosystem goods and services

Classification	Type

Provisioning	Renewable Energy
	    Hydropower, wind, geothermal, sunlight
	Non-renewable energy
	    Nuclear, coal, natural gas, crude oil
	Metal ores
	    Fe, Cu, Cr, Au, Pb, Zn, Ag, Mo, Ti, Al
	Sand, stone
	Non-Metallic minerals
	    Apatite, clay, gypsum, feldspar, garnet, potash (K_2O), salt (NaCl), soda ash, diatomite, barite, tripoli, talc, pumice, perlite, mica, quick lime, and other non-metallic minerals
	Wood
	Fish
	Soil
	Grass
	Water (Irrigation, Power generation, public water supply)

Regulation and Maintenance	Detrital Matter Carbon sequestration (Photosynthetic CO2) Pollination Nitrogen mineralization Phosphorous mineralization Nitrogen deposition from atmosphere

2) Land use: Cropland, Timberland, and Pasture/Rangeland

Section S8: Results

Table S27. Comparison of renewability (%) of cellulosic ethanol with gasoline and corn ethanol

Feedstock	Inputs from economy		Direct inputs from nature		Feedstock ECEC as waste and residues	% renewability	% renewability
	Ren. ECEC	Non-ren. ECEC	Ren. ECEC	Non-ren. ECEC	Renewable ECEC		considering ECEC of feedstock from waste and agricultural residue as free, i.e. (zero)
Corn Stover-1	2.6E+18	9.8E+18	1.9E+18			31.1	31.1
Corn Stover-2	1.7E+18	5.1E+18			1.8E+19	79.1	25.0
Switchgrass	1.2E+18	5.0E+18	3.9E+17			24.8	NA
Yellow poplar	5.9E+16	2.3E+18	2.1E+18			48.0	NA
Newsprint	3.9E+16	1.6E+18			1.0E+19	86.7	2.4
MSW	2.6E+16	3.5E+18			1.2E+19	77.1	0.7
Corn ethanol	3.0E+17	4.8E+18	1.2E+18			23.8	NA
Gasoline	2.8E+17	4.3E+19		2.8E+20		0.1	NA

Note: ECEC values in this table correspond to 3.79E+06 liters for ethanol and 3.67E+07 liters for gasoline.

Table S28: Industrial Cumulative Exergy Consumption (ICEC) for producing 1 million gasoline equivalent gallons of various fuels obtained from hybrid- ECOLCA based on market-based allocation

Cumulative consumption of resources given in Tables S28 (ICEC) and S29 can be expressed in various units such as mass, energy, ecological cumulative exergy consumption where appropriate using conversion factors provided in Section 5. Ethanol to gasoline ratios provided in Fig. 2 in the main paper are based on Tables S28 and S29.

Example: ICEC consumption of water for 1 million gallons gasoline equivalent of newsprint ethanol is 3.97E+11 J. Exergy content of water is 4.94 J/kg or 4.94 J/ liter. Hence water consumption per 1 gasoline equivalent liter of newsprint ethanol is = 3.97E+11 J * 1/1000000*1/3.79*1/4.94 = 21.2 liter. 1 gallon = 3.79 liter.

Unit: Joule

	Crude oil	Natural gas	Coal	Nuclear	Sunlight	Hydroelectricity	Geothermal	Wind electricity
Corn stover 1	3.08E+13	6.06E+13	1.04E+13	6.83E+11	3.89E+16	3.87E+11	1.60E+10	3.56E+09
Corn stover 2	2.20E+13	1.97E+13	3.22E+12	3.71E+11	2.15E+15	2.10E+11	8.71E+09	1.94E+09
Switchgrass	2.52E+13	1.85E+13	3.21E+12	3.66E+11	6.14E+16	2.07E+11	8.59E+09	1.91E+09
Yellow Poplar	9.36E+12	1.02E+13	2.08E+12	2.23E+11	6.72E+16	1.26E+11	5.24E+09	1.17E+09
Newsprint	1.37E+13	2.58E+12	1.40E+12	1.64E+11	1.50E+15	9.27E+10	3.84E+09	8.54E+08
MSW	7.47E+12	1.92E+13	1.34E+13	1.84E+12	2.94E+14	1.04E+12	4.30E+10	9.58E+09
Gasoline	2.08E+14	7.95E+12	3.76E+12	4.39E+11	3.19E+14	2.48E+11	1.03E+10	2.29E+09

	Fe	Cu	Pb	Zn	Au	Ag	Mo	Ti	Al
Corn stover 1	7.22E+09	9.95E+11	5.02E+08	1.30E+10	3.33E+10	1.78E+09	3.94E+10	7.31E+07	4.90E+08
Corn stover 2	4.86E+09	7.38E+11	3.72E+08	9.62E+09	1.89E+10	1.01E+09	2.24E+10	4.15E+07	2.78E+08
Switchgrass	7.42E+09	6.94E+11	3.50E+08	9.05E+09	1.85E+10	9.86E+08	2.19E+10	4.05E+07	2.72E+08
Yellow Poplar	3.82E+09	4.48E+11	2.26E+08	5.84E+09	1.21E+10	6.47E+08	1.43E+10	2.66E+07	1.78E+08
Newsprint	3.52E+09	5.44E+11	2.75E+08	7.09E+09	4.22E+09	2.25E+08	5.00E+09	9.27E+06	6.22E+07
MSW	2.59E+09	2.42E+11	1.22E+08	3.16E+09	1.81E+09	9.67E+07	2.15E+09	3.98E+06	2.67E+07
Gasoline	4.86E+09	7.38E+11	3.72E+08	9.62E+09	1.89E+10	1.01E+09	2.24E+10	4.15E+07	2.78E+08

Note: 1.44 gallons ethanol= 1 gasoline gallon equivalent in terms of driving a 2006 Chevrolet Impala by unit distance.

Contd.

	Cr	Stone	Sand	Non-Metallic minerals	Nitrogen from mineralization	Phosphorous from mineralization	Nitrogen from atmospheric deposition	Detrital matter
Corn stover 1	4.35E+07	1.34E+11	1.41E+10	5.02E+11	1.86E+10	1.27E+10	1.24E+10	3.70E+13
Corn stover 2	2.47E+07	8.61E+10	9.17E+09	3.45E+11	4.88E+08	3.32E+08	3.25E+08	1.43E+12
Switchgrass	2.41E+07	7.07E+10	7.77E+09	2.75E+11	1.66E+10	1.13E+10	1.10E+10	3.08E+13
Yellow Poplar	1.58E+07	4.52E+10	3.06E+09	2.77E+10	1.82E+10	1.24E+10	1.21E+10	3.36E+13
Newsprint	5.52E+06	1.36E+10	1.82E+09	2.45E+10	3.71E+08	2.53E+08	2.47E+08	1.07E+12
MSW	2.37E+06	8.45E+10	4.08E+09	1.15E+10	1.04E+07	7.08E+06	6.92E+06	1.72E+10
Gasoline	2.05E+06	6.07E+09	1.90E+09	5.26E+09	1.25E+07	8.54E+06	8.35E+06	3.90E+10

	Wood	Grass	Fishery	Water	Soil
Corn stover 1	3.16E+11	3.05E+10	1.70E+09	6.24E+12	3.16E+12
Corn stover 2	1.88E+11	1.52E+10	1.06E+09	7.56E+11	7.26E+10
Switchgrass	2.02E+11	1.66E+10	1.05E+09	8.13E+11	1.41E+11
Yellow Poplar	1.26E+11	1.21E+10	5.63E+08	7.17E+11	8.18E+11
Newsprint	1.06E+11	1.36E+10	5.34E+08	3.97E+11	5.50E+10
MSW	9.05E+10	2.40E+09	3.84E+08	8.13E+11	1.42E+09
Gasoline	8.49E+10	3.30E+09	4.36E+08	2.81E+11	2.73E+09

Table S29: Pollination service and land use for producing 1 million gasoline equivalent gallons of various fuels

	Pollination (hives*day)	Cropland (ha)	Pasture/Rangeland (ha)	Timberland (ha)
Corn stover 1	2.23E+01	1.13E+03	4.50E+00	1.70E+01
Corn stover 2	1.48E+01	2.48E+01	2.25E+00	9.26E+00
Switchgrass	1.62E+01	3.34E+01	1.04E+03	1.15E+01
Yellow Poplar	1.38E+01	2.41E+01	1.10E+03	6.30E+00
Newsprint	1.22E+01	1.86E+01	2.01E+00	4.72E+00
MSW	8.80E-01	3.00E-01	3.54E-01	4.31E+00
Gasoline	2.16E+00	6.78E-01	4.87E-01	4.22E+00

Graphs: Results for market value-based allocation

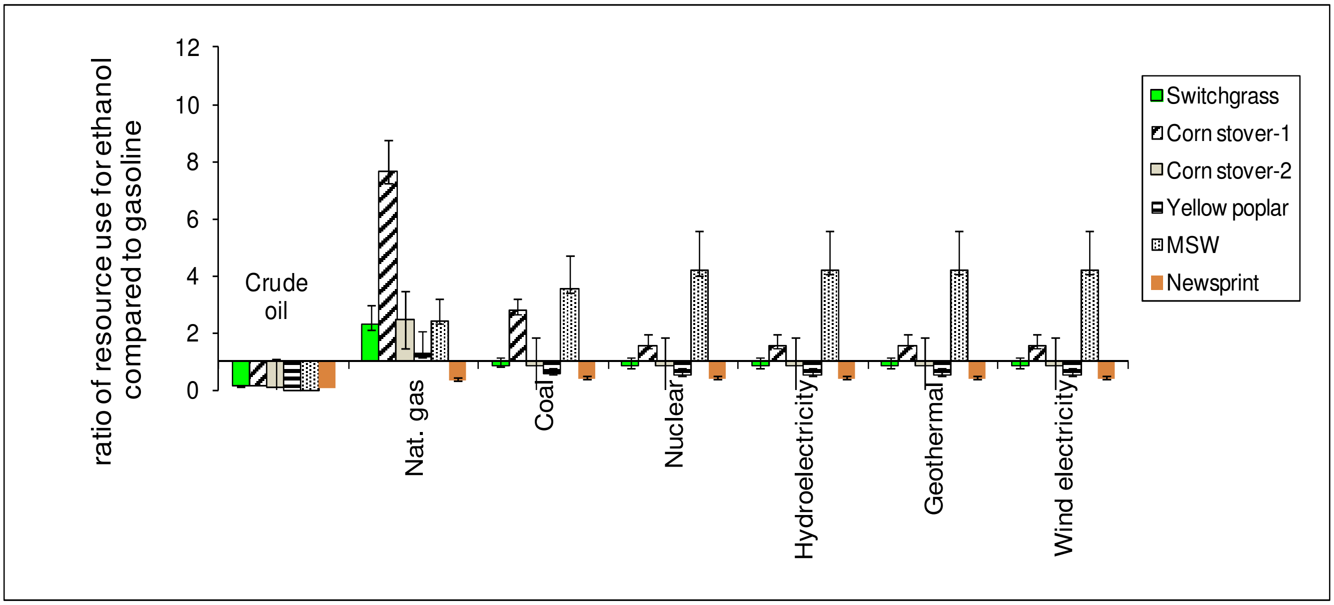


Fig.S1. Relative consumption of various energy types for cellulosic ethanol with respect to gasoline. Error bars represent the range obtained from sensitivity analysis (market value-based allocation).

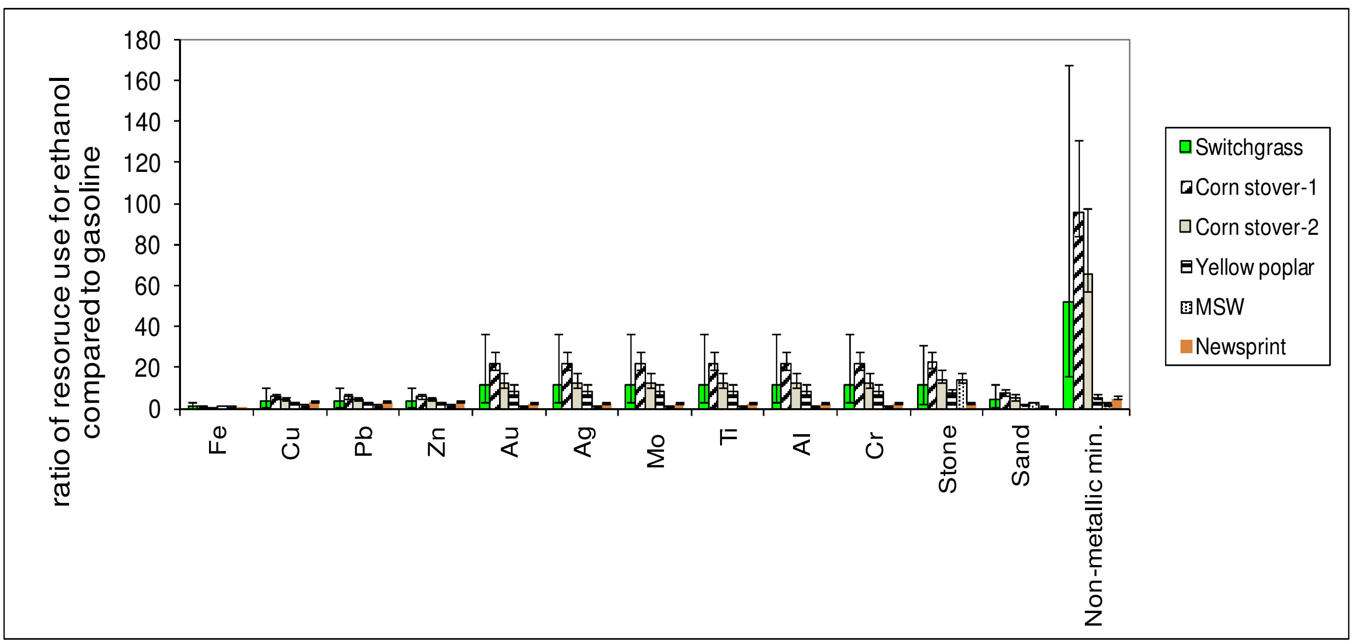


Fig.S2. Relative consumption of metal ores, stone, sand and non-metallic minerals for cellulosic ethanol with respect to gasoline (market value-based allocation). Non-metallic minerals include apatite, clay, gypsum, feldspar, garnet, potash (K_2O), salt (NaCl), soda ash, diatomite, barite, tripoli, talc, pumice, perlite, mica, quick lime, and other non-metallic minerals.

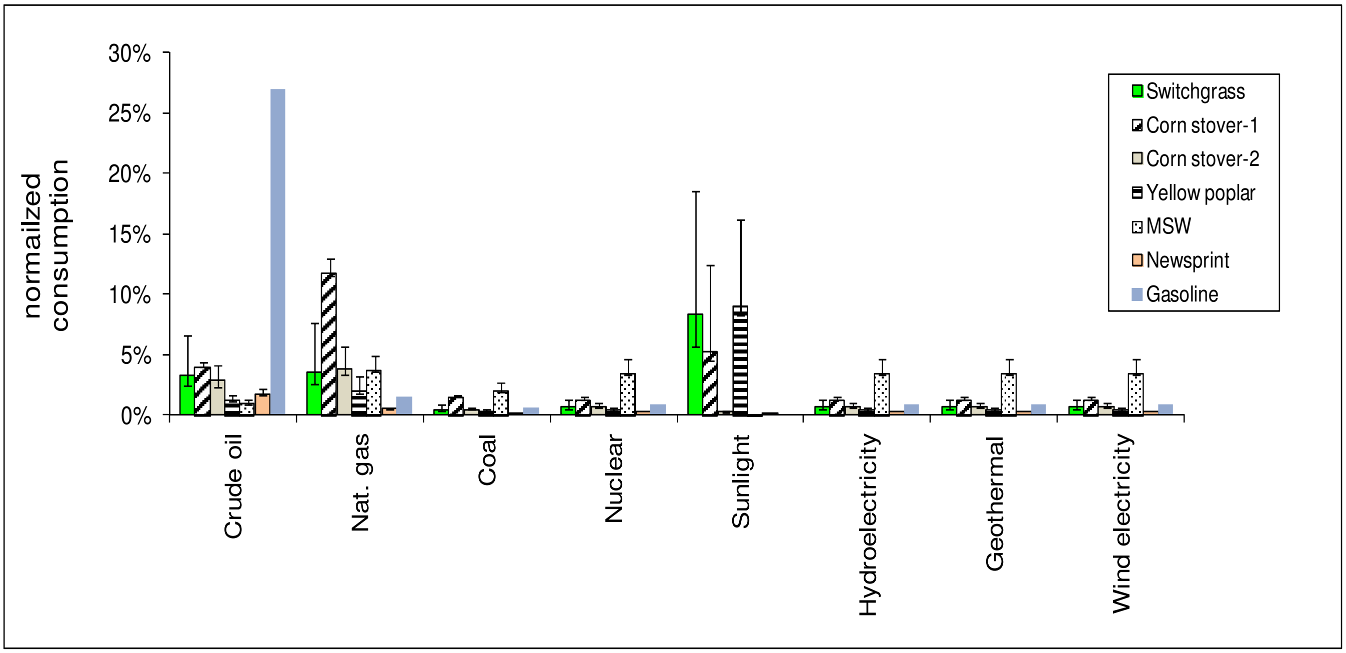


Fig. S3. Percent of the US energy flows (1997) consumed when meeting 30% of the US gasoline demand. Error bars represent the range obtained from sensitivity analysis (market value-based allocation).

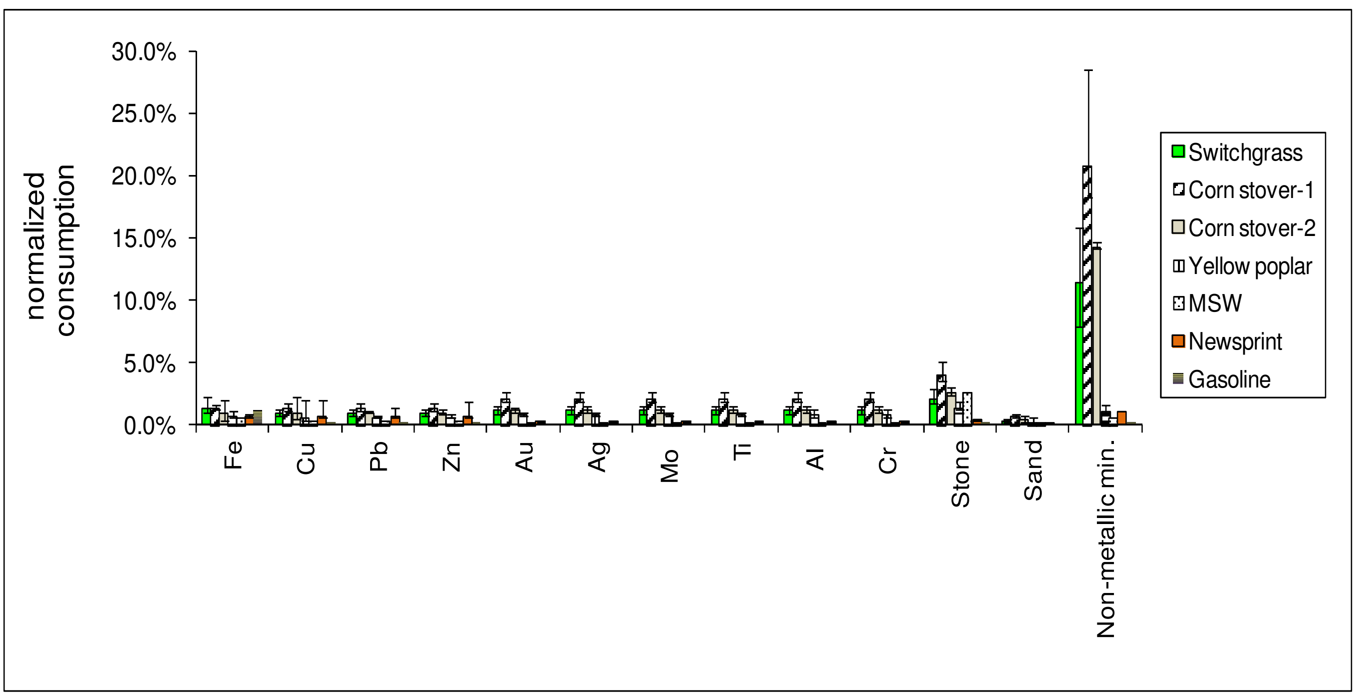


Fig.S4. Percent of the US metallic ores and non-metallic minerals (1997) consumed when meeting 30% of the US gasoline demand (market value-based allocation).

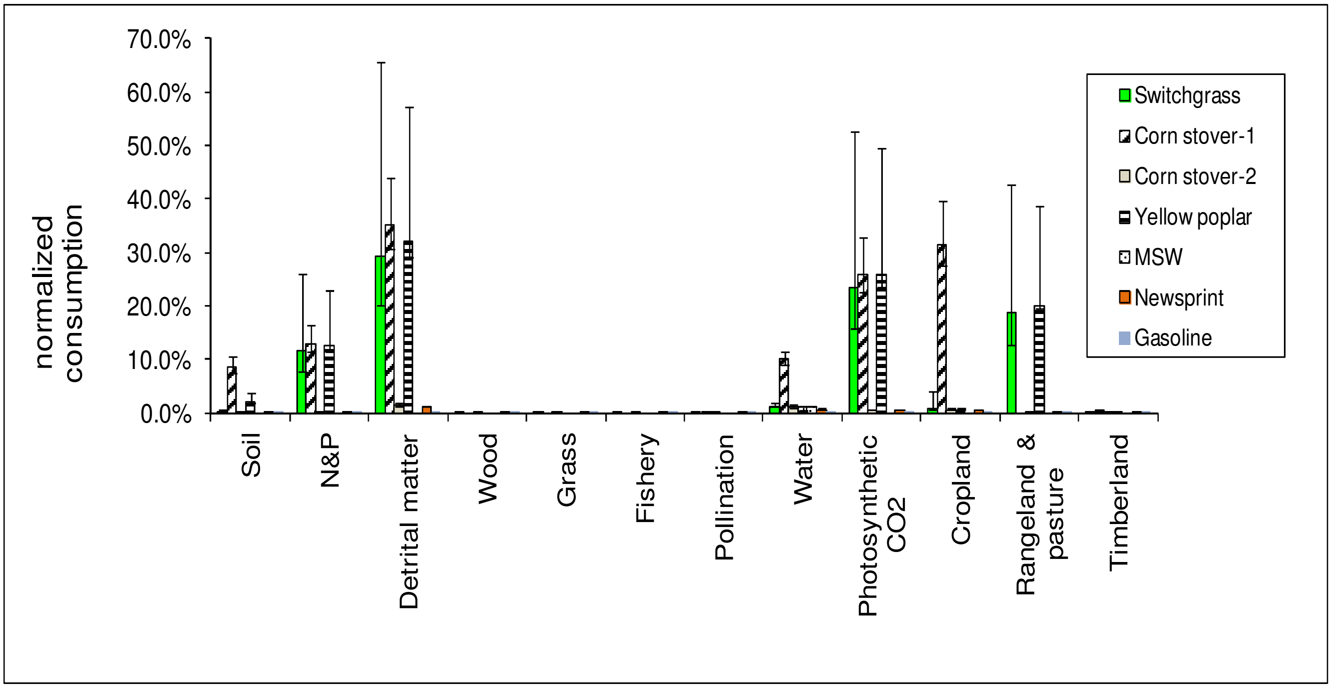
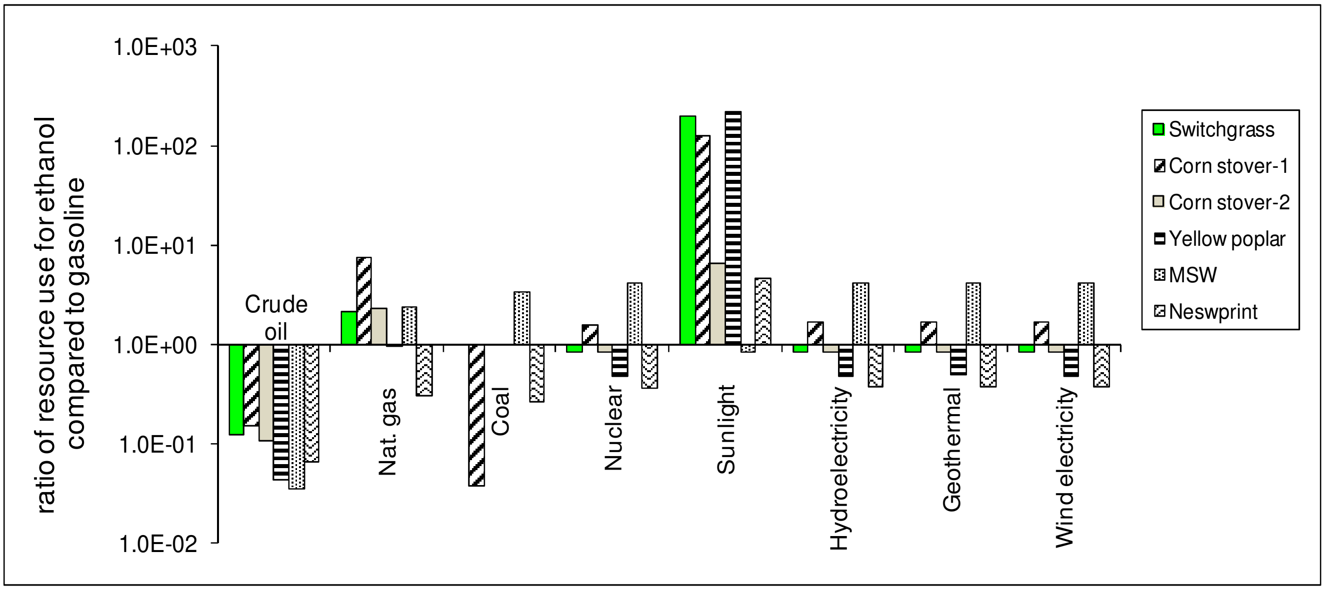


Fig.S5. Percent of flows of the US ecosystem goods and services (1997) consumed when cellulosic meeting 30% of gasoline demand (market value-based allocation).

Graphs: Results for displacement method allocation



Note: Missing columns for coal and natural gas are due to negative values that result when the amounts of resources avoided (displaced) are larger than the amounts consumed.

Fig.S6. Relative consumption of various energy types for cellulosic ethanol with respect to gasoline. Error bars represent the range obtained from sensitivity analysis. Displacement method for allocation.

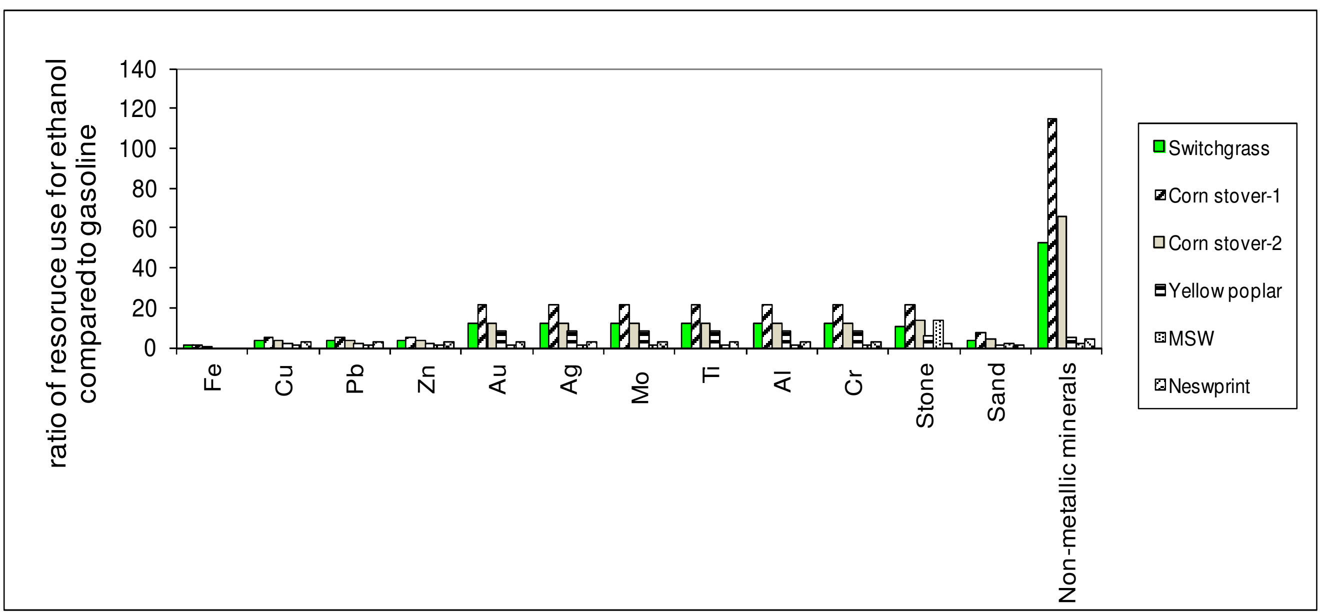


Fig.S7. Relative consumption of metal ores, stone, sand and non-metallic minerals for cellulosic ethanol with respect to gasoline. Displacement method for allocation.

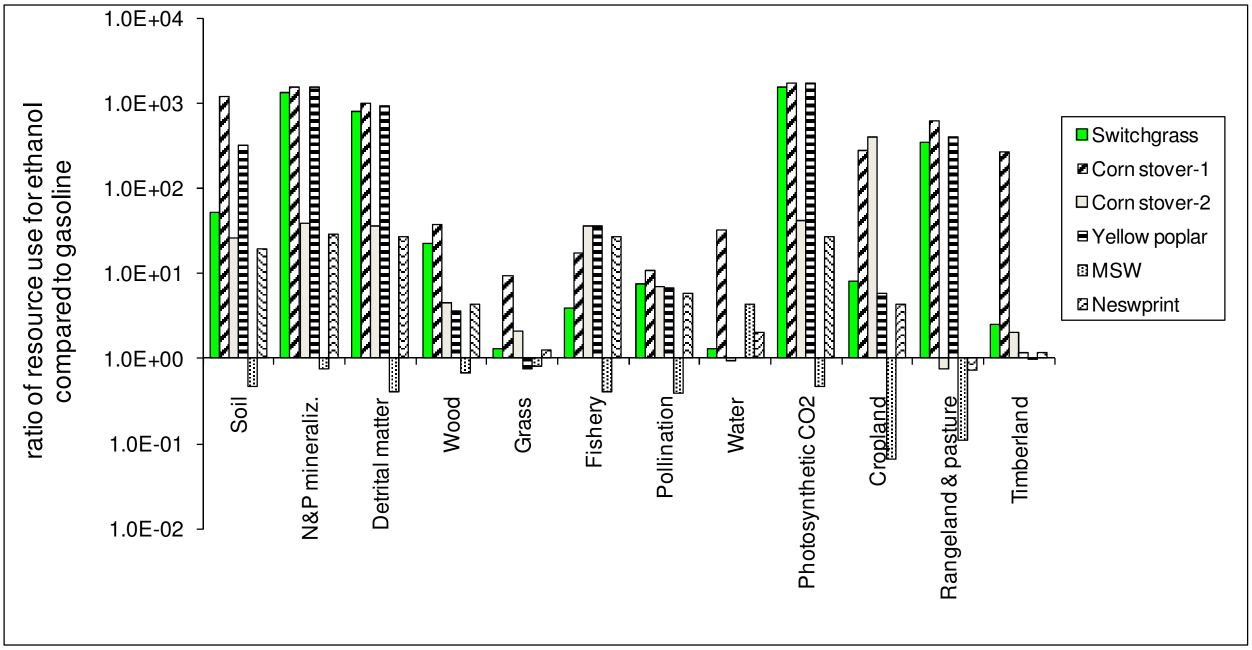


Fig.S8. Relative consumption/use of various ecosystem goods and services and land for cellulosic ethanol with respect to gasoline. Displacement method for allocation.

Graphs: Renewability vs return on energy investment graph

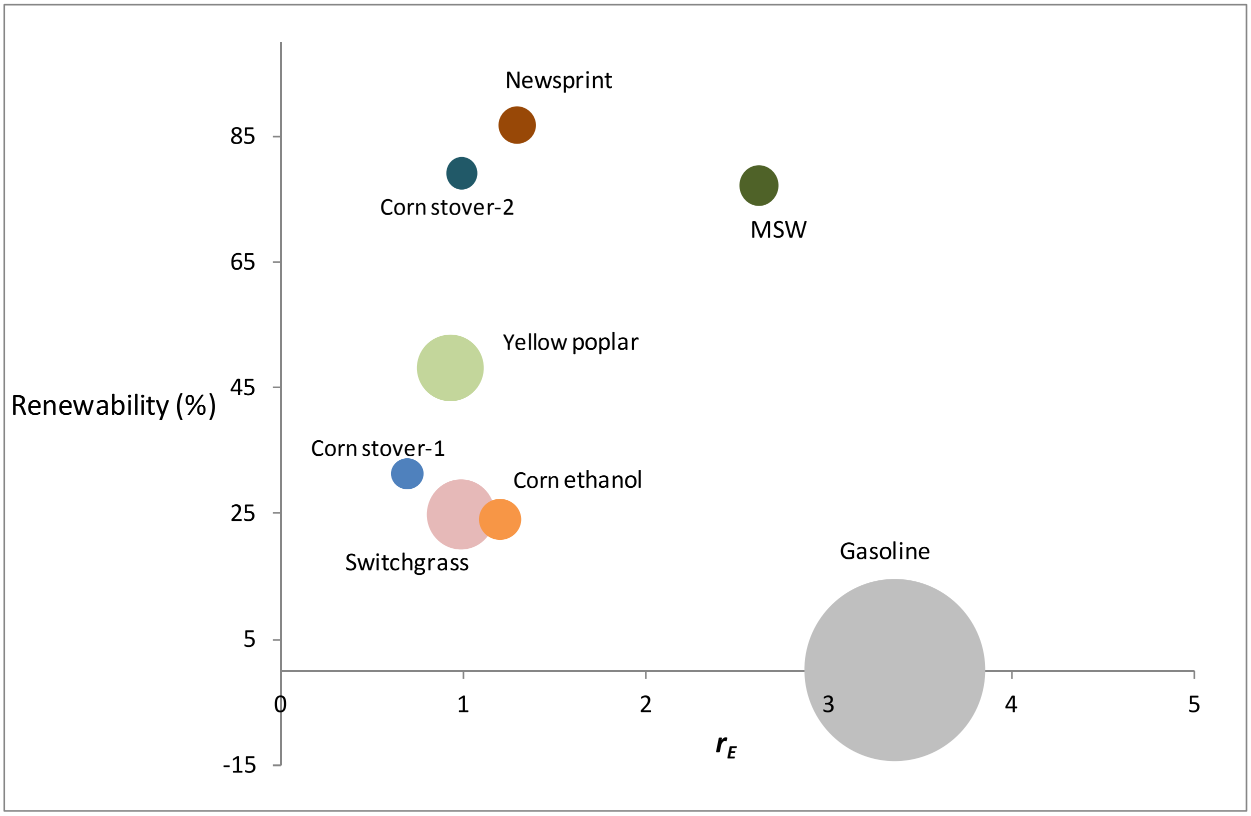


Fig.S9. Renewability vs return on energy investment and production potential. For a reference, the size of a bubble for corn ethanol represents 27.9 billion gasoline equivalent liters produced in the US in 2009.

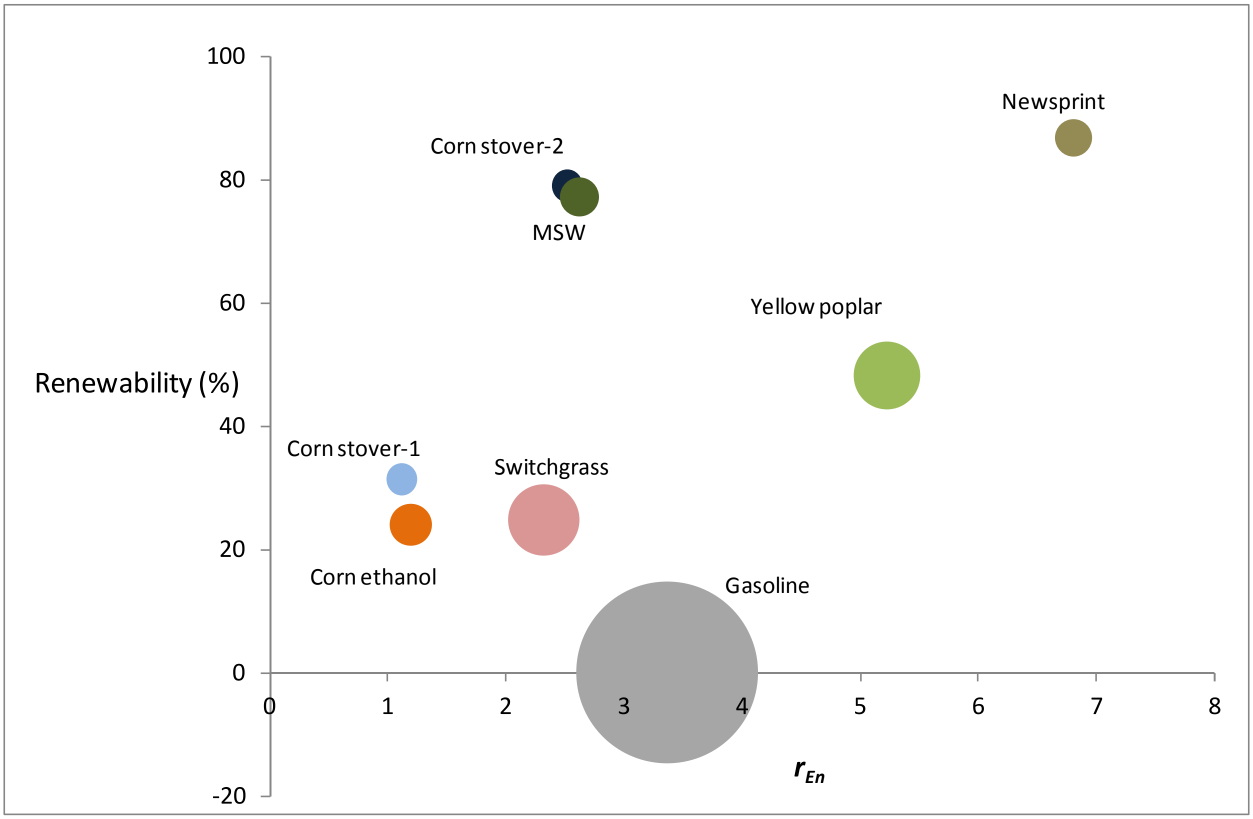


Fig.S10. Renewability vs return on energy investment (non-renewable) and production potential.

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