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Supporting Online Material for

Greater Transportation Energy and GHG Offsets from Bioelectricity Than Ethanol

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Supporting Online Material

Greater transportation energy and GHG offsets from bioelectricity than ethanol

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Transportation Energy:

Table S1. Gross transportation output of the bioenergy fuel cycle for ethanol and bioelectricity[a].

	Corn	Switchgrass
Harvest:		
Harvest Mass (kg ha^{-1} y^{-1})	8,746	13,450
Harvest Energy Content (MJ ha^{-1} y^{-1})[b]	157,427	242,101
Ethanol:		
Gross Ethanol Production (MJ ha^{-1} y^{-1})	73,424	108,855
Gross Gasoline Equivalent (l ha^{-1} y^{-1})[b]	2,335	3,462
Electricity:		
Gross Electricity Production (MJ ha^{-1} y^{-1})[c]	52,140	80,184
Gross Electricity Production (kWh ha^{-1} y^{-1})	14,483	22,273

[a]All values based on EBAMM data[1] unless indicated otherwise.
[b]Heat contents are 31.45 MJ l^{-1} for gasoline and 18 MJ l^{-1} for biomass[1]. For both ethanol and bioelectricity, the corn cases use only the kernels and the switchgrass case uses the total harvested biomass. The relatively small distribution energy costs (1.7% of throughput for cellulosic case) were not included[2].
[c]Based on thermal efficiency of 32% for biomass boiler[2], 92% transmission efficiency[2] and 90% electric vehicle battery charging efficiency[3].

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Table S2. EBAMM fuel cycle inputs for ethanol and bioelectricity pathways.[a]

	Corn	Switchgrass
Ethanol:		
Net Primary Coal Inputs (MJ ha^{-1} y^{-1})	29,513	-3,595
Net Primary NG Inputs (MJ ha^{-1} y^{-1})	19,774	1,001
Net Nuclear and Renewables Inputs (MJ ha^{-1} y^{-1})	1,951	63
Total Net Electricity Inputs (kWh ha^{-1} y^{-1})[b]	4,310	-158
Net Primary Petroleum Inputs (MJ ha^{-1} y^{-1})	2,727	7,145
Net Gasoline Eqiuvalent Inputs (l ha^{-1} y^{-1})[c]	78	204
Bioelectricity:		
Net Primary Coal Inputs (MJ ha^{-1} y^{-1})	724	763
Net Primary NG Inputs (MJ ha^{-1} y^{-1})	582	2,136
Net Nuclear and Renewables Inputs (MJ ha^{-1} y^{-1})	1,589	383
Total Net Electricity Inputs (kWh ha^{-1} y^{-1})[b]	441	327
Net Primary Petroleum Inputs (MJ ha^{-1} y^{-1})	2,727	7,297
Net Gasoline Eqiuvalent Inputs (l ha^{-1} y^{-1})[c]	78	209

[a]All values based on EBAMM data[1] unless indicated otherwise. Inputs account for agriculture and biomass energy conversion steps of the fuel cycle. Energy conversion step excludes capital equipment and water related energy costs because EBAMM included data for biorefineries but not for electricity plants. These exclusions are expected to be small relative to other larger fuel cycle and vehicle cycle consumption for ethanol[1] and bioelectricity[4] pathways.

[b]For use in net transportation analysis, the net electricity inputs are calculated at potential point-of-use (field-to-tank) based on thermal efficiency conversions (34% coal and 42% natural gas[2]), 92% transmission efficiency[2], and 90% electric vehicle battery charging efficiency[3].

[c]For use in net transportation analysis, liquid fuels inputs calculated at potential point-of-use (field-to-tank) based on petroleum to gasoline conversion efficiency of 90%[1].

Table S3. Input energy for vehicle cycle (vehicle material recovery and production, component fabrication, assembly, and disposal/recycling) of battery electric vehicles (BEV) and internal combustion vehicles (ICV).

Energy Source	Primary Energy[a]	Energy ICV[b]	Energy BEV[c]
Coal	0.146 MJ km^{-1}	$1.21*10^{-5}$ kWh km^{-1}	$2.00*10^{-5}$ kWh km^{-1}
Natural gas	0.159 MJ km^{-1}	$1.62*10^{-5}$ kWh km^{-1}	$2.68*10^{-5}$ kWh km^{-1}
Petroleum[d]	0.083 MJ km^{-1}	$2.36*10^{-3}$ l km^{-1}	$3.90*10^{-3}$ l km^{-1}
Other	0.027 MJ km^{-1}	$7.01*10^{-6}$ kWh km^{-1}	$1.16*10^{-5}$ kWh km^{-1}

[a]GREET 2.7 vehicle cycle energy for ICV scaled by the vehicle lifetime of 257,440 km (160,000 miles)[5].

[b]Energy at point of vehicle. Conversion of coal and natural gas to electricity accounts for thermal efficiency (34% coal and 42% gas[2]), 92% transmission efficiency[2] and 90% electric vehicle battery charging efficiency[3]. Other energy source assumed to be primarily electricity and includes accounting of battery charging efficiency.

[c]Vehicle cycle for BEV is 1.65 times ICV primarily due to the battery and battery replacement during the vehicle lifetime[6,7].

[d]Petroleum energy is given as energy in petroleum for primary energy and as energy in gasoline for ICV and BEV energy (gasoline conversion efficiency is 90% and gasoline heating value is 31.45 MJ l^{-1}).

Table S4. EPA vehicle efficiency data[a] for battery electric vehicles (BEV) and internal combustion vehicles (ICV).

Make	Engine	Efficiency (city/highway)[b]			Description
		$kWh\ 100km^{-1}$	$l\ 100km^{-1}$	$km\ MJ^{-1}$	
Small Car	BEV	20/25	-	1.4/1.1	2001 Ford Th!nk, Ni-Cd, 27 kW AC
Small Car	ICV	-	7/6	0.5/0.6	2001 Suzuki Swift 4 cyl, 1.3 L, Man. 5-spd, Reg.
Midsize Car	BEV	18/16	-	1.5/1.7	2000 Nissan Altra, Lithium-Ion, 62 kW AC Ind.
Midsize Car	ICV	-	11/8	0.3/0.4	2000 Nissan Altima 4 cyl, 2.4 L, Man. 5-spd, Reg.
Small SUV	BEV	17/21	-	1.7/1.3	2003 Toyota RAV4 2WD, Ni Metal Hydride
Small SUV	ICV	-	9/8	0.3/0.4	2003 Toyota RAV4 2WD 4cyl, 2L, Man 5spd, Reg
Fullsize SUV	BEV	34/45	-	0.8/0.6	2002 Ford Explorer 2WD, PbAcid, 67kW AC Ind
Fullsize SUV	ICV	-	16/12	0.2/0.3	2002 Ford Explorer 2WD 6cyl, 4L, Man, 5spd Reg

[a]EPA recently updated efficiency ratings for all vehicles years to reflect more realistic driving conditions[8]. Improved efficiency for ethanol relative to gasoline is small relative to differences between BEV and ICV efficiency[6].

[b]Energy efficiency ($mi\ MJ^{-1}$) calculated based on gasoline LHV of 31.45 $MJ\ l^{-1}$.

Table S5. Gross transportation for ethanol and bioelectricity ($km\ ha^{-1}\ y^{-1}$).

	Ethanol City	Bioelectricity City	Ethanol Highway	Bioelectricity Highway
Corn:				
Small Car	35,750	58,295	41,709	45,499
Midsize Car	20,854	64,326	27,806	71,748
Small SUV	24,827	69,091	30,785	54,866
Fullsize SUV	14,896	34,545	19,861	25,909
Switchgrass:				
Small Car	53,002	89,650	61,835	69,971
Midsize Car	30,918	98,924	41,223	110,338
Small SUV	36,807	106,252	45,640	84,376
Fullsize SUV	22,084	53,126	29,445	39,844

Table S6. Transportation for ethanol and bioelectricity accounting for fuel cycle energy (km ha^{-1} y^{-1})[a].

	Ethanol-City	Bioelectricity-City	Ethanol-Highway	Bioelectricity-Highway
Corn:				
Small Car	12,870	55,062	23,389	42,514
Midsize Car		61,380	187	68,310
Small SUV		65,846	9,346	51,919
Fullsize SUV	1,548	32,840	9,559	24,339
Switchgrass:				
Small Car	50,663	85,089	58,801	65,176
Midsize Car	29,966	95,555	39,764	106,174
Small SUV	35,572	102,416	43,690	80,340
Fullsize SUV	21,249	50,986	28,058	37,462

[a]Fuel cycle accounts for energy inputs and co-products. Petroleum inputs are accounted as transportation costs using ICV efficiencies while coal, nautral gas, and electricity inputs are accounted as transportation costs using BEV efficiencies. Negative distances occur if the distance that could be traveled with fuel cycle inputs (petroleum via ICV and electricity, coal and natural gas via BEV) is greater than the distance traveled with the gross ethanol output.

Table S7. Net transportation for ethanol and bioelectricity accounting for fuel cycle and vehicle cycle energy (km ha^{-1} y^{-1})[a].

	Ethanol-City	Bioelectricity-City	Ethanol-Highway	Bioelectricity-Highway
Corn:				
Small Car	10,231	36,450	19,318	30,315
Midsize Car		40,393	143	41,743
Small SUV		41,399	7,570	35,648
Fullsize SUV	1,369	26,601	8,648	20,516
Switchgrass:				
Small Car	40,276	56,328	48,566	46,475
Midsize Car	23,751	62,882	30,385	64,881
Small SUV	27,562	64,391	35,385	55,163
Fullsize SUV	18,799	41,299	25,382	31,578

[a]Vehicle cycle inputs are the product of the fuel cycle distance (Table S6), the per mile vehicle cycle energy input (Table S3), and the vehicle efficiencies (Table S4). Net transportation is not calculated for cases in which the fuel cycle distance (Table S6) is negative.

Table S8. Hybridization efficiency improvement (Conventional : Hybrid) from reported EPA fuel economies[8].

City	Highway	Vehicle
1.60	1.25	Honda Civic Hybrid 4 cyl, 1.3 L, Automatic (variable gear ratios), HEV, Regular Honda Civic 4 cyl, 1.8 L, Automatic 5-spd, Regular
1.52	1.06	Nissan Altima Hybrid 4 cyl, 2.5 L, Automatic (variable gear ratios), HEV, Regular Nissan Altima 4 cyl, 2.5 L, Automatic (variable gear ratios), Regular
1.89	1.19	Ford Escape Hybrid FWD 4 cyl, 2.5 L, Automatic (variable gear ratios), Regular Ford Escape FWD 6 cyl, 3 L, Automatic 6-spd, Regular
1.75	1.16	GMC Yukon 1500 Hybrid 2WD 8 cyl, 6 L, Automatic (variable gear ratios), Regular GMC Yukon 1500 2WD 8 cyl, 6.2 L, Automatic 6-spd, Gasoline or E85

Table S9. Net transportation for ethanol and bioelectricity with hybrid efficiencies for the ICV's and IGCC efficiency for electricity production (mi ha^{-1} y^{-1})[a].

	Ethanol-City	Bioelectricity-City	Ethanol-Highway	Bioelectricity-Highway
Corn:				
Small Car	25,985	43,043	27,290	37,147
Midsize Car	5,272	49,208	1,464	52,274
Small SUV	14,769	48,634	12,114	44,168
Fullsize SUV	10,783	32,442	11,350	25,659
Switchgrass:				
Small Car	62,316	65,941	59,806	56,709
Midsize Car	35,285	76,153	32,220	81,030
Small SUV	49,934	74,979	41,763	68,108
Fullsize SUV	32,171	49,938	29,237	39,387

[a] IGCC efficiency of 40%[2] and hybridization efficiency improvements in Table S8.

Table S10. GHG reductions by offsetting gasoline use with gross output from ethanol and bioelectricity pathways (Mg CO_2e ha^{-1} y^{-1})[a].

	Ethanol-City	Bioelectricity-City	Ethanol-Highway	Bioelectricity-Highway
Corn:				
Small Car	6.9	11.3	6.9	7.5
Midsize Car	6.9	21.3	6.9	17.9
Small SUV	6.9	19.3	6.9	12.3
Fullsize SUV	6.9	16.0	6.9	9.0
Switchgrass:				
Small Car	10.2	17.4	10.2	11.6
Midsize Car	10.2	32.8	10.2	27.5
Small SUV	10.2	29.6	10.2	19.0
Fullsize SUV	10.2	24.7	10.2	13.9

[a]Based on gasoline offset with a life cycle emission rate of 94.0 g CO_2e/MJ gasoline.

Table S11. GHG emissions due to fuel cycle processes (Mg CO_2e ha^{-1} y^{-1}).

	Ethanol		Bioelectricity	
	Corn	*Switch*	*Corn*	*Switch*
Agriculture	2.70	0.97	2.70	0.97
Energy Conversion[a]	4.33	0.03		
Feedstock Trans.	0.17	0.26	0.17	0.26
Ag Co-Products	-1.82			
Refinery Co-Products		-0.54		
Distribution[b]	0.10	0.15		

[a]Energy conversion step excludes capital equipment and water related energy costs because EBAMM included data for biorefineries but not for electricity power plants. These exclusions are expected to be small relative to other larger fuel cycle and vehicle cycle consumption for ethanol and bioelectricity pathways.
[b]Ethanol distribution inputs are based on emissions rate of 1.4 g CO_2e MJ^{-1}.

Table S12. Fuel cycle GHG offsets (gross gasoline offsets - net fuel cycle emissions) (Mg CO_2e ha^{-1} y^{-1}).

	Ethanol-City	Bioelectricity-City	Ethanol-Highway	Bioelectricity-Highway
Corn:				
Small Car	1.4	8.4	1.4	4.7
Midsize Car	1.4	18.5	1.4	15.0
Small SUV	1.4	16.4	1.4	9.5
Fullsize SUV	1.4	13.2	1.4	6.2
Switchgrass:				
Small Car	9.4	16.1	9.4	10.4
Midsize Car	9.4	31.6	9.4	26.2
Small SUV	9.4	28.4	9.4	17.7
Fullsize SUV	9.4	23.4	9.4	12.6

Table S13. Total GHG reductions (gross offset - fuel cycle - vehicle cycle) (Mg CO_2e ha^{-1} y^{-1})[a].

	Ethanol-City	Bioelectricity-City	Ethanol-Highway	Bioelectricity-Highway
Corn:				
Small Car	1.0	5.6	0.7	2.5
Midsize Car		15.4	1.4	11.5
Small SUV		13.0	1.1	6.8
Fullsize SUV	1.4	11.5	1.1	4.9
Switchgrass:				
Small Car	7.8	11.8	7.5	7.1
Midsize Car	8.4	26.7	8.1	20.8
Small SUV	8.3	23.2	8.0	13.6
Fullsize SUV	8.7	20.9	8.5	10.7

[a]Vehicle cycle inputs are the product of the fuel cycle distance (Table S6) and the GREET vehicle cycle emissions[2] rate 13.1 Mg CO_2e $lifetime^{-1}$. BEV's are assumed to have an emissions rate that is 1.65 times the ICV rate. Net transportation is not calculated for cases in which the fuel cycle distance (Table S6) is negative.

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